Planning, Designing, and Constructing Tension Leg Platforms

API RECOMMENDED PRACTICE 2T
THIRD EDITION, JULY 2010

REAFFIRMED, JUNE 2015

energy API®

AMERICAN PETROLEUM INSTITUTE

Planning, Designing, and Constructing Tension Leg Platforms

Upstream Segment

API RECOMMENDED PRACTICE 2T
THIRD EDITION, JULY 2010

REAFFIRMED, JUNE 2015

AMERICAN PETROLEUM INSTITUTE

Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

Foreword

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually by API, 1220 L Street, NW, Washington, DC 20005.

Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

This recommended practice for planning, designing, and constructing tension leg platforms incorporates the many engineering disciplines that are involved with offshore installations, either floating or fixed. Defined herein are guidelines developed from the latest practices in tension leg platforms, and adapted from successful practices employed for related structural systems in the offshore and marine industries.

A tension leg platform (TLP) is a vertically moored, buoyant, compliant structural system wherein excess buoyancy of the platform (in excess of weight and riser loads) maintains tension in the mooring system. A TLP may be designed to serve a number of functional roles associated with offshore oil and gas exploitation. It is considered particularly suitable for deepwater applications. A TLP system consists of many components, each of which has a precedent in the offshore or marine industry. The uniqueness of a TLP is in the systematic influence of one component on another. Consequently, the design is a highly interactive process which should account for functional requirements, component size and proportion, equipment layout and space allocation, hydrodynamic reaction, structural detail, weight and centers of gravity, etc. All disciplines involved in the design process should anticipate several iterations to achieve proper balance of the design factors. This publication summarizes available information and guidance for the design, fabrication, and installation of a TLP system.

These recommendations are based on published literature and the work of many companies who are actively engaged in TLP design. As with earlier editions of this publication, it represents a snapshot of the state of the art and practice of TLP design. As new technology develops, this publication will be updated to reflect the latest accepted design and analysis methods.

Each section of this publication covers a specific aspect of tension leg platforms. The main text contains basic engineering design principles which are applicable to the design, construction, and operation. Equations for analyses are included where appropriate. In many cases these equations represent condensations of more complete analysis procedures, but they can be used for making reasonable and conservative predictions of motions, forces, or component strength. More detailed discussions of these engineering principles, describing the logic basis and advanced analytical concepts from which they were developed, are given in the commentary. The designer and operator are encouraged to use the most current analysis and testing methods available, and bring forth to the Institute any newfound principles or procedures for review and consideration.

Contents

Contents

Contents

Contents

Page

Figures

Tables

Planning, Designing, and Constructing Tension Leg Platforms

1 Scope

This recommended practice is a guide to the designer in organizing an efficient approach to the design of a tension leg platform (TLP). Emphasis is placed on participation of all engineering disciplines during each stage of planning, development, design, construction, installation, and inspection.

2 Normative References

The following referenced documents are indispensible in the application of this standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Specification 5L, *Specification for Line Pipe*

DNV-RP-B401 [1], *Cathodic Protection Design*

NACE SP0176 [2], *Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated With Petroleum Production*

3 Terms, Definitions, Acronyms, Abbreviations and Symbols

3.1 Terms and Definitions

For purposes of this document, the following terms and definitions apply.

3.1.1
added mass
Effective addition to the system mass, which is proportional to the displaced mass of water.

3.1.2
bluff body
An opaque object located in a fluid flow stream and developing a high drag force because it lacks streamlining.

3.1.3
braces
Structural members that serve to stiffen the hull structure and provide deck support.

3.1.4
bulkhead
Stiffened vertical or horizontal load bearing diaphragm.

3.1.5
connector
A riser device used to latch and unlatch risers and lower marine riser packages to subsea equipment, or a tendon device used to latch and unlatch tendons to the foundation system and to connect the tendon to the platform.

---

[1] Det Norske Veritas, Distribution Department, NO–1322 Høvik, Norway, e-mail: distribution@dnv.com.
[2] NACE International, 1440 South Creek Drive, Houston, Texas, 77084-4906, www.nace.org.

3.1.6
deck beam
Secondary structural element spanning between intermediate girders and/or main girders.

3.1.7
deck plate
Flat plate or grating spanning between deck beams.

3.1.8
deck structure
A multilevel facility consisting of trusses, deep girders, and deck beams for supporting operational loads.

NOTE See Figure 1.

3.1.9
design life
Maximum anticipated operational years of service for the platform.

EXAMPLE The period of time from installation until completion of functional use of the structure.

3.1.10
elastomer
Any of the class of materials, including natural and synthetic rubbers, which return to their original shape after being subjected to large deformations.

3.1.11
extreme offset
An estimated maximum offset of the platform corresponding to given environmental conditions.

3.1.12
flat
Horizontal bulkhead in column structure.

3.1.13
flex element
Any of a variety of devices that permit relative angular movement of the riser or tendon via deformation of an elastomeric/steel laminated element in order to reduce bending stresses caused by vessel motions and environmental forces.

3.1.14
foundation
Templates and piles, or a gravity system.

NOTE See Figure 1.

3.1.15
heave
Platform motion in the vertical direction.

3.1.16
hull
Buoyant columns, pontoons, and intermediate structure bracing.

NOTE See Figure 1.

3.1.17
intermediate girder
Primary deck element spanning between main girders.

3.1.18
load
Any action causing stress or strain in the structure.

3.1.19
lock-in
Synchronization of vortex-shedding frequency and structural vibration frequency producing resonant flow induced vibration.

3.1.20
low-frequency motion
Motion response at frequencies below wave frequencies typically with periods ranging from 30 to 300 seconds.

3.1.21
lower deck
Lowest primary deck level consisting of girders, beams and plate elements.

3.1.22
main girder
Deck elements spanning between the primary load carrying subsystem.

3.1.23
mean offset
The average offset, corresponding to the average horizontal forces on the TLP in the given environmental conditions.

EXAMPLE Ball joints or elastomeric joints.

NOTE When curvature control is necessary, tapered joints may also be used.

3.1.24
mooring system
Tendons and foundation.

NOTE See Figure 1.

3.1.25
offset
Horizontal distance of the platform at any instant from its static, stillwater, still air, equilibrium position.

3.1.26
pitch/roll
Platform rotations about orthogonal horizontal axes.

3.1.27
platform
Hull and deck structure.

NOTE See Figure 1.

3.1.28
pontoon
Horizontal, cylindrical, or rectangular buoyancy members of the hull structure which interconnect with columns to form a frame below the waterline.

3.1.29
preload
A load purposely induced in a component to improve its in-service strength, fatigue life, or sealing capabilities.

3.1.30
pretension
Tension applied to a tendon in its static, zero offset equilibrium position.

3.1.31
primary load carrying subsystem
Structure tying column tops together and supporting deck levels.

NOTE This structure may consist of trusses, box girders, plate girders or a combination thereof.

3.1.32
ringing
High-frequency vertical vibration of the TLP spring-mass system excited by impulsive loading.

3.1.33
riser joint
A section of pipe, with couplings on each end.

NOTE A riser joint may have provision for supporting integral and non-integral auxiliary lines (flowlines, choke and kill lines, control bundles, etc.) and buoyancy devices.

3.1.34
risers
Vertical pipes connecting the TLP with the seabed for purposes of drilling, production, or connecting to pipelines.

NOTE See Figure 1.

3.1.35
setdown
The increase in TLP platform draft with offset due to tendon system restraint.

3.1.36
springing
The high-frequency vertical vibration of the TLP spring-mass system excited by cyclic loading at or near the TLP pitch or heave resonant periods.

3.1.37
subsea well template
A structural frame, which provides location and anchor, points for the subsea wellheads, riser systems, and guidance systems.

3.1.38
surge
Horizontal motion of the platform in the plant north-south direction.

3.1.39
sway
Horizontal motion of the platform in the plant east-west direction.

3.1.40
tendon
A system of components, which form a link between the TLP platform and the subsea foundation for the purpose of mooring the TLP.

3.1.41
tendon access tube
A conduit within a platform column between the bottom of the column and the tendon top connector through which a tendon passes.

3.1.42
tendon connector
A device used to connect a tendon to the platform hull (top connector) or to the foundation template (bottom connector).

3.1.43
tendon element
Each of the similar or identical but discrete structural components which, when assembled with the flex elements, top and bottom connectors, and any other special components, comprise a complete tendon.

3.1.44
tension leg
The collective group of tendons associated with one column of the platform.

3.1.45
tension leg platform
TLP
Includes the entire above plus all deck equipment and hull marine systems.

NOTE See Figure 1.

3.1.46
tensioner
A device, usually pneumatically or hydraulically powered, used to apply tension to tendons or risers.

3.1.47
tensioner systems
Units used to maintain risers in tension as the platform moves in response to wind, waves, and current.

NOTE Horizontal motions, heave, and setdown of the platform necessitate changes in length of the risers. Tensioners accommodate these movements, as well as relative angular motion between the platform and riser, while maintaining a nearly constant tension on the risers.

3.1.48
upper deck
Upper or roof deck level consisting of girder, beam, and plate elements.

3.1.49
well system
Risers, riser tensioners, wellhead, and subsea well templates.

NOTE See Figure 1.

3.1.50
yaw

Platform rotation about the vertical axis.

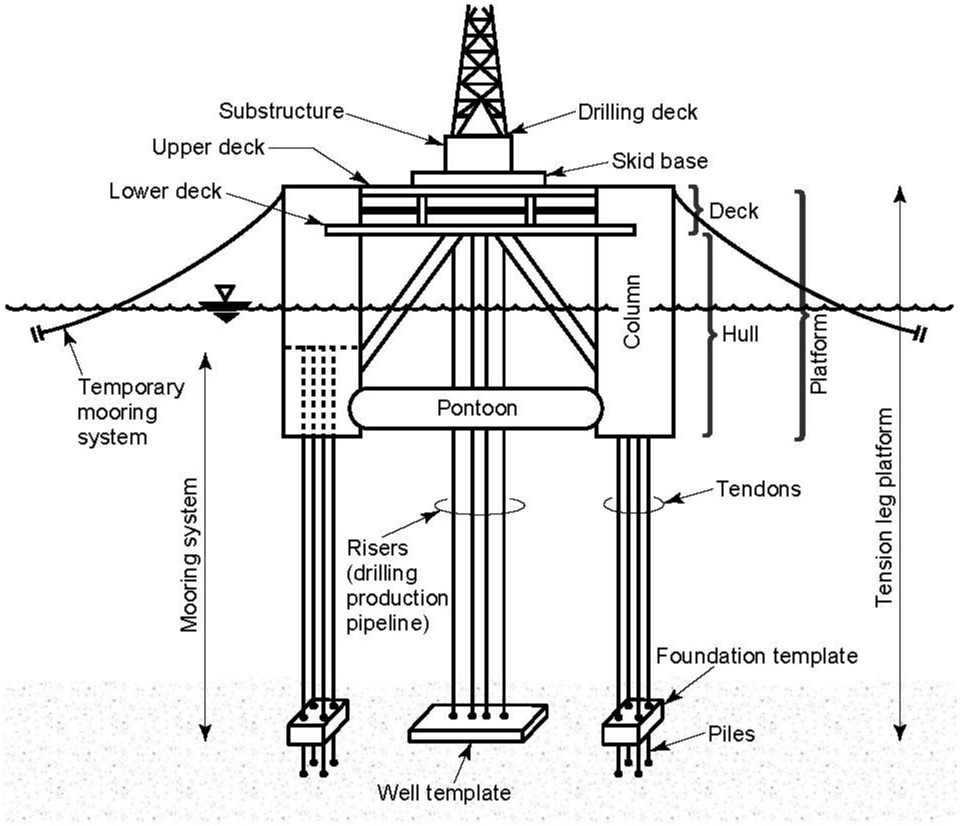


Figure 1—TLP Terminology

3.2 Acronyms and Abbreviations

AFFF	aqueous film-forming foam
B	platform buoyancy
CFD	computational fluid dynamics
DP	dynamic positioning
HDWL	high design water level
LDWL	low design water level
PR	riser pretension (at the top of riser, where attached to platform)
PT	tendon pretension (at the top of the tendon where attached to the platform)
RAO	response amplitude operator

SCR	steel catenary riser
TLP	tension leg platform
VIV	vortex-induced vibration
VCG	vertical center of gravity
WB	weight of ballast in platform
WDC	weight of deck structure
WDP	weight of all equipment in or on deck
WHP	weight of all equipment and stored liquids in the hull
WHS	weight of hull structure
WM	miscellaneous weight

3.3 Symbols

A	projected area
A_{c}	projected area per unit length
A_{y}	amplitude of vortex-induced vibration
a_{i}	amplitude of ith wave component
C	damping matrix
C_{A}	added mass coefficient
C_{D}	drag coefficient
C_{M}	virtual mass coefficient (for fluid acceleration) $CM = CA + 1$
C_{S}	shape coefficient (may also account for shielding)
C_{s}	shape coefficient
D	member diameter
F	force vector
F	total force per unit length [Equation (9)]
f	vortex shedding frequency
f_{n}	natural frequency of vibration
F_{D}	drag force
F_{d}	drag force per unit length

$F_{\mathrm{drag}}(t)$	dynamic viscous drag force
F_{i}	inertia force per unit length
F_{W}	wind force
$F_{\mathrm{wind}}(t)$	dynamic wind force
$F_{\mathrm{wd}}^{(2-)}(t)$	second-order time dependent drift force
$f_{\mathrm{wv}}^{(1)}(t)$	first-order time dependent wave force
$F_{\mathrm{wv}}^{(1)}(\omega_{\mathrm{i}})$	frequency dependent first-order wave exciting force per unit wave amplitude
$F_{\mathrm{wv}}^{(2+)}(t)$	second-order time dependent springing force
$F(\omega)$	fourier transform of force vector
H	wave height
H/L	wave steepness
H_{S}	significant wave height
K	stiffness matrix
K	Keulegan-Carpenter number
k	wave number
k_{a}	$kD/2$
L	wavelength
M	inertial mass matrix
$P_{\mathrm{ij}}^{(2-)}(\omega_{\mathrm{i}}, \omega_{\mathrm{j}})$	real part of second-order difference-frequency quadratic force transfer function in bichromatic waves
$P_{\mathrm{ij}}^{(2+)}(\omega_{\mathrm{i}}, \omega_{\mathrm{j}})$	real part of second-order sum-frequency quadratic force transfer function in bichromatic waves
$P(x)$	probability density function
$Q_{\mathrm{ij}}^{(2+)}(\omega_{\mathrm{i}}, \omega_{\mathrm{j}})$	imaginary part of second-order sum-frequency quadratic force transfer function in bichromatic waves
$Q_{\mathrm{ij}}^{(2-)}(\omega_{\mathrm{i}}, \omega_{\mathrm{j}})$	imaginary part of second-order difference-frequency quadratic force transfer function in bichromatic waves

R_e	Reynold’s number
S	Strouhal number
$S_\mathrm{aa}(\omega)$	wave elevation spectrum
S_ff	wind force spectrum
S_uu	wind gust spectrum
$S_\mathrm{xx}(\omega)$	response spectrum
t	time
T_f	incremental tension due to foundation mis-positioning and the instantaneous offset
T_i	individual tendon load sharing differential
T_l	incremental tension due to load and ballast condition/weight variations/design margin
T_m	incremental tension due to overturning moment from wind and current forces
T_max	design maximum tension
T_min	design minimum tension
T_o	design pretension at mean water level
T_P	spectral peak period
T_r	tension variation due to heave, pitch, and roll oscillations at their natural frequency (ringing and springing, including possible underdeck slamming loads)
T_s	incremental tension caused by setdown due to static and slowly varying offset (wind, wave drift, and current)
T_t	incremental tension due to tide/storm surge water level variation
T_v	tension-induced by vortex shedding responses of an individual tendon
T_w	tension variation from wave forces and wave-induced vessel motion about the mean offset (including any coupled tendon responses)
u	instantaneous water particle velocity (speed and direction)
u'	instantaneous velocity variation from sustained wind
$\dot{u}$	water particle acceleration
Vc	current velocity normal to member axis
V_c	water particle velocity (includes current)

V_r	reduced velocity
V_{wd}	instantaneous wind speed
V_z	mean wind speed
Y_{rms}	rms VIV motion amplitude
X	instantaneous displacement of body or component
χ_a	aerodynamic admittance
$\chi_{.}$	aerodynamic admittance function (see 6.2.7)
$\dot{x}$	instantaneous velocity of body or component
$\ddot{x}$	instantaneous acceleration of body or component
ω	radian frequency
σ_x	standard deviation
ε_i	phase angle of ith wave component
ρ_a	mass density of air
ρ_w	mass density of seawater

4 Planning

4.1 General

4.1.1 Configuration Selection

Most TLP designs have certain basic common features. They include one or more columns and pontoons to provide buoyancy, and tendons to moor the platform to the seafloor. The following are some of the key factors that need to be considered when developing plans for a TLP.

a) Purpose—Drilling, production, quarters, and/or other.

b) Location—Environmental, seafloor, and regulatory conditions.

c) Financial—Capital and operating costs, risk.

d) Service life.

e) Contracting strategy.

f) Construction—Materials, methods, assembly, and installation.

g) Operational requirements.

The configuration selection process focuses on selecting global design parameters and then maturing the design from conceptual design through detail design.

Recognition of the need for several iterations of the design process and operational requirements may be important in planning and scheduling the design. Time is often needed to evaluate the effects of parameter variations before rational design decisions can be made.

Due to the sensitivity of a TLP to weight and buoyancy issues, a weight, buoyancy, and center of gravity control procedure for the entire system should be incorporated into the design process at the very earliest stage. The control procedure should be one that can be used throughout the design, construction and operational life.

4.1.2 Exposure Categories

TLPs can be categorized by various levels of exposure to determine criteria for the design of new structures and the assessment of existing structures that are appropriate for the intended service of the structure.

The levels are determined by consideration of life-safety and consequences of failure. Life-safety considers the maximum anticipated environmental event that would be expected to occur while personnel are on the platform. Consequences of failure should consider the following factors:

a) historical experience;

b) the planned life and intended use of the platform;

c) the possible loss of human life;

d) prevention of pollution;

e) the financial loss due to platform damage or loss including lost production, cleanup, replacing the platform and redrilling wells, etc.

New or relocated TLPs used for oil production, oil handling, and/or drilling should be considered as having a high consequence of failure.

Lower consequences of failure and reduced exposure to life-safety may support the use of oceanographic criteria with a shorter return period. Potential applications where such reduced criteria might be applicable are as follows:

— unmanned structures; and

— field support structures not used for oil production, oil handling, or drilling.

The only criteria contained in this publication are those related to the high consequence of failure categorization. Criteria for lower consequence of failure and reduced exposure to life-safety would have to be developed and supported on a case-by-case basis.

4.2 The Design Process

4.2.1 General

An understanding of the entire design sequence and its relationship to external constraints such as financial, scheduling, equipment, and manpower requirements is essential.

In planning the design process, it is important to recognize the operator’s contracting strategy for engineering, fabrication, and installation. Depending on how the contracting is structured between the various parties involved (e.g. engineering, hull fabrication, topsides fabrication, drilling, installation, etc.), different levels of project definition may be required at different stages of the project. In addition, there may be variability in the allocation of design work between the engineering and construction entities.

The design process should include plans and schedules for possible model testing of the platform. Hydrodynamic model testing may be required in the design process to verify the analytical results and/or provide other data necessary for the design.

4.2.2 Conceptual Design

Conceptual design translates the functional requirements into naval architectural and engineering characteristics during the initial design iterations. It embodies technical feasibility studies to determine such fundamental elements as length, width, depth, draft, hull shape, mooring system, and well and riser systems to satisfy the environmental criteria, functional requirements, and installation feasibility. The conceptual design includes initial lightship weight estimates and mooring pretension.

It is the designer's responsibility to select the most suitable buoyancy distribution, tendon geometry, and pretension that will achieve the operator's functional requirements.

On drilling structures, these arrangements are heavily influenced by the well system. Experience indicates that a very close designer/operator relationship is required during the entire design process in order to produce a satisfactory design.

The distribution of buoyancy is selected to minimize the net vertical oscillating wave force on the hull by taking advantage of hydrodynamic cancellation effects, thereby reducing oscillating loads on the tendons. Typically, some combination of a surface piercing vertical column or columns and submerged pontoons is selected to provide the optimal distribution of buoyancy.

The lateral stiffness of the tendon mooring system is generally designed to result in long natural periods in surge and sway (i.e. greater than the dominant periods of the wave energy), with the resulting beneficial compliance to dynamic motion.

The vertical stiffness of the tendon system is generally selected such that the heave, roll, and pitch periods of the TLP have low natural periods relative to the dominant periods of the wave energy, so as to minimize wave amplification.

Tendon pretension is selected such that the full length of all tendons is in tension for all loading conditions over the life of the facility. Under certain circumstances, a temporary loss of tension may be acceptable if it can be demonstrated that the resulting stresses, motions due to loss of tension and retensioning, and the latching mechanism are within design limits.

Alternative designs are generally considered parametrically during this phase to determine the most practical design solution. The selected concept is then used as a basis for obtaining approximate construction and installation costs and schedule, which often determine whether or not to initiate a preliminary design.

4.2.3 Preliminary Design

Preliminary design further refines the characteristics affecting cost and performance. Certain controlling factors such as platform geometry, number, and type of wells, mooring pretension and payload should not change significantly after completion of this phase. Additionally, an associated base-case installation plan for the selected configuration is developed at this stage. Completion of preliminary design provides a precise definition that will furnish the basis for development of project plans and specifications.

4.2.4 Final Design

The final design stage yields a set of plans and specifications that form an integral part of the fabrication contract. This stage delineates precisely features such as hull shape, dynamic response, structural details, use of different types of steel, spacing and type of frames and stringers. Paramount among the final design features are weight and center-of-gravity determination. The final general arrangement is also developed during this stage. This fixes the overall volumes and areas for consumables, machinery, living and utility spaces, and handling equipment. Depending on how the project contracting is structured, installation engineering input may become significant at this stage.

The specifications developed or adopted at this stage delineate quality standards of hull and outfitting and the anticipated performance for each item of machinery and equipment. They describe the tests and trials that shall be performed successfully to have the TLP considered acceptable.

4.2.5 Detail Design

The last stage of design is the development of detailed fabrication drawings and construction specifications. These are the installation and construction instructions to yard tradesmen and are subject to the approval of the designer. Platform operation and inspection plans are also developed at this project stage.

4.3 Codes, Standards, and Regulations

A determination of the applicable codes, standards, and regulations should be made at the commencement of a project. Differences between such requirements or standards should be identified immediately, and a project decision or agreement with the responsible regulatory organization expedited.

4.4 Operational Requirements

4.4.1 Function

A TLP can perform a variety of functions such as drilling, producing, storage, materials handling, living quarters, or some combination of these. The platform configuration should be determined by integrating the equipment layouts on the decks with those aspects of system design that assure hydrodynamic and aerodynamic performance, stability, weight considerations, and constructability. The platform configuration should also allow for internal and external inspection programs consistent with the operational life of the facility.

4.4.2 Site Considerations

Environmental conditions depend on geographic location, and within a given geographic area, the foundation conditions may vary as will such parameters as design wave height and period, currents, tides, and wind speeds.

Accurate data on water depth and tidal variations are needed to fabricate tendon components so that the TLP operates at its design draft. Estimates of reservoir compaction and seafloor subsidence over the life of an oil field's depletion are also needed for the same reasons, as well as for setting deck elevation above still water.

The orientation of a platform refers to its position referenced to true north. Orientation will be controlled by the directions of prevailing and extreme design waves, winds, and currents and by operational requirements. Platform orientation also needs to be considered within the context of the full-field architecture and may involve other issues such as subsea tie-ins, onsite floating storage and/or production units, tanker offloading facilities, and marine traffic routes.

4.4.3 Arrangements

Due to the interaction between the many variables affecting arrangements, platform operations, and the human factors involved, the use of project risk assessments is recommended. Such assessments can be used to help identify potential hazards associated with installation, field start-up, and ongoing operations.

Layout and weight of equipment for mooring, drilling and/or production, consumables, and other payload items should be carefully accounted for in the design and operation. Weight and weight distribution affect both the steady and dynamic tensions in the tendons. Consideration should be given to future operations such as gas and/or water injection.

Plans for handling personnel and materials should be developed at the start of the platform design. The type and size of supply vessels and the mooring system required to hold them in position can affect the platform. The number, size, and location of boat landings, if required, should be determined. The type, capacity, number, and location of the deck cranes should also be determined. If equipment or materials are to be placed on a lower deck, adequate hatches should be provided on the upper decks. The use of helicopters should be established and adequate facilities provided.

The location and number of stairways, access routes, and boat landings should be controlled by both safety and operational requirements.

Fire protection systems, including firewalls and safe-havens, should be provided for the safety of personnel and equipment. The systems selected should be suitable for the anticipated hazards (e.g. electrical or hydrocarbon fire) and should conform to all applicable regulations.

Emergency equipment such as launchable lifeboats or survival capsules should be provided for personnel evacuation. The types of equipment and evacuation methods should meet all applicable regulations.

Provision should be made for handling spills and potential contaminants. A deck and process vessel drainage system that collects and stores liquids for subsequent handling should be provided. The drainage and collection system should meet applicable regulations.

The platform should be provided with systems for transferring ballast water to or from hull compartments (ballast system), for monitoring tank contents, and for permitting safe access to tanks and void spaces. Compartmentalization of the hull will be required to limit the effects of damage, leakage or other unintended water ingress. Such compartments may be useful for temporary ballast to control draft and stability before and during installation. Access for inspection should be provided in the design.

4.5 Environmental Considerations

4.5.1 General

Winds, currents, waves, and tides cause steady and oscillatory lateral movements, variations in tendon loads, and/or distributed loadings on the structure and its elements. The resulting TLP response requires the use of dynamic analysis methods in the design. Environmental data consistent with the analysis technique should be used.

4.5.2 Design Considerations

The design of all systems and components should anticipate extreme and normal environmental conditions that can be experienced at the site. In addition, postulated damaged conditions occurring at the time of the environmental events should be considered. Environmental loading and platform response are important design considerations for several subsystems including foundations, tendons, risers, hull, and deck equipment.

Extreme environmental conditions are those that produce the extreme response that have a low probability of being exceeded in the lifetime of the structure. For metocean events, a minimum return period of 100 years for the design event should be used unless the consequences of failure are such that a shorter recurrence interval for design criteria can be justified. The design of the structure and its key subsystems shall be such that they will be capable of withstanding the extreme metocean events in a safe condition without damage.

For earthquakes, the two-tier strength level event (SLE)/ductility level event (DLE) criteria as used for fixed offshore platforms are also applicable to TLPs (refer to API 2A-WSD). SLE and DLE criteria should be developed using a probabilistic seismic hazard assessment (PSHA) consistent with the seismic risks at the site.

Tsunami effects can generally be neglected since the kinematics velocities developed in such events tend to be much lower than design currents in deepwater.

Normal environmental conditions are those that are expected to occur frequently during the service life. Since different environmental parameters and combinations affect various responses and limit operations differently (e.g. installation, crane usage, etc.), the designer should consider the appropriate environmental conditions for the design situation.

A matrix, or scatter diagram of fatigue sea states should be developed covering the entire range of environments expected during the service life. The environments should be discretized into a convenient number of bins, identifying relevant environmental parameters and number of occurrences for each bin.

Environmental conditions associated with transportation and installation of the TLP should be considered during the structure design.

4.5.3 Environmental Data

Selection of the environmental data required is the responsibility of the operator. The dynamic nature of the TLP requires that the platform designer work closely with a meteorological-oceanographic specialist to develop data and interpretations in the form needed for the particular design/analysis methods to be used.

Recognized statistical methods and models should be applied in the assessment of extreme and normal environmental conditions. All data used should be carefully documented. The estimated reliability and the source of all data should be recorded, and the methods used in developing available data into models should be described. Sensitivity of design to poorly established parameters/distributions in statistical models should be recognized.

Selection of specific environmental conditions for design should be based on factors related to risk. Section 5.5 contains specific guidance on the choice of environmental parameters for design. API 2A-WSD gives a general discussion of most of these parameters and their specific use in design analysis for fixed platforms.

As a result of Hurricanes Ivan, Katrina, and Rita, the industry reviewed metocean requirements for the Gulf of Mexico. The result was a change to the recommended minimum 100-year return period wave heights and associated winds. Refer to API 2INT-MET for updated metocean criteria to be used in the Gulf of Mexico.

4.6 Seafloor Characteristics

4.6.1 Seafloor Surveys

The purpose of a seafloor site survey is to provide data for a geologic assessment of foundation soils and the surrounding areas and helps plan subsequent detailed geotechnical programs. It is also used to identify seafloor irregularities that could be operational hazards such as pockmarks, shallow gas, near-surface faults, debris flows, diapirism, and hard grounds.

Conventional three-dimensional 3D seismic data (marine streamer) can be used for reconnaissance geohazards mapping. However, these data are not typically processed for seafloor and near-seafloor imaging and suffer from low-resolution, high-noise, and acquisition artifacts. 3D seismic data that has been processed or reprocessed specifically for site investigation purposes (i.e. optimized lateral and vertical resolution of the seafloor and near-seafloor) can be used to supplement (or in some cases in lieu of) conventional site survey methods. These specialist 3D seismic volumes yield detailed images of seafloor and near-seafloor morphology, structure, and depositional patterns.

Useful mapping products derived from these data sets include bathymetry, seafloor renderings (artificial illumination), seafloor amplitude (surficial lithology, hydrocarbon seeps), near-seafloor isopach and structure maps, as well as cross-sectional and 3D perspective views. Higher resolution engineering surveys are typically needed to select the final TLP location and evaluate subsea flowline corridors.

This information can be gathered by deep tow survey equipment or from autonomous underwater vehicles (AUVs). These tools are outfitted with high-resolution sub-bottom profilers or frequency modulated chirp systems, sidescan sonar and swath bathymetry. Ideally the geophysical data from 3D, deep tow or AUV is confirmed with seabed geotechnical information from cores, and piezocone penetration tests, vane and/ or T-bar in-situ tests.

4.6.2 Site Investigation

Site-specific geotechnical investigations should be performed to define the various soil strata (e.g. thickness, lateral extent) and their corresponding physical and engineering properties. If practical, the soil sampling and testing program should be defined after reviewing the seafloor geophysical survey. The foundation investigation for pile supported structures should yield at least the soil test data necessary to predict axial capacity of piles in tension and compression, axial and lateral pile load deflection characteristics (including long-term creep under tendon pretension), and mudmat penetration vs resistance.

4.6.3 Seafloor Instability

Large movement of the seafloor may be caused by waves, earthquakes and soil loads (including shallow water flow). Such soil movement can impose significant lateral and vertical forces against foundations. The scope of geotechnical site investigations in areas of seafloor instability should be sufficient to develop design criteria for the effects of soil movement.

4.6.4 Scour

Scour is removal of seafloor soils caused by currents and waves, and can result in removing vertical and lateral support for foundations. Where scour is a possibility, it should be accounted for in design to avoid failure or overstressing of foundation elements.

4.7 Systems Design

4.7.1 Platform

4.7.1.1 There are several variations of platforms that can be distinguished by platform use (i.e. production-only, drilling-only, or drilling/production). Some example variations are shown in the following.

a) Production well platform without drilling capability—This type of structure should be considerably smaller and lighter than a drilling/production platform. Production risers generally are attached to the deck structure. Wells may be pre-drilled using a semisubmersible or may be tied back to the facility from subsea completions.

b) Drilling platform without production facility capability—This wellhead type of structure should also be considerably smaller and lighter than a drilling/production platform. Drilling risers generally are attached to the deck structure.

c) Drilling/production platform with drilling at deck level through a well bay—This type of platform includes facilities for both drilling and production. Its size may be large to support the associated weight requirements.

4.7.1.2 Many functional requirements of a platform require special attention during the planning stages of design. In all cases, personnel and material requirements should be considered in relationship to the safety and efficiency of the platform. The following critical requirements will significantly impact the design and layout of the platform.

a) Drilling facilities—The number, type, weight, and location of drilling rigs should be ascertained prior to commencement of design.

b) Production facilities—The weight, area, and center-of-gravity of the production facilities should be determined insofar as possible prior to commencement of design of the platform. Because platform design is sensitive to the values of weight, area, and center of gravity, these values should not be permitted to deviate beyond specified tolerances, otherwise redesign may be required.

c) Drilling/Production risers—Sufficient clearance should be provided between risers and adjacent structural members to avoid interference during severe environmental conditions.

d) Well systems—The number of platform wells, completion and workover method, minimum well spacing, and well bay location have a direct influence on the size and layout of the deck structure and the hull. These features should be determined prior to commencement of preliminary platform design.

e) Hull compartmentation—Hull damage from falling objects, boat collision, or other means should be considered during the design. The subdivision of the hull should allow for accidental flooding of at least one watertight compartment. Damage control procedures should be developed during the design phase and included in the operating manual. Bulkhead configurations, tank layouts, and tank access openings should be designed to facilitate periodic internal tank inspections.

f) Airgap—The minimum clearance between the lowest deck and any underdeck temporary maintenance equipment and a wave crest is an important parameter in the design of the TLP. The airgap has an effect on the center of gravity and in turn the maximum and minimum tendon tensions. The designer has two general options: provide a minimum deck clearance or allow for wave impact in the design of the platform.

g) Installation procedures—The floating stability of the hull prior to the installation of the tendons is a critical element of the installation process.

4.7.2 Tendon System

The tendon system consists of the tendons, and ancillary components needed for operation, including load measurement systems and inspection or monitoring apparatus.

The tendon system restrains motion of the platform in response to wind, waves, current, and tide to within specified limits. The tendons connect points on the platform to corresponding points on a seafloor foundation. By restraining the platform at a draft deeper than that required displacing its weight, the tendons are ideally under a continuous tensile load that provides a horizontal restoring force when the platform is displaced laterally from its still water position. Generally very stiff in the axial direction, the tendon system limits heave, pitch, and roll response of the platform to small amplitudes while its softer transverse compliance restrains surge, sway, and yaw response to within operationally acceptable limits.

The number of tendons is determined by the platform configuration, loading conditions, and design philosophy, including intended service requirements and redundancy considerations based on sound engineering design practice. The designer should allow for the possibility of material deterioration during the service life of the platform and provide a means of detecting and repairing such defects.

The tendons may take one of several forms as described in the following.

a) Tubular Members with Connectors—The members may be designed to be completely void, partially void, or fully flooded. They may be fabricated as one piece or constructed from separate tubular body and end connectors by welding or otherwise fixing the end connectors to the tubular. The members may be made of metal or composite fiber reinforced resins (e.g. carbon fiber/epoxy composites), with either integral or metallic connectors.

b) Tubular or Solid Rod Members with Welded Connections—The tubulars are fabricated from seamless or rolled and welded steel and are designed to be welded together, prior to or during offshore installation, to form a continuous tendon element.

c) Tendon Strand—These tendons are fabricated from small diameter high tensile strength wire or fiber strands and are formed into bundles. These tendons are designed to be installed offshore using a continuous one-piece spooling operation to minimize the need for intermediate connectors.

Investigating items such as coupled tendon/platform motions, vortex-induced vibrations (VIVs), and the fatigue life of complex mechanical and welded connections requires a high level of technical sophistication. The designer is encouraged to make use of modern but proven equipment and analytical methods.

Critical tendon components, because of their lack of previous use or complexity, may warrant extensive engineering development and prototype testing to determine the fatigue, fracture, and corrosion characteristics and the mechanical capabilities of the components.

The time required to fabricate the tendons may be comparable with the duration required to construct the hull and deck structure. Consideration should be given to the fabrication lead-time requirement of the tendons to avoid unnecessary delays in installation. Tendon fabrication specifications, including material, welding and NDE requirements, also need to be established early in the project.

Installation of the tendons may require the use of large capacity lifting and handling equipment. Installation procedures and their implication to the design should be considered early in the planning stages. Onboard storage area, if required for the tendons during installation, can affect the layouts of the deck and hull and warrants early attention during design.

4.7.3 Foundations

There are several types of foundations that may be utilized for a TLP. Examples include:

a) a foundation consisting of individual piles, to which individual tendons are directly connected;

b) a foundation consisting of a foundation template anchored to the ocean floor by piles (driven or suction), which carry both lateral and tensile loads from multiple tendons connected to the template;

c) shallow foundations such as non-piled gravity foundations (e.g. concrete caisson foundations) to which the tendons are directly attached;

d) combination of items a) and b) with a template for each leg or one template common to all legs;

e) auxiliary foundations consisting of anchor piles, deadweight clumps, drag anchors, or other types of anchors to which a catenary mooring system is attached for use during installation or operation.

Three commonly used types of piles for TLPs are the driven pile, suction pile, and suction/gravity pile. Other pile types that can be considered, but as of this writing have not been used for TLPs, are drilled and grouted and combination driven-drilled and grouted piles. The type most appropriate for a particular foundation will depend on the soil conditions at the site and the pile performance, as well as on the installation equipment available. Further discussion on these pile types can be found in API 2A-WSD.

4.7.4 Well Systems

The design of a well system should achieve cost effective safety and reliability in the containment, control, and transmission of produced fluids from the oil or gas reservoir to the processing system. While risers are an integral part of the well system, they can also be used for other functions, such as for pipeline connections. Systems will commonly be capable of being run and retrieved by vertical deployment from the deck.

Integration of the design of the well systems into the design of the TLP should be an early priority. The selection of well riser tension levels, the platform motion effects, the effect of thermal loads when wells and tendons are congruent, and riser/hull clearances are examples of items requiring close coordination. The weight and size of the well system equipment will have a significant impact on hull size and cost.

Different types of risers between the platform and seafloor may be utilized, including integral and non-integral risers, and risers integral to the tendons. Drilling blowout preventers (BOPs) and well completion systems may be located either at the platform deck level or subsea. Anticipated workover frequency and wellhead maintenance will influence the decision as to surface or subsea completions. Anticipated changes in future operation (e.g. gas lift or water injection) might require the need for flexibility within components selected.

Well component design and selection should be primarily based on reliability and safety of the system. Field proven technology and equipment should be used where possible. Design reliability should include redundancy, backup procedures, and fail-safe designs whenever practical. Component and well system reliability studies could be useful in determining the consequences of failure, and identifying those components needing a higher degree of reliability. Identification of those components that cannot be retrieved to the surface, the consequences of such components being damaged, and how to mitigate the consequences should be considered. In all cases, consideration should be given to an acceptable means of stopping the well flow near the seafloor in the event of an accident.

4.7.5 Facilities

The planning and selection of facilities involve many problems that are unique to compliant structures. The selection and design of the facilities should consider the platform motions. Facilities will have interfaces between individual systems and the overall structure, including dynamic load input from drilling rigs, sharing of utilities between drilling/production systems and hull systems, and escape means for various damage states. Such loads and interfaces should be identified and considered.

TLP facilities design should recognize the highly interactive nature of the design process, and the importance of proper coordination and integration of drilling rig, production, hull systems, and structural needs. Specific definition of all facilities criteria and requirements early in the design process should prevent changes in the platform resulting from changes in facilities. There should be close coordination between the facilities and structural designers throughout the design project to ensure that routine interactions, changes, and interfaces are properly addressed.

Facilities and drilling layouts should be considered in the initial stages of design when the development of the overall configuration is being made. Layouts should initially be guided by the overall function of the platform and should include the influences of well location(s), production systems needs, accommodation requirements, and area classification considerations. Facilities construction, whether fully integrated, semi-integrated, or modular, will affect the layout and weight as well. Damage control, personnel safety and evacuation, and spillage/containment requirements also influence the facilities layout. It may be beneficial to examine a variety of facilities layouts.

Weight, center of gravity (CG), and space requirements should be managed to develop a facility efficient in cost and operation. Weight management is the key to controlling parameters that affect the stability and global performance of a floating structure.

The design process should consider the use of “growth allowances” in the form of weight and space factors, which can help in two respects. First, platform facilities have a tendency to grow during the design process with potentially detrimental implications. Thus, realistic allowances for weight and space growth during the design process should help to prevent major design recycling at late stages. Second, experience has shown that the originally intended operational parameters for offshore facilities frequently are no longer adequate once the facility has been in operation for several years. Accordingly, it is appropriate to utilize space and weight growth allowances as a means of allowing flexibility in future operations. Operational growth scenarios should also include examination of the weight or space flexibility that may be gained by the removal of certain facilities at later stages in the operation.

Benefits may result from keeping the design growth and operational growth allowances separate during design. Operational growth allowances can easily be preempted by unexpected design problems, but the implications to future facility operation should be considered.

Both design growth allowances and operational growth allowances should recognize the impact of weight and space on floating facilities.

4.8 Fabrication and Installation

4.8.1 Fabrication Methods

The method of platform fabrication should be considered as part of the preliminary design since the method selected will significantly affect not only structural design but also the feasibility of fabrication at a chosen site.

There are four basic methods of platform fabrication as described in the following.

a) Deck floatover—With this method, the deck is constructed in one piece separately from the hull, floated (usually by barge) over the hull and lowered and mated to it using controlled ballast and jacking procedures. Outfitting of the deck is usually completed prior to deck mating.

b) Modules—With this method, the deck facilities are installed in the form of stacked modules on top of the hull. This is generally done at a final outfitting facility prior to final tow to the installation site. Modules may be designed to carry global loading between columns, or to “float” on sliding supports. In the latter case, a structural frame connecting the columns should carry the global loading between columns.

c) Integral deck and hull—With this method, the deck is constructed integrally with the hull. A sufficiently deep dry dock or a convenient, sheltered deepwater site is a prerequisite for this type of construction. Outfitting of the deck may be completed together with the construction of the deck subassemblies (as in modular construction) or may take place subsequent to deck and hull construction.

d) Deck lifting—The deck is constructed in one piece and is lifted and integrated offshore.

4.8.2 Fabrication Site Selection and Preparation

The proper selection and preparation of the fabrication site is instrumental to the successful construction. Important considerations are as follows:

a) Coastal site—The fabrication yard should have a deepwater dry dock or means for transferring the hull into the water. It may be skidded onto a submersible barge or launched directly into the water. If the dry dock does not have sufficient depth, the use of auxiliary buoyancy and/or stability modules to support the hull during construction may be acceptable.

b) Sheltered offshore construction area—Deepwater construction facilities may be located offshore, away from the fabrication yard, and in sufficiently deep and sheltered waters to allow convenient access for either floatover deck mating or integral deck construction.

c) Deepwater channel—For wet tow, a deepwater channel should be available to permit towing the completed structure to sea. The minimum channel depth should be sufficient to allow the platform to be towed at a draft commensurate with specified stability criteria. Alternatively, for dry tow, a site which allows placement of the structure on a dry tow transport vessel is required.

4.8.3 Transportation

Precautions should be taken during transportation to sea to avoid damage to the structure. Transportation can be either by towing or by carriage on a mobile heavy-lift vessel. Escort tugboats to provide protection against damage should be considered. Stability criteria for transportation should be selected as appropriate for the time, duration, and location of the route as well as for the degree of damage protection and control afforded. The ability to either outrun (i.e. avoid storms) or to seek a safe harbor during a storm will have a significant effect on the motion requirements for the transportation. Specific transportation requirements will depend on whether or not the vessel is manned.

4.8.4 Installation Equipment

The function, type, and size of the major equipment selected for installation can affect the design and should be considered during the planning stages of design. For example, the response of the platform will change considerably during the transition from freely floating to vertically restrain; therefore, the temporary restraining equipment should be sized accordingly.

4.8.5 Installation

In planning the installation of subsea well and mooring template(s), due consideration should be given to avoiding interference with seafloor returns of well cuttings and grout. These factors should also be considered in design of the connection equipment and methods to be used for the risers and tendons. The final design of production template(s), well system, temporary mooring system, foundation templates, and the piles will depend on the installation methods and equipment selected.

4.9 Materials, Welding, and Corrosion Protection

4.9.1 Materials

Selection of the strength and quality levels for steel, cement grout, concrete, and other materials for the platform, foundation, and other components will generally follow the criteria commonly used for offshore structures. This publication emphasizes steel as the primary structural material but specifically does not preclude the consideration of other materials. Future revisions of this recommended practice (RP) will cover these other materials as appropriate.

Critical locations in the platform may require specification of steel with enhanced properties consistent with predicted loadings. Strength, toughness, and fatigue resistance of the specified platform materials shall be consistent with expected fabrication practices and the inspectability of each critical location during service.

Steel for the tendons may be higher strength structural steel and will affect the method of tendon fabrication and inspection as well as tendon type and service. The tendons operate under high cycle fatigue stresses superimposed on the mean stress tensile load in a seawater environment. The material should have acceptable properties in the final condition to meet the requirements of strength, toughness, and resistance to corrosion and corrosion fatigue. The material should possess adequate fracture toughness so as to withstand the largest nonrejectable weld flaw allowed by the tendon fabrication specification at design maximum loads and minimum exposure temperatures. Resistance to stress corrosion cracking under operating conditions is critical since detection of such cracks is difficult during service. In-service inspection requirements, intervals, and methods of determining allowable defect size should be considered.

4.9.2 Welding and Inspection

Selection, qualification, and application of welding and weld inspection procedures will generally follow criteria used for offshore platform fabrication where applicable (e.g. platform, foundation templates, etc.).

Where welding is prescribed in the fabrication of tendons, the resulting weldments should have strength properties exceeding those of the tendon parent material. Fabrication procedures should be followed which assure the required properties in the installed tendon. These properties may be more difficult to obtain in a weldment than in the parent steel, especially as the strength level increases. Consideration may be given to fabricating the tendons without any weld, however, the effect on cost, availability and fabrication lead-time should be accounted for.

The inspection method should be sufficient to detect and locate all potentially damaging flaws. This requires consideration of the local geometry as well as the toughness of the material and the applied stress. Inspection methods should be designed and tested to demonstrate an adequate ability to detect, resolve, and size defects.

4.9.3 Corrosion Protection

Steel materials should be protected from the effects of corrosion by the use of a corrosion protection system that is in accordance with DNV-RP-B401, or NACE SP0176. The corrosion protection systems include coatings, cathodic protection, corrosion allowance, and corrosion monitoring. Overprotection that may cause hydrogen embrittlement and coating damage should be avoided.

4.10 Safety and Reliability

The design should maximize the safety of personnel and the protection of property within a framework of efficient, cost effective design. Safety and reliability depend on the ability of a facility to survive the loads anticipated over the installed life. The designer should examine not only the intact facility and structure, but also examine the structure under damaged conditions and ensure that the remaining strength, fire resistance, and escape means are adequate.

Qualitative reliability analyses of certain systems such as the tendon system are possible. Such analyses can help to understand the differing degrees of reliability among designs utilizing different numbers of tendons, different types of connectors, and/or end terminations, etc. Such analyses can help assess reliability versus system cost, and pinpoint critical elements deserving special attention.

Hull damage state scenarios should be developed with the implications of compartment flooding. Facilities design should consider damaged state scenarios and possible implications upon the deck structural system. Personnel escape routes should be designated for damaged states, and alternate routes provided. Damage control systems, including firefighting means, ballast redistribution capabilities, and backup power supplies should all be selected considering the need for reliable operation during periods of severe service. Redundant means of monitoring major platform functions, such as trim, ballast condition, etc., should be considered.

4.11 Operating and In-service Manuals

4.11.1 Overview

The designer should provide manuals that communicate to the operator the correct practices to be used for safe and efficient operation of the platform. These manuals describe the practices and procedures necessary for normal operations; maintenance, in-service inspection and emergency procedures for damage state conditions and other emergency situations. Operating personnel should be required to review and understand the operating and in-service manuals. A description of information typically included in the manuals is noted in 4.11.2 through 4.11.10.

4.11.2 TLP Overview

Typical information includes a description of the TLP system and its function, including its location and orientation, the general overview of platform (hull, deck, tendons, foundations, risers and facilities). Information on certification, operational modes, global performance characteristics, and allowable deck loading plans should also be included.

4.11.3 Operation of Marine Systems

Information on the ballast and bilge system, hull hydraulic systems, hull ventilation, vents and sounds, oily drain pumps, marine instrumentation and load monitoring (both tendon tensions and weight management) should be included for safe operation of the TLP.

4.11.4 Support Operations

Procedures for handling supply boat operations, crew shift changes, helicopter operations, collision avoidance, and preparation of daily reports should be included. Operating and in-service manuals should document the sizes and classes of support equipment (e.g. helicopters and supply boats) for which the facility is designed.

4.11.5 Extraordinary Operations

Procedures for extraordinary operations, such as tendon removal, should be clearly identified prior to installation of the TLP. Associated monitoring requirements for such operations should also be prescribed.

4.11.6 Emergency Operations

Procedures for emergency operations should be clearly identified prior to the installation of the TLP. Critical procedures may include how to react to the following:

a) loss (or significant change) of tendon tension,

b) flooded hull compartment,

c) tendon damage (including flooding),

d) adverse weather/currents (e.g. hurricane abandonment) and the time necessary to carry out the planned operations,

e) foundation failure,

f) pollution incident,

g) man overboard,

h) emergency evacuation plan,

i) emergency fire protection plan,

j) platform abandonment,

k) loss of instrumentation for load management system and guidance on manual estimation of tendon tension based on last known conditions and hand calculations,

l) drifting mobile offshore drilling unit (MODU)/vessel nearby.

4.11.7 Load Management and Allowable KG

The safe operation of the TLP requires an effective load management procedure. A careful explanation of the program used for load management should be included. This should include an overview or procedures for evaluating the following:

a) vertical loads acting on the TLP (e.g. lightship weight, tendon and riser tensions, ballast, other variable loads, etc.);

b) base configuration of the TLP;

c) summary of approved lightship weight and CG;

d) allowable deck loading;

e) capacity of cranes;

f) capacity of derrick, if applicable;

g) tank tables;

h) stability and compartmentation;

i) tendon tension calculations;

j) apparent weight calculations;

k) ballast adjustments;

l) tendon tension reconciliation;

m) allowable KG (vertical center of gravity with respect to keel).

Effects on TLP global response and load management due to weather and subsidence should be described.

4.11.8 In-service Inspection Plan

A continuing in-service inspection program is required to ensure the proper long-term maintenance of the platform and its components. Typical issues addressed in the inspection plan are as follows:

a) annual inspection,

b) hull tanks,

c) welded joint inspection,

d) hull gauging,

e) watertight integrity,

f) hull corrosion control,

g) underwater survey,

h) tendon and foundation,

i) risers,

j) inspection sheets.

4.11.9 Construction Manual

An overview of the fabricated TLP structure should be included as documentation for offshore personnel and for long-term management of the asset. Information on repair procedures, structural steel materials used, material certifications and welding procedures should be included.

4.11.10 Reference Drawings and Arrangements

Generally the manuals include a full set of reference drawings and arrangements. The following is a typical list that should be included:

a) general arrangements,

b) fire plans,

c) hull structural plans,

d) lifesaving equipment plans,

e) deck structural plans—primary,

f) deck structural plans—secondary,

g) hull systems P&IDs,

h) electrical area classifications,

i) emergency power system one-lines,

j) tank capacity plans,

k) deck load plan.

5 Design Criteria

5.1 General

This section defines the criteria commonly needed for the design of a TLP. The format of the design criteria is consistent with Section 6, and those sections that deal with the design of the various subsystems.

Design and analysis of a TLP and the associated subsystems require that a series of design load cases be specified and checked. This requires that each phase of construction, transportation, installation, and operation be coupled with appropriate design environmental events and associated safety factors. These design environmental events and safety factors are selected based on a calibration of the design code equations or as part of a probabilistic design analysis. Specification of the load cases also requires establishing the detailed condition, including the allowable range of weight and center of gravity variations of the platform.

Other environmental conditions, including long-term data for fatigue analyses, etc., are also needed for various design activities.

This publication is based on working stress design (WSD) principals. There have been efforts over the past 20 years to address load and resistance factor design (LRFD) principals in tension leg platforms, but these have been abandoned because of the dynamic nature of platform response wherein the final extreme response cannot reasonably be broken down into the component responses to individual load components. However, one significant advance in achieving more uniform risk levels which is included in this publication has been to include the concept of response-based criteria, wherein the variability and uncertainty of response to a multi-parameter environment is addressed in the specification of the design environment.

5.2 Safety Categories

5.2.1 General

The design checking procedures described herein are based on safety categories being applied to load cases. A safety category includes a specification of environmental conditions and safety factors that together are used to check the overall reliability and adequacy of a design. There are four different types of safety categories used in this recommended practice.

5.2.2 Category A—Operational Conditions

This category is used to assure that the structure meets criteria for operational capabilities. Considerations for this safety category include the acceptability of deflections and vibrations.

5.2.3 Category B—Extreme Conditions

This category is used to determine the serviceable strength of a structure. Category B applies to conditions that will occur only rarely in the life of the structure. The structure is designed to survive conditions without significant probability of its subsequent serviceability being compromised. Platform conditions to be covered include intact, damaged, and tendon removed cases.

5.2.4 Category S—Survival Conditions

This category is used to determine reserve strength of a structure to overload conditions, which are expected to occur very rarely during the life of the structure. The TLP should be designed to survive these conditions without loss of life, damage to the environment or total loss of the platform. Depending on the nature of the design, the yielding or failure of components or local areas of structure may be acceptable, provided no progressive failure is initiated.

For the TLP, the survival category also includes, at a minimum, required global load cases for deck clearance and minimum tendon tension, which are specified to ensure that the structure is inherently robust in its ability to deal with rare conditions. Inclusion of hull structural strength checks in survival conditions is not explicitly recommended, but is at the option of the operator.

5.2.5 Category C—Fatigue Conditions

This category is intended for the design of the structure against fatigue failure. This applies principally to components whose fatigue life will limit the service life of the overall structure. The structure will generally be designed such that its components have a minimum fatigue life greater than the structure’s required service life, with adequate margin of safety to account for uncertainties such as material properties, fabrication tolerances, inspection practices, ability to access for inspection, maintenance and repair, and criticality of the consequences of failure. The structure will be designed to facilitate the inspections appropriate to assure against premature failures. Easy inspection and repair or replacement may justify the use of particular components with an expected fatigue life that does not have a high probability of exceeding the service life of the structure.

5.3 Operational Requirements

Design criteria dictated by operational requirements should be reviewed during each iteration of the design. The cost and weight consequences of these requirements should be fully established for the operator before a final design decision is made.

Examples of such requirements may involve:

- limiting motions to meet requirements of facilities,
- simultaneous drilling and production,
- consumables resupply procedure and frequency,
- inspection and maintenance procedures and schedule,
- manning schedule and rotation.

5.4 Stability Requirements

5.4.1 General

Stability should be established for relevant in-place operating and pre-service conditions, for both intact and damaged states of the structure.

5.4.2 In-place Condition

The in-place TLP is a compliant structure. Stability of a TLP in the in-place condition is typically provided by the pretension and stiffness of the tendon system, rather than by the waterplane area and moments. Traditional measures of hydrostatic free floating stability (i.e. metacentric height without mooring stiffness) are not appropriate in the in-place condition of a TLP, but are replaced instead by the global performance minimum and maximum tension criteria based on a full dynamic analysis, and by serviceability limits on pitch and roll motions. Global performance load cases to demonstrate adequacy of design ensure that the system is sufficiently constrained by the tendon system in the intact, damaged, and tendon removed conditions, and is safe from overturning in all environmental conditions considered.

Hull damage scenarios to be considered, however, should be, at a minimum, the same as for damaged stability requirements for column stabilized MODU as prescribed in the applicable code [e.g. International Maritime Organization (IMO), class or coastal state regulations], including extent of damage and all pertinent definitions.

NOTE Unlike a MODU, the waterline of a TLP is affected by tide, storm surge, seabed subsidence, and draw-down (setdown) due to environmental loading. The vertical extent of damage should be adjusted accordingly.

5.4.3 Pre-service Conditions

The intact and damaged stability in all free-floating conditions prior to final installation (e.g. float-off, deck integration, wet tow, prior to initial tendon tensioning) should, in general, satisfy requirements applicable to column stabilized mobile offshore drilling units, as promulgated by the U.S. Coast Guard in the United States. In other locations, IMO MODU Code, or coastal state requirements, along with class society rules, may apply.

Marginal stability may be accepted for marine operations of short duration operation such as during deck integration at quay side or platform installation at the offshore site, provided that in these marginal stability conditions controlled transient ballasting, provision of reliable weather forecasts, limited weather windows, and close monitoring of the system status are used to provide and demonstrate an adequate safety level.

During installation or transient ballasting down conditions, it may not be practical to provide reinforcement against collision over the full range of waterlines. In such cases, rigorous procedures should be developed to ensure that such flooding will not occur. These should include consideration of collision, leakage through the ballast system and other systems and/or structure, reliability and redundancy in pumping arrangements and redundancy of power supply.

Planning and risk assessment should also include the definition of restricted criteria, and a procedure to return to the reinforced waterline should the installation operation be aborted.

Pre-service stability requirements can have a substantial influence on bulkhead placement and general arrangements of the hull. Care should be taken to review the applicable stability rules before entering the conceptual design phase. Hull sizing and arrangements should consider the ability to recover from damage, and carry sufficient ballast weight margin to accommodate unexpected growth in vertical center of gravity, which will adversely impact stability in pre-service conditions.

5.4.4 Weight Control

All TLP design and construction should include careful weight control procedures. This includes the following:

a) a detailed breakdown of component and module estimates during design;

b) weighing or accurate estimation of components during construction;

c) tracking of weights during assembly and commissioning;

d) an inclining test of the completed TLP, when possible.

The final weight condition of the platform includes weight, vertical and lateral center of gravity, and estimates of the mass moments of the system. An example of a good reference for weight control procedures can be found in ISO 19901-5.

5.4.5 Inclining Tests Weight and CG Determination

An inclining test should normally be conducted when construction is as near to completion as practical, to accurately determine the platform weight and the position of the center of gravity. Changes of on board load conditions after the inclining test and during service should be carefully accounted for.

5.4.6 Alternate Weight and CG Determination

Some platform configurations are not stable in the free-floating condition as a fully assembled configuration. With such systems it may not be possible to perform a traditional inclining test of a reasonably complete portion of the platform. In other cases, the TLP may be integrated on location with deck structure or modules being installed on an installed hull. In cases where an inclining test is not utilized, alternate means of determining the weight and center of gravity of the TLP may be utilized. Such alternate methods include accurate weighing of TLP or components using certified load cells, and careful weight control methods and procedures to assemble the final weight and CG of the completed system.

5.5 Environmental Criteria

5.5.1 General

Environmental criteria should be associated with the safety category being considered. Philosophically, the environments specified for use in this publication are response-based, i.e. a 100-year design event is an environment that is expected to lead to 100-year responses. This is achieved either by use of traditional design criteria (independent of TLP sensitivity) supplemented by a probabilistic design analysis, or by an environmental scanning process to determine appropriate criteria for the TLP system, again supplemented by a probabilistic design analysis. The probabilistic analysis or scanning process can be performed as a calibration for a class of TLPs in a given environment, or can be performed for an individual project.

There can be different design events at a given return period that can govern different responses of the TLP.

NOTE TLPs are sensitive to a number of different environmental loadings and the extreme responses of TLPs are not necessarily produced by the highest wave or highest wind conditions.

Because of its compliant and dynamic nature, criteria for design of a TLP require a reasonably complete specification of the environment, including wave significant height, period, and spectral form, wind velocity and spectrum, current profile, and water level (tide and storm surge). Directional distributions are sometimes significant. In general, detailed site-specific conditions, rather than generic regional conditions, should be used for floating systems. Selection of the actual data needed should be made only after consultation with both the platform designer and meteorological/oceanographic specialists.

For the Gulf of Mexico, the collection and analysis of metocean data should also follow the recommendations in API 2INT-MET.

Available statistical data and/or realistic statistical and mathematical models should be utilized to develop the description of environmental conditions. Considerations include:

— operating environmental conditions are important both during the construction and during the service life of a platform,

— extreme and survival conditions are important in formulating platform design loadings.

All data used should be documented in project design reports as to source, analysis methods, and assumptions in interpretation. The quality and the source of all data should be recorded. The methods employed in developing data into the desired environmental values should be reported as part of project documentation.

The following sections briefly describe the environmental parameters that should be specified for use in design. For guidance on actual values to use in design, the designer should refer to data collected at the intended site, to appropriate oceanographic numerical models, and to API 2INT-MET.

5.5.2 Wind

Wind is significant in TLP design and analysis. Both steady wind and fluctuating wind components should normally be used. A wind spectrum is normally used to represent fluctuating wind components, although use of gust values is acceptable if these are shown to provide an equivalent response to use of a full wind spectrum. API 2A-WSD provides guidance on wind gust modeling and wind spectra.

5.5.3 Waves

Wind driven waves are a major source of environmental forces on offshore platforms. Such waves are irregular in shape, can vary in height and length, and may approach a platform from one or more directions simultaneously.

Because of the random nature of the sea surface, the sea state is usually described in terms of statistical wave parameters such as significant wave height, spectral peak period, spectral shape (including spectral width), and directionality. Other important sea state parameters which may affect TLP response are the maximum up and down crossing wave height and the maximum crest height.

The statistical maximum crest height that a platform may experience has been shown to depend on the plan view size of the platform. Forristall [142] describes methods for predicting local maxima based on traditional point statistics. This procedure was adopted in API 2INT-MET.

5.5.4 Current

Current data collected at the site should be included in the design criteria if available. Currents should include wind driven, tidal, and background circulation components. In deepwater the currents might produce large system loads. Near boundary currents such as the Gulf Stream and loop current, currents due to meanders and eddies should be considered. Deep current profiles have been identified in the Gulf of Mexico and elsewhere, and should also be included if likely to occur. Recent descriptive names of such currents include cold core eddy, submerged current, and submerged jets. Bottom boundary currents in some areas such as the Sigsby Escarpment have also been identified. Current profiles over the entire water column are important to calculation of loads on, and VIV of, tendons and risers.

5.5.5 Tide and Water Level

Tidal components for design include astronomical, wind, and pressure differential tides. A high design water level (HDWL) and low design water level (LDWL) should be established for each design event. The tidal range will affect the required tendon pretension (minimum tension) and will contribute to maximum tension.

5.5.6 Joint Statistics

Environmental data such as wind, tide, wave, and currents can have specific relationships regarding their interaction and joint occurrences. A commonly used assumption of taking the combined maximum of each parameter might not always produce the worst design condition, or may be excessively conservative. When collecting data or performing analytical work, the various relationships should be included if possible. Of particular importance are wind/wave, wave height/wave period, wave/current, wind/current and wave/tide relationships.

5.5.7 Physical Properties

Various seawater physical properties, such as temperature, salinity, and oxygen content, may be important for steel requirements, corrosion, and buoyancy calculations. Further guidance can be found in API 2A-WSD. In areas where substantial density differences may occur, the ranges should be accounted for in design load cases.

5.5.8 Ice

In far northern or far southern climates, floating ice or atmospheric icing can affect the loading on the platform (refer to API 2N).

5.5.9 Earthquakes

Seismic accelerations should be considered for areas that are determined to be seismically active. Both vertical and horizontal accelerations are important for TLP design. The horizontal accelerations excite tendon transverse modes, while vertical accelerations directly excite heave, pitch, and roll responses of the TLP. Soil liquefaction leading to foundation failure is also a concern. The degree of risk for seismic activity in the United States is shown in API 2A-WSD. Local regulations and conditions should be considered and may result in more stringent requirements.

5.5.10 Marine Growth

The type and accumulation rate of marine growth at the design site should be evaluated for determining design allowances for weight, hydrodynamic diameters, and drag coefficients. Refer to API 2A-WSD for appropriate guidance.

5.6 Design Load Cases

5.6.1 General

Defining a design load case requires selection of the following parameters:

- project phase,
- platform condition,
- environment and safety factors.

5.6.2 Definition of Loads Acting on Structure

All appropriate load types shall be quantified and included for each design case. Load types and design parameters are discussed in the following sections. Table 1 shows how the parameters may be combined to define design cases. This table is intended only to provide an example and is not necessarily complete. Other environmental criteria may be used if properly justified.

5.6.3 Project Phase

5.6.3.1 General

This describes the phase of the platform or component, e.g. hull construction, deck transport, platform in-place. The construction, float-out, load-out and transportation phases have various loading conditions that should be examined. These conditions are described by the stage of construction, draft during tow, or stage of load-out.

5.6.3.2 Fabrication

Loading conditions imposed on the hull and deck during fabrication could control the structural design of some components. Intact and damaged stability of the freely floating hull shall be ensured at all phases of the fabrication.

Table 1—Project Design Load Cases

Design Load Case	Safety Category	Project Phase	Platform Configuration[e]	Design Environment	Annual Probability of Exceedance
1	A	Construction	Various		
2	A	Load out	Intact	Calm	
3	B	Hull/deck mating	Intact	Site specific	
4	B	Tow/transportation	Intact/damaged	Route	Varies
5	A	Installation	Intact	Installation	Varies
6	A	In place	Intact	One-year normal	≤1
7	B	In place	Intact	100-year extreme	0.01
8	S	In place	Intact	1000-year extreme	0.001
9	B	In place	Damaged—no compensation	One-year normal	≤ 0.01[a]
10	S[b c]	In place	Damaged—no compensation	10-year reduced extreme	≤ 0.001[a]
11	B	In place	Damaged—compensation	10-year reduced extreme	≤ 0.01[a]
12	S[b c]	In place	Damaged—compensation	100-year extreme	≤ 0.001[a]
13	B	In place	Tendon removed (planned)	10-year reduced extreme	≤ 0.01[a]
14	S[b c]	In place	Tendon removed (planned)	100-year extreme	≤ 0.001[a]
15	C	In place	Intact	Annual scatter diagram	1
16	SLE[d]	In place	Intact	SLE seismic	Varies
17	DLE[d]	In place	Intact	DLE seismic	Varies

NOTE This table is indicative of the types of load cases to be checked, and is not intended to imply adequate number of load cases.

[a] Probability of exceedence includes nominal probability of damage or tendon removal occurring.

[b] Pile check, if performed, in survival conditions uses reduced safety factor.

[c] Survival check with damage or tendon removed is against disconnect (not zero tension) and may be response-based.

[d] See Section 4 and API 2A-WSD for definition of SLE, DLE.

[e] In all cases, platform configuration should consider both minimum weight and maximum weight variations.

5.6.3.3 Transportation

The freely floating platform behaves like a semisubmersible during transportation to the installation site. Since it is free to pitch and roll, lateral deck accelerations can be larger than after installation. Since it is free to heave, and heave resonant periods tend to be short, adequate deck clearance with the waves should be verified.

Alternately, the hull, deck, or complete TLP can be transported on a barge or heavy lift vessel. In this case, the motions of the combined barge/TLP component shall be used in determining accelerations, loads, and clearances.

5.6.3.4 Installation

The stiffness and mass properties change as the platform is transformed from a freely floating vessel to a vertically moored platform, thus changing the dynamic response characteristics. The tendons and their handling equipment should be designed for loading conditions representative of the various installation phases.

5.6.4 System Condition

5.6.4.1 General

This section describes the condition of the platform or component.

5.6.4.2 Intact

The platform or component is as designed.

5.6.4.3 Damaged Hull

Damaged conditions should be checked for various project phases. The transport barge or floating component should be checked with one compartment flooded.

In the in-place condition, the platform should be capable of withstanding damage in a normal condition (one-year storm) with no ballast adjustment, or a reduced extreme condition (10-year storm) with ballast adjustments.

Flooded compartments to consider, extent of damage, and associated definitions should be in accordance with that prescribed for column stabilized MODU in the applicable code (e.g. IMO, class, coastal state regulations). Within a range of 5 m (16.4 ft) above and 3 m (10 ft) below any in-place waterline, any watertight flats, or bulkheads shall be considered damaged. The location of the waterline for a TLP will vary with tide, storm surge and seafloor subsidence. This means the distance between horizontal flats will be considerably greater than the minimum prescribed for semisubmersibles in MODU codes (e.g. +5 m/−3 m). In addition, consideration should be given to the dimensions of typical supply boats used in the region of operation, and any hazards that may require an increase in vertical spacing.

At a minimum, damaged scenarios should include any single compartment adjacent to the sea, any two adjacent compartments at the waterline, any horizontal flats located in the damage zone as defined above, any compartment containing ballast pumps or machinery cooled by seawater.

5.6.4.4 Tendon Removed

For TLPs with more than one tendon per corner, it is recommended that the TLP be designed on the basis that tendons can be removed for inspection, maintenance, or replacement. In this tendon-removed condition, the TLP should be designed for combinations of static, environmental, motion induced and construction loads. This condition is a planned maintenance or construction condition, and would include appropriate ballast to maximize performance in this condition. The platform has reduced capacity while in a tendon removed condition, and careful monitoring of environment and operational weight to ensure optimum configuration and response is recommended. The platform should be capable of withstanding a reduced extreme condition (10-year storm) with Category B safety factors with one tendon removed. The platform shall be shown to survive the extreme response condition (100-year storm) without loss of the platform in the tendon-removed configuration (i.e. Safety Category S). This case is intended to be a true survival case, and is not limited to the zero tension recommendation. Because of the nature of this condition as a reduced capacity/damaged condition case with full planning and preparation, special conditions such as pinning a connector to prevent disconnect upon slack condition are acceptable in meeting survival condition requirements. The tendon-removed condition as discussed herein is not a broken tendon case.

5.6.5 Design Environments

5.6.5.1 General

5.6.5.1.1 Design environmental conditions are associated with each safety category. The important aspect of the environmental design condition used to evaluate the design response is that it be the same environment used in the calibration of the safety factors. In the context of this recommended practice, environmental conditions are also associated with response return periods, and are referred to as “design environments.”

5.6.5.1.2 The selection of the design environments should be based on either general or specific TLP response characteristics. The designer/owner is responsible for selecting appropriate design environments. Guidance on a probabilistic analysis method for selection of appropriate design environments may be found in Section 7. Further information on the sensitivity of the TLP system to selection of environment for Gulf of Mexico locations may be found in the Conoco Model Code reports (Banon, et al. 1994 [95]; Jefferys and Banon 1993 [162]; Leverette, API TAC-93-20 [176]; Spillane and Leverette 1988 [224] and 1991 [225]; Leverette and Rashedi, 1995 [178]. General methods for establishing response-based criteria are described in Schaudt, et al. 1992 [218]; Wen and Banon, 1995 [242]; Forristall et al. 1991 [141]; Spillane, et al. 1999 [226]. Traditional design environments determined as extreme n-year return wind, wave, and current events should be used for areas with insufficient environmental database to generate appropriate response based design environments. In such cases, the designer is encouraged to examine appropriate sensitivity cases to ensure that sufficient consideration is given to possible onerous combinations of events.

5.6.5.1.3 The design environment should be defined quantitatively in terms of wind (speed, direction, spectrum), wave (H_S, T_P, spectral shape, direction), current (speed and direction as function of depth), and water level (tide, storm surge).

5.6.5.1.4 The various safety categories include different return periods for the design environments. Typical design environments include the following.

5.6.5.2 Extreme Environments

Extreme environmental conditions are those that produce TLP responses having a low probability of being exceeded in the lifetime of the structure. A minimum return period of 100 years for the design response should be used for Safety Category B criteria for the intact condition unless risk analysis can justify a shorter recurrence interval.

The structure and its key subsystems shall be designed such that they will be capable of withstanding extreme environmental conditions in a safe operable condition. Similar extreme environments may be combined with damaged cases to assess the ability of the structure to survive without further damage.

5.6.5.3 Normal Environment

Normal environmental conditions are those that are expected to occur frequently during the construction and service life. Since different environmental parameters and combinations affect various responses and limit operations differently (e.g. installation, crane usage, etc.), the designer should consider the appropriate environmental conditions for the design situation.

5.6.5.4 Reduced Extreme Environment

Reduced extreme environmental conditions are those that have a low probability of being exceeded in combination with other low probability events (e.g. when the hull is damaged or a tendon is removed). Joint statistics may be used to determine a return period which, combined with the probability of damage, produces a risk level equal to that of the extreme environment. A return period of 10 years is typically used for damaged or temporary reduced capacity conditions of the TLP. For removed tendon conditions, a 10-year annual storm condition is recommended with no restriction on season for removing a tendon.

5.6.5.5 Survival Environment

Survival environmental conditions as described in this publication are those that produce TLP responses having a very low probability of being exceeded in the lifetime of the structure. A minimum return period of 1000 years for the design response should be used for Safety Category S criteria for the intact condition, unless risk analysis can justify a shorter recurrence interval. Survival conditions are used for evaluating minimum tension and deck clearance.

5.6.5.6 Calm Environment

Some operations are performed only during calm conditions. Where such a choice is available the design case is permitted to use calm conditions.

5.6.5.7 Transportation, Installation, and Marine Operations Environments

For pre-service conditions, including float-off, integration, dry or wet transport to site, and installation, the return period of environmental conditions to be considered should be related to the duration of the marine operation and the appropriate risk level. As a general guidance, the criteria in Table 2 may be applied.

Table 2—Return Period of Environmental Conditions

Duration of Use	Environmental Criteria
Up to three days	Special weather window
Three days to one week	One-year return seasonal
One week to one month	10-year return seasonal
One month to one year	50-year return seasonal
More than one year	100-year return all year

5.6.5.8 Operation Duration

5.6.5.8.1 For weather-restricted operations, there should be a margin between the design criteria and the operation criteria. As a guideline, a ratio of 0.8 for wind speed and 0.75 for wave height may be used to derive the operational criteria from the design criteria. Weather restricted operations may be divided into sequences where the operation may be aborted and brought to a safe condition (safe haven) within the remainder of the existing weather window.

5.6.5.8.2 The point of no return (PNR) should be defined as the last point in time (or a geographical point along a route) at which an operation could be aborted or returned.

5.6.5.8.3 For the critical period between any PNR and the structure reaching a safe condition, the reliability of weather window is crucial. The window duration shall have necessary margins for the following:

a) inaccuracy in operation schedule,

b) technical/operational delays, and

c) inaccuracy of weather forecast timing.

5.6.5.8.4 Generally, the forecast window duration shall be in excess of the total critical operation schedule. This, however, needs to be evaluated on background and consequences as given in the following guidelines:

a) operations with vulnerable/critical equipment need extra allowance,

b) operations with time schedule based on previous similar operations need less allowance,

c) operations in areas/time of the year where weather is difficult to predict need extra allowance.

5.6.5.9 Weather Forecast

5.6.5.9.1 Weather forecasts should be obtained before and during all marine operations. The forecast shall be issued at regular intervals, e.g. every 12 hours. For weather-restricted operations, the forecasters should preferably be present at site to provide regular weather briefing.

5.6.5.9.2 The weather forecast should be in writing and include relevant parameters such as:

a) synopsis, barometric pressure, temperature;

b) wind direction and velocity;

c) waves and swell: significant and maximum wave height, direction and period;

d) visibility, rain, snow, sleets, etc.

5.6.5.9.3 Other environmental conditions such as current, tide and surge, may also be of utmost interest for certain operations. Such conditions need real time measurements as well as regular forecast, both prior to start of and during operation.

5.6.5.9.4 Normally the weather (environmental) forecast should cover the following period 0 to 12 hours, 12 to 24 hours, 24 to 36 hours, 36 to 48 hours, 48 to 72 hours, and outlook beyond 72 hours. Any weather forecast shall give a level of confidence.

5.6.5.9.5 Transportation cases should use appropriate conditions for the transportation route.

5.6.5.9.6 Consideration should be given to possible delays in overall project when designing a major marine operation for a specific season. Criteria for partially installed systems (such as preinstalled tendons) should make allowances for possible delays, such as those due to weather, current conditions, or project schedule, in installing the rest of the system. Experience has shown that potential delays can be several months. Selected criteria should be representative of specific project conditions and factors.

5.6.5.10 Seismic

The TLP should be designed with strength and stiffness to ensure no significant structural damage occurs for the level of earthquake shaking which has a reasonable likelihood of not being exceeded during the life of the structure. The two-tier SLE/DLE criteria as used for fixed offshore platforms are also applicable to TLPs (refer to API 2A-WSD). SLE and DLE criteria should be developed using a probabilistic seismic hazard assessment (PSHA) consistent with the seismic risks at the site.

5.6.6 Safety Factors

The safety categories described above are associated with matched sets of design environments and safety factors. The safety factors are a means of ensuring an adequate level of safety above and beyond the return period of the design environment, and for accounting for other sources of variability and uncertainty. The safety factors are based on a target annual probability of exceedence level. Different safety categories generally have different target safety levels.

The safety factors for global responses are given in Section 7. The safety factors for allowable stress for the various components are given in their respective sections or in the annexes.

5.6.7 Load Types

Loading type categories are described in Table 3. The combination and severity of loads should be consistent with the likelihood of their simultaneous occurrence.

Table 3—Loading Type Category Descriptions

Load Type	Description
Dead loads	Nonvariable static weight of the platform structure and any permanent equipment that does not change during the life of the structure.
Live loads	Variable static loads that can be changed, moved or removed during the life of the structure. Maximum and minimum payloads should be considered.
Environmental loads	Loads on the structure due to the action of wind, wave, current, tide, earthquake, or ice.
Inertial loads	Motion induced loads that are consequences of the environmental loads.
Construction loads	Loads built into the structure during the fabrication and installation phases.
Hydrostatic loads	Buoyancy of, or submerged pressure on, submerged members.
Combined loads	The combination and severity of loads should be consistent with the likelihood of their simultaneous occurrence.

6 Environmental Forces

6.1 General

The purpose of this section is to describe methods for calculating forces which act on an in-place TLP due to environmental effects, such as waves, winds, currents, ice, earthquakes, etc. Forces due to platform motion responses are also significant and are discussed herein. Environmental parameters needed for these calculations are defined in Section 5. The emphasis in this section is on calculating the forces on individual members or local forces. Methods for calculating global environmental forces and platform responses caused by these environmental forces are described in Section 7.

Environmental forces should be calculated at four distinct frequency bands to evaluate their effects on the system. The four frequency bands are as follows.

a) Steady forces such as mean wind, current, and wave drift are constant in magnitude and direction for the duration of interest.

b) Low-frequency cyclic loads can excite the platform at its natural periods in surge, sway, and yaw by waves, wind and current (oscillating body in a steady current produces an oscillating force); typical natural periods are in excess of one minute.

c) Wave frequency cyclic loads are large in magnitude and are the major contributor to platform member forces and tendon system forces. Typical wave periods range from 5 to 30 seconds.

d) High-frequency cyclic loads can excite the platform at its natural periods in heave, roll and pitch: typical natural periods range from 1 to 5 seconds.

6.2 Wind Forces

6.2.1 General

The wind conditions used in a design should be determined with appropriate means from wind data collected in accordance with Section 5 and should be consistent, in terms of joint probabilities of occurrence, with other environmental parameters assumed to occur simultaneously. A TLP has long natural periods in surge, sway, and yaw which may be excited by energy in the wind spectrum. The effects of the complete wind spectrum, including sustained and fluctuating winds, should be considered in determining the wind induced platform loads and responses. Such analyses may require knowledge of the wind turbulence intensity, spectra, and spatial coherence. These items are addressed below.

6.2.2 Wind Properties

6.2.2.1 General

Wind speed and direction vary in space and time. On length scales typical of even large offshore structures, statistical wind properties (e.g. mean and standard deviation of velocity) taken over durations of the order of an hour do not vary horizontally, but do change with elevation (profile factor). Within long durations, there will be shorter durations with higher mean speeds (gust factor). Therefore, a wind speed value is only meaningful if qualified by its elevation and duration. A reference value is the one-hour mean speed at the reference elevation of 10 m (32.8 ft).

6.2.2.2 Mean Profile and Gusts

A wind profile defines the vertical variation of wind speed, given a reference wind speed as defined in 6.2.2.1. Applicable mean wind profiles and gusts are defined in API 2A-WSD. Therefore, once the reference wind speed is defined, the wind speed at any elevation is also defined.

Wind gust speeds can be calculated from an hourly mean speed. The conversion equations are specified in API 2A-WSD.

6.2.2.3 Wind Spectra

As with waves, the frequency distribution of wind speed fluctuations can be described by a spectrum. Due to the large variability in measured wind spectra, there is no universally accepted spectral shape. In the absence of data indicating otherwise, the simple shape given by API 2A-WSD is recommended.

6.2.2.4 Spatial Coherence

Wind gusts have 3D spatial scales related to their durations. For example, three-second gusts are coherent over shorter distances and therefore affect smaller elements of a platform superstructure than 15-second gusts. The wind in a three-second gust is appropriate for determining the maximum static wind load on individual members; five-second gusts are appropriate for maximum total loads on structures whose maximum horizontal dimension is less than 50 m (164 ft); and 15-second gusts are appropriate for the maximum total static wind load on larger structures. The one-minute sustained wind is appropriate for total static super-structure wind loads associated with maximum wave forces. In frequency domain analyses of dynamic wind loading, it can be conservatively assumed that all scales of turbulence are fully coherent over the entire superstructure.

The variable nature of the wind field can alternatively be described by two components: a sustained component (V_z) and a gust component (u'). The calculation of the total wind speed is show in Equation (1).

$$u = V_z + u' \tag{1}$$

where

u is the instantaneous wind velocity (speed and direction);

V_z is the mean (or sustained) wind velocity;

u' is the instantaneous velocity variation from sustained wind.

6.2.3 Wind Force Relationship

6.2.3.1 The instantaneous wind force on a TLP can be calculated by summing the instantaneous force on each member above the water line. This should be calculated by an appropriate equation as shown in Equation (2).

$$F_w = \frac{1}{2}\rho_a C_s A |V_z + u' - \dot{x}| (V_z + u' - \dot{x}) \tag{2}$$

where

F_w is the wind force;

ρ_a is the mass density of air;

C_s is the shape coefficient (may also account for shielding);

A is the projected area of object;

V_z is the mean wind speed;

u' is the instantaneous speed variation from sustained wind;

$\dot{x}$ is the instantaneous velocity of structural member.

6.2.3.2 For all angles of wind approach to the structure, forces on flat surfaces should be assumed to act normal to the surface and forces on vertical cylindrical objects should be assumed to act in the direction of the wind. Forces on cylindrical objects that are not in a vertical attitude should be calculated using appropriate formulas that take into account the direction of the wind in relation to the attitude of the object. Forces on sides of buildings and other flat surfaces that are not perpendicular to the direction of the wind shall also be calculated using appropriate formulas that account for the skewness between the direction of the wind and the plane of the surface.

6.2.3.3 The total wind force on the structure may also be calculated using the total exposed area of the structure with appropriate coefficients determined by model tests or some other appropriate method.

6.2.3.4 When using the wind spectrum, it is common to linearize the force for spectral and frequency domain calculations (Simiu and Leigh, 1983 [222]; Kareem, 1980 [164]).

$$F_{\mathrm{w}} = \frac{1}{2}\rho_{\mathrm{a}} C_{\mathrm{s}} A V_{\mathrm{z}}^{2} + \rho_{\mathrm{a}} C_{\mathrm{s}} A V_{\mathrm{z}} u' \tag{3}$$

where

F_{w} is the wind force;

ρ_{a} is the mass density of air;

C_{s} is the shape coefficient (may also account for shielding);

A is the projected area of object;

V_{z} is the mean wind speed;

u' is the instantaneous speed variation from sustained wind.

The first term in Equation (3) is the constant or steady force, and the second term is linear in the fluctuating velocity. The higher-order term, which is neglected in this approximation, is generally small. It does contribute a small amount to the steady force.

6.2.4 Steady Wind Force

6.2.4.1 The first term of Equation (3) is the steady wind force. V_{z} should correspond to the mean wind speed used in generating the wind spectrum.

6.2.4.2 Commercial software programs are available for estimating the steady wind forces on a complex structure that contains many small dimensioned and spatially separated elements.

NOTE 1 This software is highly dependent on modeling parameters; having an understanding of wind tunnel tests is recommended when using and tuning these programs.

NOTE 2 Validation of the software on a similar platform type is recommended.

6.2.4.3 In addition to producing steady wind forces, steady wind can also induce vibrations of slender structural members (see 6.4 for more details on VIV).

6.2.5 Fluctuating Wind Force

The fluctuating wind force may be calculated in the time or frequency domains. In the time domain, the total wind force is calculated from a time series of the instantaneous total wind velocity using Equation (2). In frequency domain calculations, Equation (3) may be used with the wind spectrum to derive the wind force spectrum as shown in Equation (4):

$$S_{\mathrm{ff}}(f) = \chi^{2}(f)\, S_{\mathrm{uu}}(f)(\rho_{\mathrm{a}} C_{\mathrm{s}} A V_{\mathrm{z}})^{2} \tag{4}$$

where

S_{ff} is the wind force spectrum;

f is the frequency;

χ is the aerodynamic admittance coefficient;

S_{uu} is the wind gust spectrum;

ρ_{a} is the mass density of air;

C_{s} is the shape coefficient (may also account for shielding);

A is the projected area of object;

V_{z} is the mean wind speed.

In lieu of full spectral analysis, a quasistatic analysis using one-minute mean wind speed and Equation (2) can be used, if it can be demonstrated that the results (such as extreme TLP offset, etc.) are similar for both methods.

6.2.6 Shape and Shielding Coefficients

The shape coefficients in Table 4 are recommended for perpendicular wind approach angles.

Table 4—Shape Coefficients for Perpendicular Wind Approach Angels

Shape Coefficient	Object
1.5	Beams of various cross section shapes
1.5	Sides of rectangular sections
0.5	Cylindrical sections
1.0	Overall projected area of platform (should be confirmed by model testing)

Shielding coefficients may be used when the proximity of a second object relative to the first is such that it does not experience the full effect of the wind (Simiu and Scanlan, 1978 [221]; DNV-RP-C205; Hoerner, 1965 [153]; Meyers, Holm, and McAllister, 1969 [191]).

6.2.7 Aerodynamic Admittance

Wind gusts measured at two locations become uncorrelated as the distance between the two locations increase. When the lateral dimensions of a structure are large, the reduction in gust forces can be accounted for by an aerodynamic admittance factor. Simiu and Scanlan, 1978 [221], present data on transverse gust correlations which can be used to determine admittance factors. The aerodynamic admittance coefficient χ modifies the force equation as shown in Equation (5)

$$F_{\mathrm{w}} = \frac{1}{2}\rho_{\mathrm{a}} C_{\mathrm{s}} A V_{\mathrm{z}}^{2} + \rho_{\mathrm{a}} \chi C_{\mathrm{s}} V_{\mathrm{z}} u' \tag{5}$$

where

F_w is the wind force;

ρ_a is the mass density of air;

C_s is the shape coefficient (may also account for shielding);

A is the projected area of object;

V_z is the mean wind speed;

χ is the aerodynamic admittance coefficient;

u' is the instantaneous speed variation from sustained wind.

The admittance coefficient is frequency dependent, is smaller for higher frequencies, and varies between 0 and 1. A value of χ =1.0 is conservative and appropriate for low-frequency wind oscillation, and should be used for high frequencies when data is not available to establish a lower value.

6.2.8 Wind Tunnel Data

6.2.8.1 Wind pressures and resulting forces may be determined with properly executed wind tunnel tests on representative models. An example of tests for a semisubmersible is given in Macha and Reid (1984) [184]. Such tests may be suitable for a similarly shaped TLP.

6.2.8.2 In wind tunnel test, special attention should be paid to model scale, boundary layers thickness and test Reynolds number. The model should be as large as possible within the limitations of the testing facility.

6.2.8.3 In lieu of exhaustive wind tunnel test, software calibrated to model test on the same or similar structures can be used to estimate wind forces.

6.3 Current Forces

6.3.1 General

The current velocity used in design should be determined by the means described in 5.5.4 and should be consistent (as to return period) with other design parameters such as wave height and wind velocity. The joint statistics of current and other environmental events should be considered.

Ocean currents can cause two major effects on TLP members—drag force and vortex induced vibration or VIV.

6.3.2 Current Drag

The drag force exerted on a bluff cylindrical member by a current is proportional to the square of the current velocity. The drag force acts in the direction of the component of current that is normal to the member axis. The drag coefficient should be based on the best empirical data available. Drag force can be determined using the formula in Equation (6).

$$F_d = \frac{1}{2}\rho_w C_D \int A_c (V - \dot{x})\left|V - \dot{x}\right| dl \qquad (6)$$

where

F_d is the drag force;

ρ_w is the mass density of water;

C_D is the drag coefficient;

A_c is the projected area per unit length;

V is the current velocity;

$\dot{x}$ is the instantaneous velocity of structural member.

The current effect is not limited to producing steady drag forces. Current can also produce low-frequency excitation and damping. The damping effect is especially important in low-frequency range where damping from other sources is small. The current induced damping should be considered for all low-frequency motion analyses.

The current drag coefficient of the hull should be obtained by model testing.

6.4 Vortex-induced Vibrations (VIV)

6.4.1 General

6.4.1.1 When a flow, either air or fluid, passes a blunt body, vortices are shed around the body. The normal shedding pattern of the vortices is asymmetric and alternating between the two sides of the body. As a result, the alternating vortices generate an alternating lift (normal to the direction of flow) force and a drag (parallel to the flow direction) force. Normally, these forces are randomly distributed along the body. The net force on the body is of little or no consequence. If, however, the body is capable of vibrating, the vortices are in phase along a significant segment of the body, and the vortices are being shed at or near one of the body's natural frequencies, the body may be excited to vibrations of significant amplitude. The vibration induced by the lift force is called transverse VIV and that induced by the drag force is called in-line VIV.

6.4.1.2 Currents acting with nearly uniform speed over a substantial portion of the body are more likely than waves to excite such vibration. Wind also can generate VIV on slender structural members.

6.4.1.3 The VIV response of a structure, either a rigid hull or a flexible member such as a tendon or a riser, is normally function of vortex shedding frequencies, properties of the structure such as natural frequency, mode shapes and damping, current profile etc.

6.4.1.4 Unlike other forced vibrations, VIV is a self-limiting phenomenon—the vibration amplitude is normally limited to a few (rarely more than two times) structure diameters. Although the amplitude is relatively small in many cases, the fatigue damage caused by VIV can be very severe if the structure is not properly designed.

6.4.1.5 Tendon VIV can affect tendon fatigue, hull fatigue if hull vibration is excited by the tendon VIV and hull accelerations, which could limit topsides operations.

6.4.1.6 The consequence of tendon VIV response can be:

— tendon structural fatigue,

— increase of drag loading on the tendon, and

— hull vibration induced by tendon VIV.

These consequences should be considered in platform designs, if tendon VIV is predicted.

6.4.1.7 For the risers on a TLP, fatigue damage, and drag amplification are the most important consequences of VIV.

6.4.1.8 In addition to tendon and risers, TLP hull of certain shapes (single circular column) may also be subject to VIV or VIM (Leverette et al. 2003 [179]). VIV of hull structures is also referred as VIM, or vortex induced motions. More recently, VIM in multi-column floaters including TLP has been observed (Rijken et al. 2004 [212]; Waals et al. 2007 [241]). It can have adverse impact on fatigue life of steel catenary risers. The potential of hull VIV should not be ignored and should be examined and evaluated during the design.

6.4.1.9 Slender structural members above the water line can also have severe vibrations induced by wind vortex shedding, if not designed properly. In general, wind induced vibrations are in higher frequencies than current induced vibrations. In a TLP design, wind-induced vibrations should be examined for all slender members, either on the topsides or on the hull.

6.4.2 Important Parameters

There are two important parameters in evaluating VIVs.

The first one is the vortex shedding frequency, which can be estimated by the formula in Equation (7).

$$f = S\,\frac{V_\mathrm{c}}{D} \qquad (7)$$

where

f is the vortex shedding frequency;

S is the Strouhal number;

V_c is the current velocity normal to member axis;

D is the member diameter.

The Strouhal number (S) varies with Reynolds number and cross section shape. It has a nominal value of 0.2 for TLP columns, tendons and risers in the relevant range of Reynolds numbers in currents.

For other shapes, the Strouhal number can be in the range of 0.12 to ~ 0.2.

The second parameter is the reduced velocity. VIV is a hydroelastic phenomenon whose amplitude is not amenable to prediction by conventional methods of forced oscillation analysis. The vibration amplitude has, however, been correlated with a nondimensional parameter called the reduced velocity, V_r, which is defined as:

$$V_\mathrm{r} = \frac{V_\mathrm{c}}{f_\mathrm{n}\,D} \qquad (8)$$

where

V_r is the reduced velocity;

f_n is the natural frequency;

V_c is the current velocity normal to member axis;

D is the member diameter.

A typical plot of VIV amplitude vs V_r has a bell shape with the highest amplitude in the range of $V_r = 4 \sim 8$ (see Figure 2).

In this plot, the amplitude of cylinder motion in the transverse direction, A_y, is normalized by the cylinder diameter, D, and the reduced velocity V_r is defined as a function of the velocity U. The plot also shows the influence of the vortex shedding frequency (f_s) on the response frequency (f).

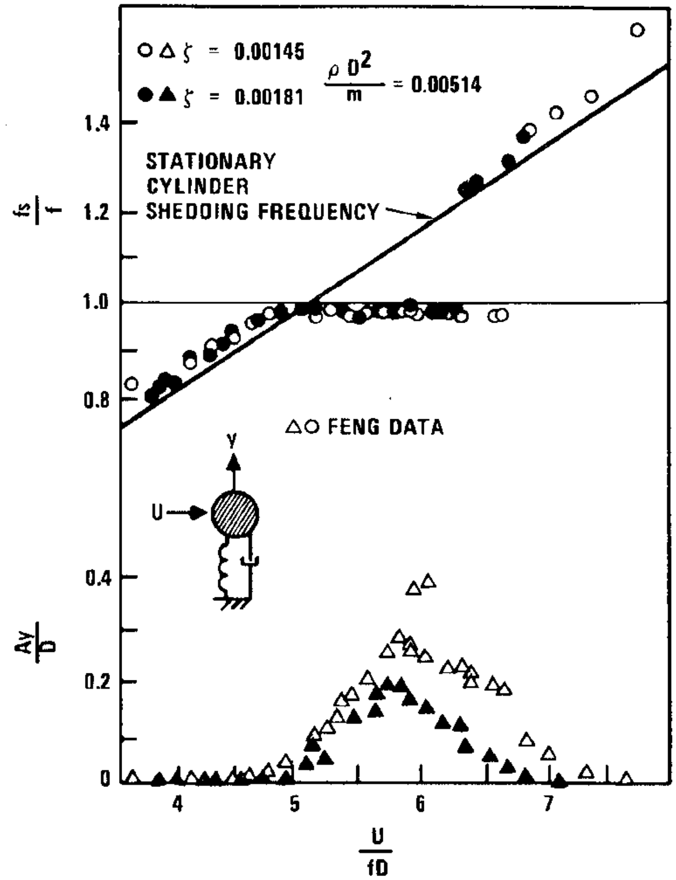


Figure 2—VIV of a Spring-supported, Damped Circular Cylinder [3]

6.4.3 Current- and Wind-induced VIV

Ocean currents and wind can both cause VIV in slender structures. VIV can occur in both crossflow and in-line (same direction as the flow) directions.

Crossflow VIV can occur both in currents and wind when the reduced velocity is in the range of:

$$4.7 < V_r < 8.0$$

In-line VIV can occur in currents when the reduced velocity is in the range of:

$$1.0 < V_r < 3.5$$

---

[3] Feng, 1968 [139].

In-line VIV can occur in wind when the reduced velocity is in the range of:

$$1.7 < V_r < 3.2$$

6.5 Wave Forces

6.5.1 General

6.5.1.1 The wave spectrum and/or deterministic wave height and period used in the design should be determined as discussed in 5.5. When applied with other environmental parameters the wave parameters should be consistent with respect to return period.

6.5.1.2 Two approximate methods for calculating wave forces are commonly used. These are the Radiation/diffraction theory (Newman 1977 [199]; Sarpkaya and Isaacson, 1981 [215]; Mei, 1983 [188]; Chakrabarti, 1987 [113]) and the WFE (Morison, et al. 1950 [193]). Recommendations for wave force theory selection are given in 6.5.4.

6.5.1.3 The calculation methods for the first-order wave force (the portion linearly proportional to wave height) described in 6.5.2 and 6.5.3 produce wave forces in the wave frequency range. Higher-order wave forces are discussed in 6.5.5. The total wave forces on a member should include both first and higher-order forces.

Radiation/Diffraction Theory

6.5.1.1 General

Wave forces are calculated in radiation/diffraction theory by the integration of the total hydrodynamic pressure field acting on a body. The method is appropriate when the body is large relative to the water motion amplitude so that viscous forces are relatively unimportant, and that the body is sufficiently large relative to the wavelength such that the wave field is modified by the body through diffraction and radiation.

Analytical solution exists for the simplest case of linear wave diffraction around large fixed circular cylinder (MacCamy and Fuchs, 1954 [183]) but generally a boundary element method (Brebbia and Walker, 1980 [105]; Newman and Lee, 2001 [202]) based numerical solution is required for practical problems. Details of the radiation/diffraction method are described in Section 7.

6.5.1.2 Hull Inundation for Low-column Designs

In most conventional TLP designs, the columns are high and no green water can reach the column top. In some TLP designs, column top elevations are reduced. As a result, green water during extreme design events can run over the column top.

When the column top is lowered and wave crests can pass over the top of the column, diffraction/radiation panel model analysis is no longer as accurate. The wave effects on low-column TLPs should be evaluated and quantified, either with calibrated empirical numerical tools or with model tests.

The effects of a low column can be as follows.

a) Reduced wave and wind loads on upper column, resulting in less tendon “ringing,” less wave drift, and less wind load.

b) Reduced overturning moment, and possibly reduced maximum tendon tension.

c) Reduction in minimum tendon tension—The overtopping water generates a vertical downward force; statically (weight of the water) and dynamically (downward acceleration). This downward force would reduce the minimum tendon tension on the tendons directly underneath and potentially cause slack tendons. Special attention needs to be paid in this aspect for low-column designs.

d) Modification to wave reflection effects resulting in different (and usually reduced) wave crest enhancement.

6.5.2 The Wave Force Equation (WFE)

6.5.2.1 General

6.5.2.1.1 When body members are relatively slender or have sharp edges, viscous effects may be important and the wave force may be expressed as the sum of drag and inertia forces. The wave force equation (WFE) is an empirical formula for calculating forces on a member for given water velocity and acceleration conditions (Morison, 1950 [193]; Ippen, 1966 [160]; Newman, 1977 [199]; Sarpkaya and Isaacson, 1981 [215]). It is based on the assumption that the presence of the member does not appreciably alter the waveform. The wave force equation in Equation (9) has been modified to account for the velocity and acceleration of the structure.

$$F = F_\mathrm{d} + F_\mathrm{i} \tag{9}$$

$$F_\mathrm{d} = \frac{1}{2}\rho_\mathrm{W} C_\mathrm{D} D\,|u - \dot{x}|\,(u - \dot{x}) \tag{10}$$

$$\begin{aligned} F_\mathrm{i} &= \frac{\pi}{4}\rho_\mathrm{W} C_\mathrm{A} D^2(\dot{u} - \ddot{x}) + \frac{\pi}{4}\rho_\mathrm{W} D^2 \dot{u} \\ &= \frac{\pi}{4}\rho_\mathrm{W} D^2 (C_\mathrm{M}\dot{u} - C_\mathrm{A}\ddot{x}) \end{aligned} \tag{11}$$

where

F is the total force per unit length;

F_d is the drag force per unit length;

F_i is the inertia force per unit length;

ρ_W is the mass density of seawater;

C_D is the drag coefficient;

C_A is the added mass coefficient;

C_M is the virtual mass coefficient (for fluid acceleration);

D is the member diameter;

u is the instantaneous water particle velocity (speed and direction);

$\dot{u}$ is the water particle acceleration;

$\dot{x}$ is the is the instantaneous velocity of structural member;

$\ddot{x}$ is the instantaneous acceleration of structural member.

6.5.2.1.2 The water velocities and accelerations can be calculated from one of the several wave theories.

6.5.2.1.3 The drag and inertia force components are vector quantities which act in the directions of the normal components of velocity and acceleration vectors, respectively. The drag and mass coefficients are empirical coefficients which are generally coupled with a wave kinematics theory. They should be used with the same theory that was used in their derivation.

6.5.2.1.4 In the situation where current and waves occur simultaneously, prediction of the kinematics can be complex. A simple way is to vectorially combine the water particle velocities from the contributing wave and current systems. However, if the current is not uniform, then this superposition is not correct. Vectorial combination is conservative, and is generally used as the best available method.

6.5.2.2 Drag Coefficients

6.5.2.2.1 The drag coefficient is a function of Reynolds number, Keulegan-Carpenter number, roughness, and other factors. Model tests do not normally cover the appropriate parameter ranges. Field tests have been conducted on fixed offshore platforms, but member sizes are not indicative of TLP hull members. Coefficient determination will require careful extrapolation of test results. Commonly accepted values are between 0.6 and 1.2 (Sarpkaya and Isaacson, 1981 [215]). Values well below 0.6 have been shown to occur for low Keulegan-Carpenter numbers (Verley and Moe, 1980 [240]).

6.5.2.2.2 For members subject to VIV, such as TLP tendons and risers, the drag coefficient can be significantly amplified from the static values in 6.5.3.2.1 (between 0.6 and 1.2). Blevins (1990) [100] lists three expressions that illustrate drag amplification due to VIV as shown in Equation (12).

$$\frac{C_D \mid A_y > 0}{C_D \mid A_y = 0} = \begin{cases} 1 + 2.1(A_y / D) & \text{Blevins (1990)} \\ 1 + 1.043(2Y_{\mathrm{rms}} / D)^{0.65} & \text{Vandiver (1983)} \\ 1 + 1.16\left\{\left[\left(1 + 2A_y / D\right) f_n / f\right] - 1\right\}^{0.65} & \text{Skop et.al. (1977)} \end{cases} \qquad (12)$$

where

C_D is the is the drag coefficient;

A_y is the amplitude of vortex induced vibration;

D is the member diameter;

Y_{rms} is the rms VIV motion amplitude;

f_n is the natural frequency of vibration;

f is the vortex shedding frequency.

6.5.2.2.3 The drag coefficients in presence of VIV should be carefully derived from a VIV analysis.

6.5.2.3 Mass Coefficients

The mass coefficients are frequency dependent. Model tests are often the most appropriate way to produce sufficiently accurate estimates of C_M (see 7.8). The frequency dependent portion of a mass coefficient is the added mass coefficient, which can be estimated by 3D diffraction/radiation analysis. For large individual cylindrical members, C_M can vary from about 0.5 to 2.0 for the practical range of diameters and wavelengths based on theoretical analysis. For short waves where the vessel dimensions or column spacing are on the order of half a wave length, interaction effects may become important. This may be checked with a 3D diffraction calculation which implicitly considers interaction effects.

6.5.3 Force Calculation Method Guideline

6.5.3.1 The basic assumptions associated with each of the theories should be considered when selecting the force calculation method. Figure 3 (Pearcey, 1979 [206]) provides a general guideline for applicability of the diffraction and WFE methods based on the ratio of structure member diameter to wave height. Another criterion for selecting the method is the ratio of member diameter, D. and wavelength L, (need to consider wavelengths over the range of energy in the wave spectrum) as shown in Figure 4. In the figure, K, denotes the Keulegan-Carpenter number defined based on maximum water particle velocity, k, is the wave number, and a is the characteristics radius ($D/2$). When the ratio D/L is relatively small, flow separation rather than wave diffraction becomes important and WFE may be used. If the D/L is large, (D/L > 0.15 ~ 0.2), wave diffraction effects dominate and hence a diffraction/radiation method should be used. However, the importance of the structure members should be considered when selecting the method and caution should be taken to ensure that the wave load and other associated hydrodynamic properties such as particle velocities are not underestimated. Figure 4 also shows region of K vs D/L space bounded by maximum wave steepness in which nonlinear wave effects are important.

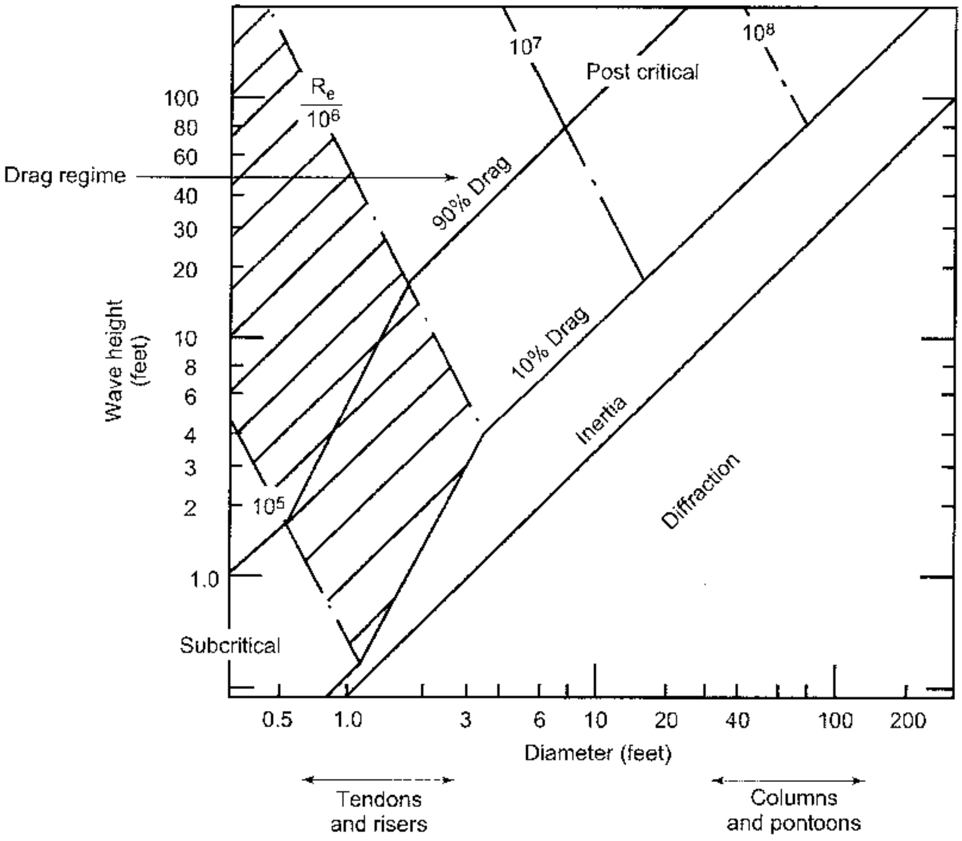


Figure 3 — Wave Force Calculation Method and Guideline for Wave Forces on Cylindrical Members

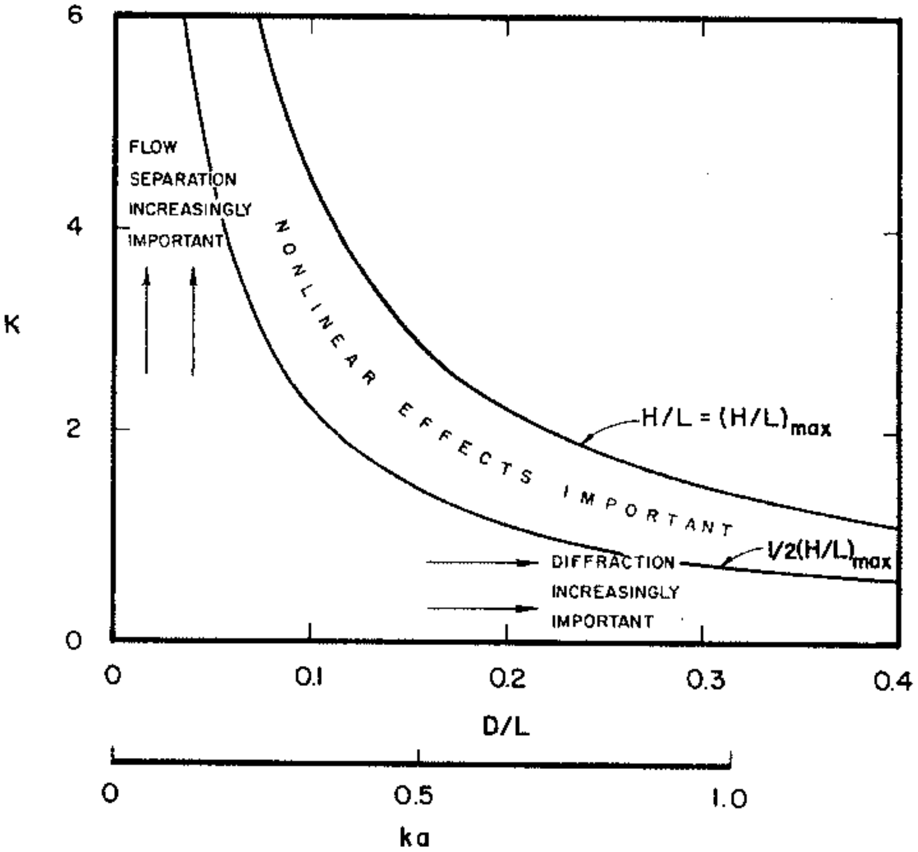


Figure 4 — Wave Force Regimes [4]

6.5.3.2 Some TLP hulls consist of both large and small members. In this case, both diffraction and the WFE may need to be used. Computations should preferably be performed with both force formulations included in the software. When applying the WFE, it is desired that the fluid velocities with the influence of the hull should be used whenever possible, instead of the velocities calculated from wave theories without the disturbance by the hull.

6.5.4 Other Hydrodynamic Forces

6.5.4.1 Subharmonic and Super-harmonic Wave Forces

6.5.4.1.1 When second-order terms in the potential theory, or when finite wave height kinematics are used with the WFE, then it can be shown that several different phenomena occur.

a) In regular waves, a steady wave-drift force is generated in the horizontal plane. In the case of diffraction theory, this steady force results from free surface integrals and the evaluation of the full Bernoulli equation over the body boundary. From WFE, the steady drift force results from the free surface integral and viscous effects.

b) In regular waves, both potential theory and WFE predict a steady vertical force. Additionally, potential theory predicts a double frequency force in the vertical direction.

---

[4] Sarpkaya and Isaacson, 1981 [215].

c) In irregular waves, the potential theory and WFE predict a steady and a slowly varying horizontal force called the wave-drift force. In potential theory this occurs at the difference frequencies of the wave energy. A current adds to the drift force through an interaction with the viscous forces resulting from wave kinematics.

d) In irregular waves, both potential theory and WFE predict sum frequency forces, which, when they occur at pitch/roll/heave resonant frequencies, excite springing responses (Naess 1994 [195]). In regular waves, potential theory predicts double frequency forces.

6.5.4.1.2 Subharmonic Wave Forces normally have periods greater than 30 seconds and are produced by the difference of wave components in wave frequencies ($0.033 < f < 0.2$ Hz, or $5 < T < 30$ s). Subharmonic or slow drift or difference frequency wave forces can cause large motions in surge, sway and yaw, if their natural frequency falls in the range of the exciting forces. In TLP designs, these low-frequency forces cannot be ignored. Due to the sensitivity to spectral peak periods, a range of periods should be checked.

6.5.4.1.3 Details of sub-harmonic and super-harmonic forces are described in Section 7.

6.5.4.2 Damping

6.5.4.2.1 Damping in resonant modes is important in the calculation of responses.

6.5.4.2.2 Verley and Moe (1980) [240] have published work investigating the drag for very small oscillations of large cylinders. Model tests can be used to determine the damping, but the viscous effects are Reynold's number dependent. Care should be exercised when estimating full-scale damping values from model test results.

6.5.4.2.3 Special attention should be given to the high Reynolds number, low Keulegan-Carpenter number dependence of damping for vertical mode resonance.

6.5.4.2.4 The presence of current, waves, or both generally increases damping. (Wickers and Huijsmans, 1984 [245]; Simiu and Leigh, 1983 [224]). For severe condition responses, the damping should be estimated using techniques such as model tests or time domain calculations.

6.5.4.2.5 The damping in the vertical modes (heave, roll and pitch) includes contributions from structural and soil damping, as well as from hydrodynamics. These should be estimated with consideration for the mode shapes and the strains in the various parts of the system. This is especially important in the calculation of the springing response which contributes significantly to the tendon fatigue damage.

6.6 Ice Loads

Superstructure icing can affect tendon tension and increase local wind loads due to increased frontal area. Wave induced motions of floating ice can impose local impact forces which should be considered in the design of the structure.

6.7 Wave Impact Forces

Wave slap and wave slamming forces should be evaluated for local effect on structural or flotation members and, if warranted, be included in the overall solution of the equation of motion. Wave slap forces on the columns are a potential source of tendon "ringing" responses, and should be evaluated for design of column structure. For hull external appurtenance design, wave slamming forces due to wave particle velocities and wave run-up jets should be considered for locations subject to free surface encounter (possibly including top of column).

6.8 Earthquakes

For TLP sites where earthquakes are a concern, appropriate ground acceleration time histories should be obtained. For TLP tendon tension responses, the vertical ground motion is much more critical than horizontal ground motion. For foundations, both vertical and horizontal motion may be important. Additional guidelines for earthquake ground motion are referred to in API 2A-WSD.

6.9 Accidental Loads

The potential for accidental loads arising from various kinds of collision, dropped or swung objects, or other events should be considered in the design of the structure. Consideration should be given to employing active and passive measures in the design to resist or absorb such loads. These measures could include, but not be limited to, thickening deck plate in areas where material handling is performed, shielding risers in the wave zone, or determining the energy absorption capacity of the structure and/or mooring system. For the latter consideration, such absorption capacity should be consistent with the size and actual speed of vessels working close to the platform.

6.10 Fire and Blast Loading

Offshore facilities treating hydrocarbons have a potential, however small, for either fire or explosion or both. The result of an explosion from a structural aspect is an overpressure that tends to dissipate with distance. Any object in the vicinity of this explosion interacts with the overpressure. Fire causes a thermal loading on nearby objects which in turn causes both deformation and stress. Prolonged thermal loading also can result in changes in material modulus and yield point. The design of an offshore structure should include a systematic treatment of these potentially adverse loadings.

7 Global Response

7.1 Purpose and Scope

The purpose of this section is to describe methods for performing the response analysis and global performance design checks of tension leg platforms. Environmental information needed for the analysis is presented in Section 5, and the derivation of environmental forces and moments on the platform is given in Section 6. This section presents methods for calculating platform motions, mooring system loads, and loading on the structure.

7.1.1 General

7.1.1.1 The design of a tension leg platform requires the application of analysis methods to estimate a variety of responses that are not commonly considered in the design of conventional fixed offshore structures. Environmental forces result in steady and dynamic platform displacements and loading on the overall TLP system.

7.1.1.2 Analysis methods of varying degrees of complexity have been adapted from practices developed for design and analysis of ships, semisubmersibles, large volume gravity-base platforms, and steel space-frame structures. These methods may be characterized as linear or nonlinear, frequency domain or time domain, and deterministic or probabilistic. The methods will be discussed below in the context of the several relevant modes of response. Emphasis is placed on the evaluation of static and dynamic response to a combined environment which includes forcing from a number of sources, i.e. wind, wave, current, storm surge, etc.

7.1.1.3 The design checks in this section are structured around the concept of global performance load cases or limit states, which are described in Section 5. The response analysis and design checks described in this section are based on working stress design. However, because of the dynamic and multivariate nature of TLP response, these necessarily include elements of probabilistic and reliability based design.

7.2 System Modeling

7.2.1 TLP response to an extreme environment is complex, with forcing that is generally time-varying and resulting from a number of sources. Since the total response includes contributions from a number of different components, the modeling procedures should account for the statistics of joint occurrence of forces, and the TLP system response to this combined forcing.

7.2.2 There are various ways of calculating both the forces acting on the TLP in an extreme environment, and the system response to these forces. Both time and frequency domain response models have been validated against field or model test data. Properly applied, either modeling approach is acceptable for use in design. However, it is noted that all practical design methodologies include various approximations. None of these methodologies are exact, and appropriate effort is needed to calculate the response with reasonably accuracy commensurate with current experience. It is stressed that both validation and proper application are prerequisites for using any calculation methodology for detailed design checking.

7.2.3 Existing TLP designs have been developed primarily using frequency domain tools enhanced with statistical extremal distributions developed from physical model tests. Therefore, there is a base of experience associated with these methods. On the other hand, recent developments in time domain simulation procedures indicate that these may be capable of predicting the observed nonlinear response characteristics, including independently predicting the distribution of extreme statistics for the global responses. Time domain calculations may thereby provide a numerical procedure that can use model tests for confirmation, rather than using the model test results as a direct part of the calculation.

7.2.4 The design procedures defined in the following sections may be based on either frequency or time domain methods, or a combination thereof. However, time domain methods may be required for some detailed response analyses, particularly for transient or highly nonlinear conditions that may be an integral part of some designs. For instance, the detailed analysis of local tendon behavior, especially near slack conditions, requires time domain simulations. Other load cases, such as transients during installation and lock-off, may also require time domain simulations.

7.2.5 The use of model tests for global analysis confirmation is encouraged. Model tests and numerical analysis are not to replace one another, but rather to complement each other. Model tests provide an independent check of the system response in waves (also wind and currents, if included), and are generally a more complete model of the physics than most computational models. Model testing is sensitive to the skill of the practitioner and, as in the case of numerical analysis, good engineering judgment and practice shall be applied. See 7.7 for a discussion of model testing practice.

7.3 Static and Mean Response Analysis

7.3.1 Introduction

Static and mean response analysis consists of determining the static equilibrium with no wind, wave, or current present, and then determining a mean position due to steady environmental loads acting on the platform. The determination of a mean or equilibrium position is necessary to proceed with a dynamic analysis in the frequency domain or time domain.

7.3.2 Static Equilibrium in Still Water Condition

7.3.2.1 The determination of the static equilibrium (or “weight balance”) with the “still water” condition is fundamental to sizing of the TLP and is the starting point for further analysis. A static equilibrium analysis should be performed for each loading condition to be analyzed.

7.3.2.2 Determination of the static equilibrium should include the following:

a) the total platform weight associated with each loading condition to be analyzed;

b) the total platform displacement (the total platform buoyancy) for each draft to be analyzed;

c) all riser and tendon tensions acting on the platform in each loading condition to be analyzed;

d) all hook loads that are significant for the loading cases to be analyzed.

7.3.2.3 The platform weight should include the weight of all structural elements, permanent appurtenances, and all equipment permanently mounted on the platform. In addition the platform weight should include all temporary loads that are appropriate to the loading condition to be analyzed. These temporary loads should include the weight of equipment, consumable supplies, ballast, marine growth or ice on the structure, and any other temporary weights that are appropriate for the loading case being analyzed.

NOTE The various loading cases (identified in 5.6) may involve significant variations in temporary or removable weights and loads to be included in static equilibrium analysis.

7.3.2.4 A general representation of the vertical force balance of the TLP in static equilibrium is given by Equation (13).

$$B = W_{DC} + W_{HS} + W_{DP} + W_{HP} + W_B + P_R + P_T + W_M \tag{13}$$

where

B is the platform buoyancy (total buoyancy of the platform for a given draft);

W_{DC} is the weight of deck structure;

W_{HS} is the weight of hull structure;

W_{DP} is the weight of all equipment in or on deck including production equipment, drilling equipment, utilities equipment, marine equipment, consumables, stored liquids, quarters, lifesaving equipment, and weights anticipated with future growth;

W_{HP} is the weight of all equipment and stored liquids in the hull;

W_B is the weight of ballast in platform;

P_R is the riser pretension (at the top of riser, where attached to platform);

P_T is the tendon pretension (at the top of the tendon where attached to the platform);

W_M is the any other weight appropriate for the loading case considered including, if appropriate, ice loading, marine growth, and any significant hook loads.

A similar static equilibrium balance should be performed for other degrees of freedom of the platform. Because of the balance of displacement, weight, and pretension, it is important that the various weight components be estimated as accurately as possible. During design, it is normal to include weight margins for all components that are consistent with the confidence bounds of the estimates. Since future payload cannot be increased without modifying the hull displacement, this helps minimize the number of design iterations that may be required. See 12.2.3 and 14.4.4 for further comments on weight estimation and control.

7.3.3 Tidal Effects

Changes in buoyancy due to tidal effects can significantly affect mean tendon tensions. Therefore, the choice of a tide condition for static equilibrium analysis is important. Changes in tide conditions should be considered in evaluating the various maximum responses of interest:

a) a high mean water level tends to increase maximum tendon tensions, hydrostatic loading on the hull, and current loading on the hull, and tends to decrease deck clearance;

b) a low mean water level tends to decrease minimum tendon tensions and to decrease the horizontal restoring forces for a given horizontal offset.

These effects of tide may be taken into account by performing a static balance at the various appropriate tide levels to provide a starting point for further analysis or by making allowances for the appropriate tide level in calculating extreme responses. For example, the effect of the highest tide level consistent with the probability of simultaneous occurrence of other extreme environmental conditions should be taken into account in estimating maximum tendon tensions.

7.3.4 Mean Response Analysis

7.3.4.1 The analysis of the TLP response to mean or steady environmental forces is used to determine the initial condition for time or frequency domain analysis of the platform dynamic response. The dynamic analysis of risers or tendons often requires an estimate of mean platform position as input for further analysis.

7.3.4.2 The estimate of mean response should begin with the still water condition discussed in the previous section. Then the following effects should be added.

a) Tendon and riser effects including pretension, tendon/riser weight in water (catenary effect), foundation mis-positioning, and platform “setdown” effects. Platform setdown increases tendon/riser tension as the platform's horizontal displacement increases. In some cases, tendon/riser stretch is important and should be included in modeling tendon/riser effects.

b) The mean forces and moments acting on the platform due to wind.

c) The mean forces and moments acting on the platform due to wave-drift and current forces.

d) The effect of current forces on the risers and tendons.

e) The determination of the mean response is an iterative process since the various contributing loads are dependent on the platform setdown.

NOTE An analysis of mean response will be required for various loading cases (identified in 5.6). Weight variations and tidal variations might be important in addition to changes in wind, wave, and current forces, and should be included in the loading cases used for analysis of mean response.

7.3.4.3 The steady offset and setdown are important outputs from the analysis of mean response. Figure 5 illustrates the nonlinear behavior of the horizontal restoring forces versus horizontal offset for a typical TLP. The slope of the curve at any offset position is the horizontal stiffness of the system at that position. Figure 5 illustrates that the horizontal stiffness increases with TLP offset.

7.3.4.4 If the wind, wave, and current directions are assumed collinear and incident on an axis of symmetry of the vessel, the mean response analysis can be done considering responses only in the direction of the environment. In such cases, three degrees of freedom are eliminated from the platform response and only platform heave, surge, and pitch in the direction of the environment need be considered. This simplification to a two-dimensional (2D) problem is often used in preliminary design calculations. Since the wind loading on the topsides is rarely coincident with a vessel axis of symmetry, a full 3D mean response analysis should be performed for detailed design.

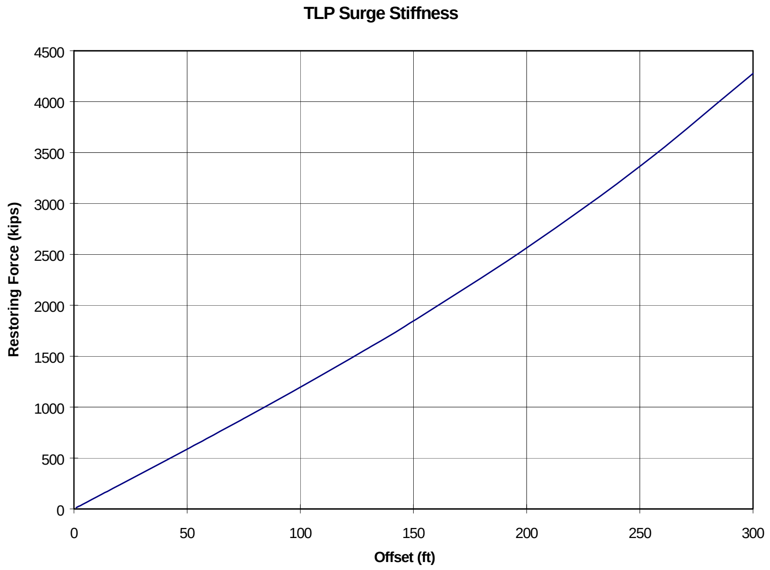


Figure 5—TLP Restoring Force with Offset

7.4 Equations of Motion and Solutions

7.4.1 Introduction

7.4.1.1 This section describes the equations of motion governing the dynamic responses and discusses the frequency domain and time domain techniques used to solve these equations.

7.4.1.2 Frequency domain analysis is the closed form solution of ordinary or partial differential equations by means of Laplace or Fourier transform techniques. Frequency domain analysis has been applied extensively to problems of floating vessel dynamics to estimate responses to random wind, wave and current excitation including hydrodynamic loads, platform motions and accelerations, and tendon loads and angles.

7.4.1.3 The most significant limitation of frequency domain techniques for solving the equations of motion is that nonlinearities in the equations must be ignored or replaced by linear approximations. A number of approaches for approximating nonlinearities are available, including statistical linearization (Roberts and Spanos, 2003 [214]) and decomposition of the nonlinear system into an ordered set of linear equations (Voltera modeling; Im, Powers and Park, 1998 [158]). The strength of the frequency domain technique is that it is more computationally efficient than the time domain technique.

7.4.1.4 Frequency domain techniques are often applied in preliminary design. For application in detailed design, frequency domain analysis should be supplemented with statistical extremal distributions developed from physical model tests or validated time domain simulations. In cases where both time and frequency domain techniques are applicable, the frequency domain technique often has the advantage of computational efficiency.

7.4.1.5 Time domain analysis is the direct time integration of the equations of motion, allowing the inclusion of system nonlinearities. For example, models for drag forces that are quadratic functions of fluid velocity can be directly incorporated without approximation. Also, the system stiffness matrix can be updated with each time step to account for time-dependent variation in platform geometry as it impacts the restoring forces. This advantage over frequency domain techniques is gained at the expense of increased computing time and increased complexity in processing the calculation results.

7.4.1.6 The hydrodynamic loads due to wave radiation and diffraction are normally computed in the frequency domain, regardless of whether they are subsequently incorporated in frequency domain or time domain motion response solution procedures. Consequently higher-order hydrodynamic effects are ignored to some degree in all TLP response calculation procedures.

7.4.2 Equations of Motion

The forces acting on the system are generally a function of both time and vessel position. In order to separate the forces into discrete components that allow simple solution, a number of assumptions and linearizations are usually made. The expression generally used to describe the system response is given by Equation (14).

$$M(t)\ddot{x} + C(t)\dot{x} + K(t)x = F(x,t) \tag{14}$$

where

$M(t)$ is the is the inertial mass matrix;

$C(t)$ is the is the damping matrix;

$K(t)$ is the is the stiffness matrix;

$F(x,t)$ is the is the external force vector.

7.4.3 Linear System Solution

Transforming Equation (14) into the frequency domain, the motions of a TLP can be modeled by the following N-degree-of-freedom set of differential equations as shown in Equation (15):

$$M(\omega)\ddot{x}(\omega) + C(\omega)\dot{x}(\omega) + Kx(\omega) = F(\omega) \tag{15}$$

The time-dependent force vector includes the many external forces discussed in Section 6. These forces are often categorized by their frequency relative to the resonant frequencies of the platform/tendon/riser system. The relevant frequency bands of forcing include the following:

a) nearly steady forces that can be considered static because they vary at frequencies much lower than any platform resonant frequencies;

b) slowly varying forces near the surge, sway, and yaw natural frequencies;

   NOTE These responses typically have periods in the range of one to four minutes.

c) forces at the same frequencies as the waves (wave frequencies);

d) forces at frequencies near the TLP heave, pitch, and roll natural frequencies;

   NOTE These resonances typically have periods in the range of one to five seconds.

e) short duration transient or impulsive forces that are likely to excite TLP heave, pitch, and roll natural frequency responses.

7.4.4 Uncoupled Model

For the complete TLP system, including tendons and risers, the components of Equation (14) are very complex and include coupling between various loading and response components. To make the problem more manageable, a common simplification is to limit the system model to a single rigid body supported by massless springs, and explicitly exclude tendon and riser displacements. Neglecting such tendon/riser coupling effects leads to a system model with only the six degrees of freedom described by Figure 6. The fixed coordinates are coincident with the principal directions of the platform when the platform is at rest. The simple modeling approach that assumes no interaction between tendon/riser dynamic response and the platform dynamic response is called ”uncoupled analysis.” In the uncoupled model, the inertia effects of the tendons and risers on the platform can be approximated by modification of the platform inertia matrix.

A convenient coordinate system is a body-fixed, right-handed coordinate system with origin at the mean position of the center of gravity of the platform (or some other convenient location such as the keel). For the simple model described in Figure 6, the position vector coordinate is given by Equation (16).

$$X = \begin{cases} X_1 & \text{Surge} \\ X_2 & \text{Sway} \\ X_3 & \text{Heave} \\ X_4 & \text{Roll} \\ X_5 & \text{Pitch} \\ X_6 & \text{Yaw} \end{cases} \tag{16}$$

7.4.5 Coupled Models

7.4.5.1 The uncoupled approach may be useful in conceptual and preliminary design work, but it has serious shortcomings that limit its applicability for detailed design work. The coupling of the tendons/risers with the rigid body has a significant impact on the TLP response, particularly as water depth increases and the tendon/riser mass becomes a significant portion of the system mass.

7.4.5.2 System models with more than six degrees of freedom can be developed by including displacement degrees of freedom for the tendons and risers. Such models couple the dynamics of the platform and the tendons/risers so that the dynamic reactions of the tendons and risers are part of the vessel motion solution, and the vessel dynamics are part of the tendon/riser motion solution. In a fully nonlinear numerical calculation or model test simulation, the time-varying deflected shape and top angle of the tendons and risers provide a time-varying load restraint to the vessel.

7.4.5.3 Coupled models are particularly important for deepwater [typically greater than 900 m (3000 ft)] where the total tendon/riser mass becomes a significant portion of the total system mass. This modeling approach is referred to as “coupled analysis.” The effect of the tendon and riser degrees of freedom includes modification to the tension and surge responses (see Davies and Mungall, 1991 [122]).

7.4.5.4 The mass matrix includes the mass of the platform, tendon and riser steel, equipment and variable weights, and the “added mass” of the surrounding water. Inertia effects introduced by the tendons and risers should be accounted for in coupled tendon/ riser/platform models.

7.4.5.5 The damping matrix is important in limiting platform resonant responses, and has significant contributions from platform wave radiation and from drag forces on the hull, tendons, and risers.

7.4.5.6 The stiffness matrix contains hydrostatic terms, geometric terms due to tendon/riser tension combined with platform offset to produce offset restoring forces, and elastic terms introduced by tendon and foundation flexibility.

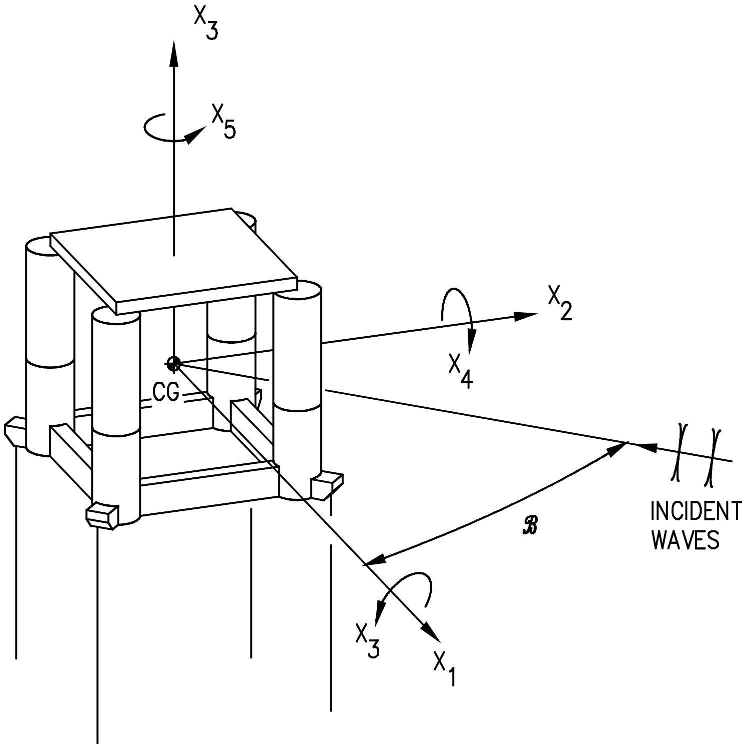


Figure 6—Simple Model for TLP Response Analysis

7.5 Frequency Domain Modeling and Solution

7.5.1 Introduction

7.5.1.1 Frequency domain analysis refers to the solution of the equations of motion by methods of harmonic analysis or methods of Laplace and Fourier transforms. The result of a frequency domain analysis is a description of the variables of interest (platform motions, platform forces, tendon forces, etc.) as functions of frequency. The method is naturally suited to the analysis of systems exposed to random environments because it provides a clear and direct relationship between the spectrum of the environmental loads and the spectrum of the system response. The system response spectrum can then be used to estimate the short-term statistics of the variable of interest.

7.5.1.2 In cases where both time and frequency domain techniques can be considered, the frequency domain often has the advantage of fewer and simpler computations. For large floating structures where wave scattering and radiation is important, the inviscid hydrodynamic properties are most conveniently calculated in the frequency domain. Frequency domain analysis (used in conjunction with model tests) has formed the basis of most wave response analysis performed in support of design for early TLPs.

7.5.1.3 In frequency domain models, the forcing and system response are computed frequency by frequency. The forcing is generally represented by spectra and applied to a linear response model. The nonlinear nature of the response is typically accounted for by linearizing the system about a steady finite deflection solution, approximating the quadratic damping with equivalent linear terms, and using nonlinear, non-Gaussian statistical models to predict extremes. For a typical TLP response, at least three excitation frequency bands plus mean responses should be considered. These are:

- mean (offset and tension);
- slow drift response;

— wave frequency response; and

— heave, pitch, and roll natural frequency response.

7.5.1.4 The mean response analysis should follow the guidelines given in 7.3.4. The system modeling used in solving the equations of motion should include the following.

a) Dynamic analyses should be based on the TLP at its mean offset and setdown position, including deflected tendons/risers and the water plane stiffness contribution to offset restoring forces. The various components of Equation (14) should be linearized based on this position, including the stiffness, damping, added mass and environmental exciting forces. This ensures, for example, that the wave frequency component of setdown-induced tension is included in the wave frequency tension transfer functions and that the wave exciting forces are based on the submerged geometry at the setdown draft.

b) In water depths beyond approximately 900 m (3000 ft), or when the mass and added mass of the tendons/risers exceeds a significant fraction of the hull virtual mass, a coupled tendon/riser/hull motions model should generally be utilized.

7.5.1.5 A coupled frequency domain model shall use linearization algorithms to represent the various nonlinear components of Equation (14). For most responses, the linearization approach provides sufficient accuracy, as verified through model testing. However, for certain responses, time domain simulation, and/or model test results are necessary to capture the full impact of the nonlinearities (see 7.2).

7.5.1.6 Different responses are dominated by different forcing combinations. For surge and deck clearance responses, the following forcing should be considered:

a) first-order inviscid hydrodynamic loads and reactions;

b) second-order difference-frequency wave-drift forces and setdown-induced buoyancy forces;

c) wind dynamic forces (low-frequency wind spectrum, linearized force, relative velocity damping);

d) hydrodynamic viscous wave/current excitation and damping forces; and

e) wave kinematic modifications by the platform (deck clearance).

7.5.1.7 For tension responses, the following forcing should be considered:

a) first-order inviscid hydrodynamic loads and reactions;

b) second-order difference-frequency wave-drift forces and setdown-induced buoyancy forces;

c) second- and higher-order sum-frequency wave springing forces;

d) wave “ringing” forces;

e) wind dynamic forces (low-frequency wind spectrum, linearized force, relative velocity damping);

f) hydrodynamic viscous wave/current excitation and damping forces; and

g) structural damping.

7.5.2 Linear System Solution

Transforming Equation (14) into the frequency domain, the motions of a TLP can be modeled by the following N-degree-of-freedom set of differential equations:

$$M(\omega)\ddot{X}(\omega) + N(\omega)\dot{X}(\omega) + KX(\omega) = F(\omega) \tag{17}$$

where the stiffness matrix K is assumed to be frequency independent.

For an uncoupled model with six rigid body degrees of freedom ($N = 6$) the displacement Vector $X(\omega)$ is given by Equation (15). For a coupled model there will be additional degrees of freedom representing the various components of the tendons and risers (which may be modeled as finite elements). Regardless of whether a coupled or uncoupled model is used (as defined in 7.4) Equation (16) will include, at a minimum, coupling between the six-degree-of-freedom rigid body motion (e.g. surge-pitch coupling).

The vector differential Equation (16) is solved frequency by frequency using conventional linear harmonic analysis techniques. A special case of the solution is where the excitation $\mathcal{F}(\omega)$ in the wave frequency band is based on a unit wave amplitude at each frequency. The resulting displacement vector $X(\omega)$ then represents the unit wave amplitude transfer function, commonly referred to as the response amplitude operator (RAO).

7.5.3 Random Excitation

The power spectrum of a variable over some frequency band can be interpreted as the variance of the variable in that frequency band divided by the width of the frequency band. A linear system that transforms the amplitude of the input to the amplitude of the output through multiplication by the RAO transforms the mean square of the input to the mean square of the output through multiplication by the square of the RAO. Thus,

$$S_{\mathrm{XX}} = (\mathrm{RAO})^2\, S_{\mathrm{aa}} \tag{18}$$

Once the system RAO and the input spectrum S_{aa} are known, obtaining the output spectrum S_{XX} follows from a simple multiplication.

7.5.4 Gaussian (Normal) Random Process

A linear transformation of a Gaussian process is also a Gaussian process. In this case, the power spectrum of the excitation and the response amplitude operator define the probability density function of the response. Assuming the response, x, is narrow banded with a zero mean value, the probability distribution function for the extreme values of a narrow band Gaussian random process is described by the Rayleigh distribution:

$$p(x) = \frac{x}{\sigma_{\mathrm{x}}^2} \exp\left\{-\frac{x^2}{2\sigma_{\mathrm{x}}^2}\right\} \tag{19}$$

The standard deviation of the response σ_x is obtained from the spectrum of the response:

$$\sigma_{\mathrm{X}}^2 = \int_0^\infty S_{\mathrm{XX}}\, d\omega \tag{20}$$

In the wave frequency band, the TLP response is primarily due to linear wave radiation and diffraction effects. Since the excitation is a linear function of wave elevation, and wave elevation records for random wave trains are well approximated as a narrow band Gaussian process, the probability density function of the extreme values of the filtered wave frequency response is well represented by the Rayleigh distribution.

7.5.5 Non-Gaussian Random Process

Tension and surge responses have been demonstrated to have non-Gaussian distributions with extreme values that typically exceed those that would be predicted by a Rayleigh distribution. This is primarily due to nonlinear forcing mechanisms (slow drift, springing, ringing forces). For frequency domain calculations, the prediction of extremes from the response spectrum should include consideration of this non-Gaussian behavior through use of appropriate distributions or factors on the Rayleigh distribution. Guidance on selection of the extreme value distribution may be found through examination of appropriate model test results, full-scale data, or validated time domain calculations.

7.5.6 Stiffness and Mass Modeling

7.5.6.1 For a general problem, the tendon/riser stiffness will contribute terms for each element of the stiffness matrix, K. This is accomplished using a fully coupled model as described in 7.4.4.

7.5.6.2 For an uncoupled model, a simple approach that can be used to model vertical vessel motions (heave, pitch, and roll) and tendon/riser tension variations is to represent each tendon and riser (or group of tendons/risers) as an elastic spring with no mass or fluid interaction effects. If this simple elastic spring model is used for modeling tendon/riser attachment point forces on the vessel, the forces can be linearized to generate the stiffness terms of K. However, this simple spring model for the tendons and risers neglects geometric nonlinearities that cause the terms of K to change depending on the offset point chosen for linearization.

7.5.6.3 In all but very shallow water, the tendon/riser mass may be an important contribution to vertical and horizontal mode natural frequencies. One simple approach is to augment the mass or added mass matrices to reflect the contribution of tendons and risers. Uncoupled time or frequency domain tendon/riser analysis may be used to generate terms added to M, K, and N to model tendon/riser dynamic effects as a function of frequency. Classic lumped-mass methods for structural dynamics analysis (Clough and Penzien, 1993 [116]) may also be used to allocate tendon and riser mass to the appropriate rigid body degrees of freedom.

7.5.7 Modeling Hydrodynamic Added Mass, Damping, and Exciting Forces

7.5.7.1 There are various assumptions and degrees of approximation that can be used in modeling hull hydrodynamics for frequency domain analysis.

7.5.7.2 The primary method accepted for design calculations is use of 3D integral equation (source-sink or panel model) techniques to model inviscid wave interactions with the hull (i.e. wave radiation and diffraction). When performed to first order, these techniques model the linear free surface effects and hydrodynamic interactions. When performed to second order, these techniques model the second-order surface potential and the first-order body/free surface interaction.

7.5.7.3 If hull members have large cross-sectional dimensions compared with the wavelength, then free surface effects become important and these methods should be employed. Also, as members become larger compared with the wavelength and member-to-member spacing then hydrodynamic interaction between the members becomes important, and again these methods are appropriate. However, the viscous drag contribution is not modeled and, if significant, should be accounted for by linearized drag terms added to the damping matrix and forcing vector.

7.5.8 Modeling of Wind, Wave-drift, and Current Forces

7.5.8.1 In frequency domain analysis, the steady and oscillatory forces due to wind, wave drift, and current can be taken into account using a number of different assumptions and approximations. In most cases it is appropriate to account for steady and low-frequency forces and moments by adding constant forces and/or moments to arrive at a quasistatic equilibrium point. The TLP dynamics, including tendon/riser stiffness, may be linearized for motions about this quasistatic equilibrium point.

7.5.8.2 For some analyses, such as the analysis of offset, it is important to account for the low-frequency motions as accurately as possible. In such cases, force or moment spectra including wind and low-frequency wave-drift excitation may be applied as input to a frequency domain model. Such an approach is useful where the response to forces or moments is linear. This does not require a linear relationship between the environment (wind speed, wave amplitude, etc.) and the forces or moments. If a force spectrum can be estimated, it can be added to the other contributions to the force vector F in Equation (16). This technique is particularly useful where the low-frequency responses (such as offset, tendon angles, tendon stresses, etc.) are needed.

7.5.8.3 The response to wind forces, including responses at all frequencies of interest, can be modeled by estimating wind force and moment spectra. For response at wave frequencies or above, the aerodynamic admittance effect may reduce the force of the wind because of wind spatial correlation effects. In such cases the aerodynamic admittance should be modeled carefully (Bearman, 1971 [97]; Kareem, 1980 [164]).

7.6 Time Domain Modeling and Solutions

7.6.1 Introduction

7.6.1.1 Time domain solution methods are generally used for final detailed design stages and for checks on frequency domain solutions. Their primary advantage is in allowing time-dependent boundary conditions and nonlinear forcing and stiffness functions. The main drawback of time domain methods is the computational burden. Periodic analysis shall be carried out over a sufficient number of cycles to achieve steady state. Irregular analysis shall be carried out for sufficient time to achieve stationary statistics. Multiple realizations of the same conditions may be necessary to generate sufficient data and to verify consistency. Care should be taken to validate the time domain model against simple cases, such as frequency domain analysis results for small amplitude wave conditions.

7.6.1.2 Time domain simulations are usually used when nonlinearities that are not accurately modeled in the frequency domain are important. Time domain methods are typically used for extreme condition analysis. They are not typically used for fatigue analysis or analysis of more moderate conditions where linearized frequency domain analysis works much more efficiently. In some cases, specific time domain simulations are run to seek a specific response (e.g. transient response due to a tendon overload). In many cases time domain simulations are used to generate statistics and extreme response factors that can be used to calibrate frequency domain models for application over a wider range of load cases.

7.6.1.3 The time domain analysis procedure consists of a numerical solution of the rigid-body equations of motion for the platform subject to external forces that may originate in the fluid motion due to waves, current, and platform motion, the platform positioning system, and other disturbing effects such as wind. Time domain analysis methods for floating bodies have been proposed by a number of authors (Cummings, 1962 [120]; Van Oortmerssen, 1976 [236]; Paulling, 1977 [205]). Since a direct numerical integration of the equations of motion is performed, effects may be included which involve nonlinear functions of the relevant wave and motion variables. Typical effects are drag forces that are nonlinear functions of the fluid velocity, finite motion and finite wave amplitude effects, and nonlinear positioning or anchoring systems. In comparison to linear frequency domain techniques, the direct numerical solution in time domain permits the user to investigate nonlinear, finite amplitude phenomena which the former method is incapable of treating directly, but this advantage is gained at the expense of increased computing time.

7.6.2 Random (Irregular) Wave Analysis

7.6.2.1 The prediction of extreme value responses should be based on irregular wave simulations. Regular wave time domain simulations are useful in testing models, and comparing with regular wave model tests, but should not be the basis of predicting design responses.

7.6.2.2 The wave time series used for simulation may be generated by a number of commonly accepted techniques, which include the following:

- measured time series of full-scale waves;
- measured time series of model scale waves;
- generation of time series by summation of random Fourier components scaled by the desired spectral shape; and

— filtering of Gaussian white noise to give a time series with the desired spectral content.

7.6.2.3 The mathematically generated signals (including model tested waves) should account for the randomness of spectral amplitudes observed in measured ocean waves (Tucker, Challenor, and Carter, 1984 [235]). Care should also be taken concerning the second and higher-order wave components. If the wave-to-load models include second-order load components and expect only linear inputs, the second-order components should be removed from measured wave histories. If the load models require a fully nonlinear input time trace, including higher-order components, then the numerical procedures should include generation of second and possibly higher-order waves in addition to the linear components.

7.6.3 Solution Techniques

There are many numerical methods that have been developed for solving the equations of motion in the time domain using direct step-by-step integration techniques.

The Newmark-Wilson method and the Runge-Kutta method are commonly used to solve a second-order differential equation. For time domain analyses performed for irregular sea states, consideration should be given to the frequency dependence of the added mass and damping coefficients. There are a number of ways that have been proposed to include the frequency dependence in time domain calculations (Van Oortmerssen, 1976 [236]). Bergdahl and Johansson (1988) [99] and Davies and Mungall (1991) [122] described the application of the convolution approach to TLPs.

7.6.4 Stiffness Modeling

This can be handled in the same manner as in frequency domain analysis (see 7.5.6). Time domain models usually include provision for large deflections/rotations, which result in the stiffness matrix being updated frequently in the simulation.

7.6.5 Modeling Hydrodynamic Added Mass and Damping

7.6.5.1 The treatment of added mass and damping for time domain calculations is based on the same principles and procedures as discussed for frequency domain calculations in 7.5.7. Besides the frequency dependent damping derived from wave radiation/diffraction theory (so called radiation damping), which mainly lies within the normal wave frequency region, there are other damping mechanisms involved in the entire dynamic system.

7.6.5.2 For instance, in high-frequency resonant motions (pitch, roll, and heave), sources of damping include foundation/soil interaction, hull and tendon structural damping, and local hydrodynamic drag effects around small members and sharp corners. A strong nonlinear coupling between heave, pitch, and roll modes is almost always ensured, so that all of these modes of damping contribute to the total system damping.

7.6.5.3 The low-frequency (surge, sway, and yaw) damping includes radiation damping, wave-drift damping, and drag effects. It also depends on the wind and current fields, and contributions come from riser and tendon hydrodynamic drag.

7.6.6 Modeling of Wind, Wave, and Current Forces

7.6.6.1 Wave Force Time Series

7.6.6.1.1 A time series of wave forces may be generated from a wave time history by use of first and second-order RAOs from diffraction analysis, plus viscous loads from a kinematics model.

7.6.6.1.2 First-order wave forces can be derived from Equation (21).

$$f_{\mathrm{WV}}^{(1)}(t) = \sum_{i=1}^{N} a_{\mathrm{i}}\, F_{\mathrm{WV}}^{(1)}(\omega_{\mathrm{i}}) \cos(\omega_{\mathrm{i}} t + \varepsilon_{\mathrm{i}}) \qquad (21)$$

where

$f_{\mathrm{WV}}^{(1)}(t)$	is the is the first-order time-dependent wave forces;
$F_{\mathrm{WV}}^{(1)}(\omega_{\mathrm{i}})$	is the is the frequency-dependent first-order wave exciting force per unit wave amplitude;
ε_i	is the is the phase angle of *i*th wave component;
a_i	is the is the amplitude of *i*th wave component;
	= $\sqrt{2\, S_{\mathrm{aa}}(\omega_i)\, d\omega}$
$S_{\mathrm{aa}}(\omega)$	is the is the spectral density function of wave elevation;
N	is the number of wave components in the Fourier series.

7.6.6.1.3 Second-order slowly varying drift (difference-frequency) forces can be derived from Equation (22).

$$F_{\mathrm{wd}}^{(2-)}(t) = \sum_{i=1}^{N} a_i a_{\mathrm{j}} \left[P_{\mathrm{ij}}^{(2-)}(\omega_i, \omega_{\mathrm{j}}) \cos\big((\omega_i - \omega_{\mathrm{j}})t + (\varepsilon_i - \varepsilon_{\mathrm{j}})\big) + Q_{\mathrm{ij}}^{(2-)}(\omega_i, \omega_{\mathrm{j}}) \sin\big((\omega_i - \omega_{\mathrm{j}})t + (\varepsilon_i - \varepsilon_{\mathrm{j}})\big) \right] \qquad (22)$$

where

$F_{\mathrm{wd}}^{(2-)}(t)$	is the is the second-order time-dependent drift forces;
$P_{\mathrm{ij}}^{(2-)}(\omega_{\mathrm{i}}, \omega_{\mathrm{j}})$	is the real part of second-order difference-frequency quadratic force transfer function in bichromatic waves;
$Q_{\mathrm{ij}}^{(2-)}(\omega_{\mathrm{i}}, \omega_{\mathrm{j}})$	is the imaginary part of second-order difference-frequency quadratic force transfer function in bichromatic waves.

These forces are only important for surge, sway and yaw in TLPs. Newman (1974) [198] has given an approximation for these matrices, using only the real part's diagonal terms, which has been very widely used. More recently, Newman (1995) [200] has shown that a better approximation utilizes the full matrices as computed without the second-order potential. This approach avoids excessive computational effort, while including the most important contributions.

7.6.6.1.4 Second-order, springing (sum-frequency) forces can be derived from Equation (23).

$$F_{\mathrm{wv}}^{(2+)}(t) = \sum_{i=1}^{N} a_i a_{\mathrm{j}} \left[P_{\mathrm{ij}}^{(2+)}(\omega_i, \omega_{\mathrm{j}}) \cos\big((\omega_i + \omega_{\mathrm{j}})t + (\varepsilon_i + \varepsilon_{\mathrm{j}})\big) + Q_{\mathrm{ij}}^{(2+)}(\omega_i, \omega_{\mathrm{j}}) \sin\big((\omega_i + \omega_{\mathrm{j}})t + (\varepsilon_i + \varepsilon_{\mathrm{j}})\big) \right] \qquad (23)$$

where

$F_{\mathrm{wv}}^{(2+)}(t)$	is the is the second-order time-dependent springing forces;
$P_{\mathrm{ij}}^{(2+)}(\omega_i, \omega_{\mathrm{j}})$	is the real part of second-order sum-frequency quadratic force transfer function in bichromatic waves;
$Q_{\mathrm{ij}}^{(2+)}(\omega_i, \omega_{\mathrm{j}})$	is the imaginary part of second-order sum-frequency quadratic force transfer function in bichromatic waves;

These forces are primarily important for heave, pitch and roll in TLPs. They have been shown to be important contributors to extreme tension in some TLPs, and tendon fatigue in almost all designs. Several authors have developed second-order diffraction analyses based on the panel (source-distribution) method. Computation of these quantities requires inclusion of the second-order potential and is extremely laborious for a sufficiently broad range of frequencies. A simpler approach based on Linton and Evans (1990) [180] has been implemented by Kim, et al. (1993) [166], and appears suitable for use at least in preliminary design.

7.6.6.2 Wave Ringing Forces

TLPs have been shown to be susceptible to nonlinear high-frequency forces from large steep waves that excite the natural frequency responses in pitch and roll. The response to these forces has been termed "ringing," because of its short-term transient nature. Ringing responses have been shown to be very important in some TLP configurations, and inconsequential in others.

See Annex A for commentary on global response high-frequency TLP responses. Section A.2 presents a discussion and further guidance on modeling of ringing and other high-frequency force and response mechanisms.

7.6.6.3 Dynamic Wind Forces

Dynamic wind forces can be derived from Equation (24).

$$F_{\mathrm{wind}}(t) = \frac{1}{2}\rho_{\mathrm{a}}\, A\, C_{\mathrm{S}}\, \chi_{\mathrm{a}} |V_{\mathrm{wd}} - \dot{x}|(V_{\mathrm{wd}} - \dot{x}) \tag{24}$$

where

ρ_{a}	is the mass density of air;
A	is the projected area;
C_{S}	is the shape coefficient;
χ_{a}	is the aerodynamic admittance;
$\dot{x}$	is the instantaneous platform velocity;
V_{wd}	is the instantaneous wind speed.

7.6.6.4 Viscous Drag Forces

Viscous drag forces can be derived from Equation (25).

$$F_{\mathrm{drag}}(t) = \frac{1}{2}\rho_{\mathrm{w}}\, A\, C_{\mathrm{D}} |V_{\mathrm{C}} - \dot{x}|(V_{\mathrm{C}} - \dot{x}) \tag{25}$$

where

ρ_w is the mass density of seawater;

A is the projected area;

C_D is the drag coefficient;

$\dot{x}$ is the instantaneous platform velocity;

V_c is the water particle velocity (includes current).

7.6.7 Output of Time Domain Analysis

7.6.7.1 The outputs of time domain analysis are time series of the responses. The results may be used in the following ways.

a) The spectrum and statistics of the response can be calculated from the time series, providing similar information to the frequency domain analysis. The wave and response time series can be used to generate equivalent linear RAOs.

b) The extreme response can be estimated directly from the peaks of the responses during a simulation. Typical methods include fitting Rayleigh, Weibull, or exponential extremal distributions to the observed peaks, and predicting the maximum from the distribution.

7.6.7.2 It is recommended that time domain analysis results be evaluated with graphical data evaluation tools to ensure that the resulting spectra and statistical fits are reasonable and well behaved. Direct comparison to frequency domain results should be used to confirm the general behavior of the model and highlight the expected differences due to nonlinearities that are not fully captured in the frequency domain model.

7.6.7.3 Long time duration simulations and multiple realizations of a given load case may be needed to ensure that maximum loads and responses are calculated with adequate statistical significance. Extrapolation of fitted extreme value distributions may not be reliable if significant nonlinearities are present in the load/response being simulated.

7.7 Hydrodynamic Model Tests

7.7.1 Purpose

Representative physical model experiments are an important part of the design process of predicting design responses. Model tests may be used either as a confirmation or calibration of analytical predictions, or to determine those responses not directly calculable with sufficient accuracy. The primary objectives of model tests may be broadly categorized as the following.

a) Tests to determine the responses of a particular design. In this case, the model experiment is treated as an analog computer that is capable of predicting the full-scale responses.

b) Verification of methods for analytical or numerical prediction of system responses. In this case, less emphasis is placed on the details of the physical model since the dimensions and parameters of the system can usually be modified more easily in the numerical model than in the physical model, even at a small scale. It is recommended to keep the physical model simple, if possible, to avoid complications that might obscure the most important results. It is more efficient to make minor parametric variations to the system through a numerical model if it can be shown through physical experiments that the numerical model is accurate. It is important to place enough emphasis on the measurement of the incident wave field. The details of the waveform should be known to the same degree of accuracy as the vessel responses.

c) The numerical predictions and model experiment results are complementary to each other. Through careful interpretation, each of these results can be used to partially circumvent the limitations of the other. One of the greatest values of model tests is that the results are obtained without requiring any a priori assumptions about the nature of the responses. This is almost never true for numerical models.

7.7.2 Sources of Error

When comparing the results of model experiments with analytical predictions, the following potential sources of discrepancies should be considered.

a) Possible errors due to scale effects. Improper scaling of the Reynolds Number is inevitable since Froude scaling is almost always used. This will affect the viscous component of fluid drag and the location of the boundary layer separation point. The latter will affect the form drag and the nature of vortex shedding.

b) Possible errors resulting from finite tank dimensions. Since most offshore engineering model tests are done with low or zero forward speed, wave reflections from the tank walls, wave absorber, etc., may have a significant influence on the test results.

c) Possible errors resulting from limitations on the accuracy of modeling physical parameters and dimensions. In some cases, the instrumentation itself might affect the responses. This should be minimized wherever possible.

d) Limitations on accuracy of the experimental results resulting from finite record lengths, finite sample rates and numerical accuracy of the data analysis procedures.

e) Discrepancies arising from assumptions made in the development of the numerical model that might not accurately depict the physical model. An example is the assumption of linearity of the responses with respect to wave height that is almost always made in the frequency domain analysis. This might cause significant discrepancies between the numerical and experimental results for very steep waves or in situations where viscous forces play an important role.

7.7.3 Modeling Parameters

Typically, the following parameters should be modeled with care in the physical model or otherwise properly accounted for in the interpretation of the results.

a) The physical dimensions of the platform. Some relatively minor dimensional features such as the radius of corners on rectangular elements might significantly affect the results. In other cases it might be unnecessary to model the complete detail. The effect of any such simplifications to the model should be considered before the model construction.

b) The mass properties of the platform, including the center of gravity and the radii of gyration.

c) The restoring force characteristics of the tendon and riser system. This usually requires modeling the axial stiffness as well as the length and submerged weight of the tendons and risers.

d) The principal physical characteristics of the tendons and risers, including the outer dimensions, mass (and added mass), and submerged weight. This might be of only minor importance if the water depth is small. In large water depths, the fluid inertia and drag forces acting on the tendons and risers might be a significant component of the total force acting on the system. The bending stiffness will affect higher modes of response if excited. The effects of mechanical damping in the tendons and risers might also be important to the system response. Numerical models can be used to determine sensitivity to these parameters.

e) The effect on stability due to internal free surfaces. For example, during the installation phase there might be a free surface in the ballast compartments that will affect the static stability. The effect on dynamic stability will probably be minimal, but should be examined.

f) The structural stiffness of any components that might affect the responses of the system. Such components include the bottom foundation, connections at the upper and lower ends of the tendons and the platform itself. Due to the difficulty and expense of scaling down material properties, most small scale platform models are considerably stiffer than the prototype. However, this is not always the case, particularly when instrumentation to measure loads is placed in series with the structural component. For example, devices for measuring tension that are attached to the model tendons might significantly reduce their effective axial stiffness, causing erroneous results.

7.7.4 Types of Tests

7.7.4.1 The types of tests that are commonly conducted and might be useful include the following:

a) tests of the full system consisting of hull, deck, tendons, and risers in the drilling and operating configurations in regular and irregular waves;

NOTE Tests with combined wind, waves, and current are more difficult to set up but can also provide useful information.

b) free oscillation tests to determine the natural period and damping of the system in various modes of motion;

c) towing tests to measure seakeeping characteristics of the platform during the transportation phase;

d) measurements of motions and interface loads during mating of deck structures with the hull;

e) measurements of system responses under simulated damage conditions or in the partially installed state;

f) tests with current or towing to determine VIM responses.

7.7.4.2 The responses that can commonly be measured include vessel motions, tendon/riser motions and internal loads, and deck clearance. Installation procedures may also be effectively tested.

7.7.4.3 In order to maximize the usefulness of the test information, a test program should be developed in advance which defines the test objectives, the needed products, the required instrumentation, and the data analysis procedures. It is desirable to have data analysis and display capabilities online during the testing so that flaws in the instrumentation, model, or data acquisition system that might affect the final results can be discovered and corrected.

7.8 Global Performance Design Equations

7.8.1 General

Global performance design responses are considered to be those motion, clearance, and tension responses that govern the overall size and configuration of the TLP. They typically include platform offset, platform yaw, minimum and maximum tendon tension, deck clearance (air gap), and deck level acceleration. The calculation of global performance design responses is based on global performance design equations evaluated for various load cases. A design load case is composed of a platform condition and an environment design condition.

7.8.2 Calculation Methodology

7.8.2.1 TLPs are dynamic systems excited by multiple loading functions in a random environment. The calculation methodology for global performance design responses is based on the fact that different TLP systems may be sensitive to different environmental loading combinations, and that the designer has the responsibility to ensure appropriate design load cases and environmental combinations subject to general guidelines given in the following sections.

7.8.2.2 The design methodology used herein is based on a working stress design with a single design safety factor for each response.

7.8.2.3 The “extreme” design load cases for most global responses are based on appropriate safety factors applied to the estimate of a 100-year return period response. The designer should ensure appropriate environmental conditions for a site and for a general TLP configuration.

7.8.2.4 The environmental criteria used in preliminary design for these load cases may be selected either from traditional 100-year environmental combination criteria (determined as, for example, 100-year wave and associated wind and current, etc.) or they may be selected based on TLP response using response-based criteria analysis. Regardless of the way environmental criteria are selected for preliminary design, the adequacy of the environmental criteria should be verified through long term response analysis applied to the final design configuration.

7.8.2.5 Long-term response analysis involves developing non-exceedence probability distributions for TLP responses of interest that account for both short-term and long-term variability in sea conditions, and from which design level responses (100-year return period, 1000-year return period, etc.) can be identified. For purposes of final verification, safety factors for the various extreme design load cases should be applied to the response levels identified from the long-term probability distributions. See A.3 for additional guidance on long-term response analysis and response-based criteria.

7.8.3 Environmental Parameters

7.8.3.1 Environmental parameters important to TLP response are provided in Table 5.

7.8.3.2 The number of parameters involved causes difficulty in specifying a single environmental condition for design. While more rigid structures are typically dominated by linear and quadratic wave forces, responses of a TLP are also affected by wind, tide/storm surge, higher-order wave drift and springing/ringing forces, currents, and wind dynamics. The TLP response to these forces is dynamic and somewhat nonlinear. In order to produce a reasonable and safe design, the designer shall evaluate and specify the design conditions appropriate for the particular TLP under consideration.

7.8.3.3 There are a number of methodologies that may be used to develop response-based design criteria. These include the following:

a) environmental scans of hindcast data to establish long term response distributions, and identify design checking environments which are expected to give design level responses (Leverette and Rashedi, 1995 [178]; Spillane and Leverette, 1991 [224]; Forristall, Larrabee, and Mercier, 1991 [141]);

b) environmental joint distributions combined with response models to develop response distributions (Wen and Banon, 1995 [242]);

c) rational approaches using 100-year contours of environmental combinations (Winterstein, et al. 1993 [247]; Leverette, et al. 1982 [177]).

Table 5—Environmental Parameters Influencing TLP Response

Environmental Condition	Environmental Parameter
Wind	Mean wind speed Mean wind direction Wind power spectral density function
Wave	Significant wave height Mean wave period Wave elevation spectral density function Mean wave direction Wave directional spreading function
Current	Surface current (speed and direction) Current profile (speed and direction)
Tide	Astronomical tide Storm surge

7.8.3.4 Specification of the design environment generally includes the following:

a) wave spectrum (significant height, spectral peak period, spectral shape, direction);

b) wind mean speed, direction, spectrum;

c) current speed, direction, profile with depth (storm current and eddy current component);

d) water level extremes (HDWL, LDWL).

7.8.3.5 In order to keep the extreme response simulation problem tractable, one simplification of the environment that is generally assumed for TLP design analysis is the use of unidirectional and coincident combinations of the environmental components. If sufficient directional information is available, the environment may be specified by TLP sector. In the more general case, and assuming the TLP to be rectangular in plan, the TLP should be checked for a minimum of three headings. (In the special case of symmetry of geometry and mass properties, this may be reduced to two headings.) The three headings should include the two broadside directions (which may be condensed to one for a square symmetric TLP) and a diagonal heading that is perpendicular to the diagonal axis of the columns, which would be 45º for a square TLP. Other headings should be checked if they would reasonably be expected to lead to a design-controlling condition.

7.8.4 Maximum Offset

7.8.4.1 The prediction of maximum horizontal excursion is important for analysis of riser and tendon systems and for specification of riser and tendon hardware. The maximum offset also partially governs the deck height requirement because of platform setdown with offset. Analysis of the horizontal motions (surge, sway, and yaw) is often termed stationkeeping analysis.

7.8.4.2 Offset is primarily an environmental response. During extreme environmental conditions, there are not normally other loads contributing to the extreme offset, except for the case where there is an auxiliary positioning system (lateral mooring or DP system). During normal operating conditions, loads from moored supply boats and other activities may contribute to the offset, but this is not generally of concern for “extreme” load cases.

7.8.4.3 The designer may consider directional distributions of environmental conditions. The assumption of collinear wind, wave, and current is appropriate in the absence of more detailed data. If enough information is available, use of appropriate noncollinear environments may be used and can result in a reduced estimate of maximum offset.

7.8.5 Environmental Forces Contributing to Offset

7.8.5.1 General

The environmental forces of interest can be classified by their frequency content as:

— steady or mean forces,

— wave frequency forces, and

— low-frequency forces.

The steady or mean forces result in a mean offset of the platform. The low-frequency forces excite motion which is below wave frequencies and predominately at frequencies near the surge, sway, or yaw natural frequencies of the platform. The wave frequency forces result in wave frequency surge, and sway motions.

7.8.5.2 Mean or Steady Forces

The following steady forces should be considered.

a) Mean wind forces (see 6.2, 7.5.8 and 7.6.6)—The wind speed used should be an average wind speed for an extended period (approximately one hour) based on the appropriate environmental conditions (return period).

b) Current force (see 6.3.2, 7.5.8, and 7.6.6)—The drag contribution due to tendons and risers should be included in estimating the total force.

c) Steady wave drift—Steady wave-drift forces result from wave diffraction and from second-order viscous effects. The interaction between waves and current can also result in steady forces which should be considered. See 7.5.8 and 7.6.6 for a discussion of these forces.

7.8.5.3 Wave Frequency Forces

The wave frequency forces are dominated by first-order drag and inertial wave loads on the platform. These forces are discussed in 6.5, 7.5.7, 7.6.5, and 7.6.6.

7.8.5.4 Low-frequency Forces

The following forces contribute significantly to low-frequency motion and should be considered:

a) Wind forces—The wind gust spectrum (see 6.2, 7.5.8, and 7.6.6) should be used to model the wind speed variation from the average wind speed. The mean wind speed which is used as a parameter in most gust spectrum models should be the same as the wind speed used to estimate the mean wind force. Simiu and Leigh (1983) [222] discuss the calculation of time varying forces on the platform from the wind gust spectrum.

b) Wave/Current forces—A force spectrum for slowly varying (low frequency) wave-drift forces should be estimated for the appropriate wave conditions (see 7.5.8 and 7.6.6).

7.8.5.5 Force Spectrum

Pinkster (1980) [210] gives a method to estimate the force spectrum from second-order potential wave drift given the steady wave-drift forces vs. wave frequency and the appropriate wave spectrum. It may also be appropriate to consider contributions from viscous wave-drift and wave/current interactions. Burns (1983) [110] gives an approximate method to estimate the effects of wave/current interactions.

7.8.6 Offset Components

7.8.6.1 The TLP horizontal motions can be conveniently divided into three contributions corresponding to the classification of forces discussed in 7.8.4.

a) Mean offset—The mean vessel offset can be estimated by developing a restoring force vs. offset function and applying the estimated mean force to give an estimate of mean offset. The restoring force function depends on setdown, tendon stretch, catenary effects, and the effect of time varying tendon tension.

b) Wave frequency motions—The wave frequency horizontal motions can be modeled by using either the frequency or time domain techniques discussed in 7.5 and 7.6.

c) Low-frequency motions—The low-frequency motions can also be modeled using either time or frequency domain techniques.

7.8.6.2 For frequency domain modeling, the force spectrum for wave drift (or total low-frequency wave forces) can be combined with the wind force spectrum to give a total low-frequency force spectrum (see 7.5.8 and 7.6.6). Assuming that the low-frequency wind and wave forces are independent, the total low-frequency force spectrum is given by the sum of the low-frequency wave force spectrum and the low-frequency wind force spectrum.

7.8.6.3 This total force spectrum can then be multiplied by the appropriate motion transfer function to obtain the desired horizontal motion. Time domain simulation can also be used to obtain the low-frequency motion. However, because the low-frequency motions are dominated by the surge, sway and yaw resonances with natural periods of approximately 60 to 150 seconds, a long time simulation is required to include a sufficient number of cycles for developing an accurate estimate of the statistical extreme. Modeling of the time series should be done carefully. The use of discrete frequencies is discussed by Tucker, et al. 1984 [235]. Other classic works in wave group spectra (e.g. Funke and Mansard, 1979 [144]), are relevant in developing time domain analysis and model test wave time series. For time simulation a time history of low-frequency forces is generated from wind and wave force spectra or directly from wind velocity and wave profile time histories.

7.8.6.4 The estimation of damping is important because low-frequency motion is dominated by a resonant response. Further discussion of damping is provided in 6.5.5.2, 7.5.7, and 7.6.5.

7.8.7 Estimating Extreme Offset for Design

Due to the contribution of the low-frequency resonance, the resulting motion (combined low and wave frequency motion) is broad banded. Figure 7 shows an example surge motion spectrum for a TLP in an extreme storm.

The estimation of the extreme value of offset should consider the wide band nature of the process and be based on wide band statistical methods.

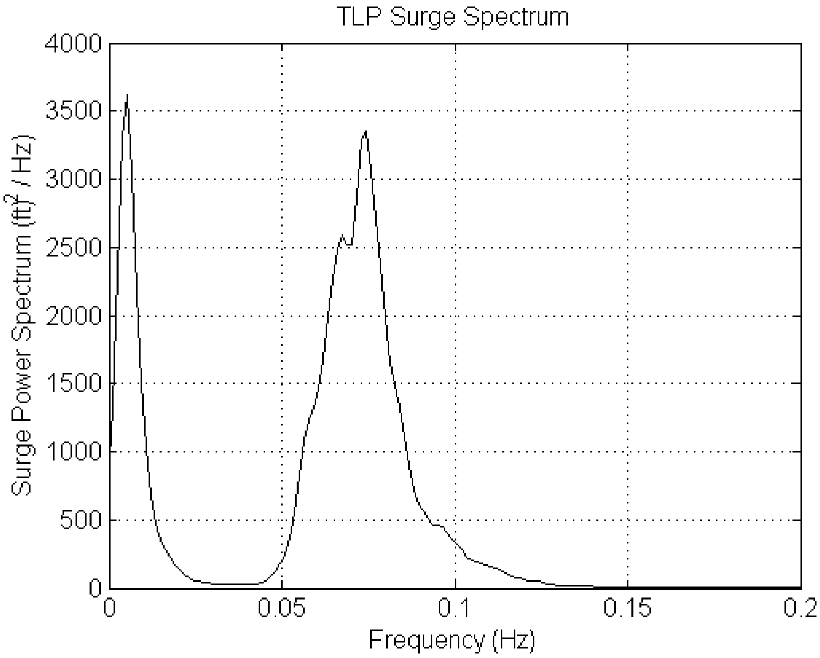


Figure 7—Surge Motion Spectrum

7.8.8 Maximum Offset Simplified Code Equation

7.8.8.1 Maximum offset has been formulated differently by various designers, while still achieving acceptable safety in design. One simple formulation that has been used in both preliminary and final design is given by:

$$x_{\text{max}} = x_{\text{mean}} + x_{\text{slow drift + wave frequency}} \tag{26}$$

where

x_{mean}	is the offset due to current, one-minute wind, and steady wave-drift forces;
$x_{\text{slow drift + wave frequency}}$	is the maximum dynamic offset derived from spectral combination of wave frequency motion and slow drift resonant offset.

7.8.8.2 It is noted that the dynamic extreme of combined low and wave frequency responses is typically non-Gaussian, and requires use of statistical factors established by means such as model tests or nonlinear simulations.

7.8.8.3 Other formulations which define other combinations of response and which can be shown to give reasonable estimates of the expected maximum offset are also acceptable for design. The use of full simulations that include all major contributors to offset variation are also acceptable for predicting design values of maximum offset.

7.8.9 Maximum Yaw

The prediction of maximum yaw is important for predicting the maximum rotation of riser and tendon top terminations and for the yaw contribution to horizontal excursions. The prediction of maximum yaw is similar to predicting maximum offsets. The methods of 7.8.3 through 7.8.7 apply to yaw prediction except that moments on the vessel shall be modeled instead of forces. This section will discuss only considerations specific to yaw which are not identified in 7.8.3 through 7.8.7.

7.8.10 Environmental Forces Contributing to Yaw

7.8.10.1 In modeling the environmental forces contributing to yaw, the designer should consider the likely conditions and environmental directions that would result in extreme yaw. For example, the wind directions resulting in the greatest steady and oscillating moments on the vessel should be considered. Modeling of wind-induced moments is particularly difficult. Consideration should be given to moments induced by spatial variability.

7.8.10.2 Noncentral center of gravity and eccentricity of the resultant horizontal environmental forces will increase yaw responses to waves. Any likely loading conditions such as nonsymmetric placement of drilling rigs or nonsymmetrical riser installations should also be considered. Checking of various wave headings may be required because symmetric wave loadings will minimize the yaw response to waves. Multi-directional seas tend to excite yaw more than uni-directional seas

7.8.10.3 Another source of yaw excitation can be vortex shedding from the columns in a steady current. Resonant coupling between the vortex shedding and yaw motion has been shown to occur in model tests, and should be checked for in high current areas (see 6.3.3 and A.1).

7.8.11 Estimating Yaw Responses

The yaw response can be estimated using the same techniques outlined for offset in 7.8.6. The modeling of damping is also important in estimating yaw response.

7.8.12 Maximum Tendon Tension

7.8.12.1 Minimum and maximum tension calculations start with the vertical weight-buoyancy balance given by Equation (13). The actual weight of the platform and the mean tension in the tendons and risers will vary by load case depending on the load case weight condition, numbers of risers, etc. Extreme tension calculations add or subtract tension variations caused by weight change and environmental response to predict design values for minimum and maximum tension.

7.8.12.2 Maximum tension is governed both by environmental conditions and by the weight and displacement of the platform (i.e. the mean pretension). The mean pretension is composed of a design value pretension (T_o), and operational variations (live load tension effects) about this design pretension. The live load variations are to some extent controllable, and the value used in design load cases should reflect the degree to which the designer/operator chooses to control the weight of the TLP. The environmental response is composed of terms that are reasonably predictable, and some terms that cannot be easily predicted even by state-of-the-art analysis techniques.

7.8.12.3 The nominal pretension is selected in order to control minimum tension, or to limit maximum offset. The components shown in Table 6 should be considered for maximum tendon tension determination.

7.8.12.4 Maximum tendon tension may be estimated using a linear superposition incorporating the effects discussed above:

$$T_\text{max} = T_\text{o} + T_\text{t} + T_\text{l} + T_\text{m} + T_\text{s} + T_\text{w} + T_\text{f} + T_\text{r} + T_\text{i} + T_\text{v} \tag{27}$$

The total wave-induced tension $T_\text{w} + T_\text{r}$ may be calculated using a design recipe as described in A.2.8.

Figure 8 illustrates the superposition of these tension contributions. This approach is adequate if a maximum design condition can be determined that accounts for the statistical characteristics of the random sea condition. The value of T_max should correspond to the maximum expected tension over the design return period. This should be determined from a statistical evaluation of the components of Equation (26), including their joint probabilities of occurrence.

Table 6—Components for Maximum Tension Determination

Tension Type		Tension Component
Quasistatic	T_o	Design pretension (at the critical tendon section, including tendon weight) at mean water level (mean tide)
	T_t	Tide/storm surge water level variation loads
	T_l	Load and ballast condition/weight variations/design margin
	T_m	Tension due to overturning moment from wind and current forces
	T_s	Tension caused by setdown due to static and slowly varying offset (wind, wave drift, and current)
	T_f	Tendon loads from foundation mispositioning at maximum platform offset
Wave-induced tension	T_w	Tension variation from wave forces and wave-induced vessel motion about the mean offset (including any coupled tendon responses)
	T_r	Loading due to heave, pitch, and roll oscillations at their natural frequency (ringing and springing, including possible underdeck slamming loads)
Individual tendon effects	T_i	Individual tendon load sharing differential (one of a group of tendons generally carries a greater share of the load because of anchor template rotational tolerances, vessel yaw, initial setting tolerances, etc.)
	T_v	Tension induced by vortex shedding responses of an individual tendon

7.8.12.5 When calculating the maximum stresses in the tendons, there are other stresses and loads that sometimes have to be included. For example, if the tendons contain fluid at a temperature other than seawater temperature, then thermal stresses should be considered.

7.8.12.6 If all of the terms in Equation (26) are taken to be extreme or maximum values, the resulting estimate of tension will be very conservative, with a much lower probability of occurrence than the return period of any one of the terms. In order to calculate a reasonable design value for maximum tension, the joint statistics of the driving functions should be considered. The joint statistics of wind, wave, current, and tide/surge can be used with the vessel response functions to estimate a tension corresponding to the design return period (see Forristall, et al. 1991 [141] and Leverette, et al. 1982 [177]).

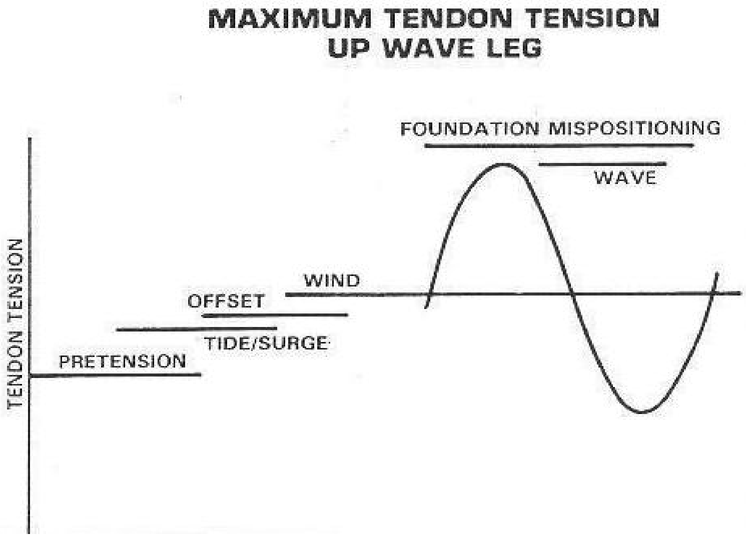


Figure 8—Maximum Tension Components

7.8.13 Maximum Tension Simplified Code Equation

7.8.13.1 Maximum tension has been formulated differently by various designers, while still achieving acceptable safety in design. One simple formulation which has been used in both preliminary and final design is given by:

$$\begin{aligned} T_{\max} = {} & T_{\mathrm{o}}(at\,HDWL) + T_{\mathrm{setdown}}(at\ max\ drift\ offset) \\ & + T_{\mathrm{wind,\ wave\ drift,\ current\ moments}} \\ & + T_{\mathrm{wave\ +\ springing\ +\ ringing}} \end{aligned} \tag{28}$$

where

max drift offset is the (offset due to current, one-minute wind, and steady wave drift) + (significant value of wave and wind slow drift) and the significant value is twice the standard deviation.

7.8.13.2 Equation (28) is generally applied to the most sensitive upwave tendon. If the dynamic terms in the downwave tendon are sufficiently large to overcome the moment effects in the upwave tendon, then the downwave tendon should be used to determine maximum tension.

7.8.13.3 Other formulations that define reasonable combinations of response and that can be shown to give reasonable estimates of the expected maximum tension are also acceptable for design. The use of full simulations that include all major contributors to tension variation is also acceptable for predicting design values of maximum tension.

7.8.14 Minimum Tension

7.8.14.1 Similar to maximum tension, the minimum tension is governed both by environmental conditions and by the weight and mean tension condition of the platform. Mean tension is composed of a design value pretension (T_0), and operational variations (live load tension effects) about this design pretension. The live load variations are to some extent controllable, and the value used in design load cases should reflect the degree to which the operator chooses to control the weight of the TLP. The environmental response is composed of terms that are reasonably predictable, and some terms that cannot be easily predicted by state-of-the-art analysis techniques.

7.8.14.2 The minimum tension is determined by superposition of pretension and environmental effects as shown in Equation (29).

$$T_{\min} = T_{\mathrm{o}} + T_{\mathrm{s}} + \left[T_{\mathrm{t}} + T_{\mathrm{l}} + T_{\mathrm{m}} + T_{\mathrm{w}} + T_{\mathrm{f}} + T_{\mathrm{r}} + T_{\mathrm{i}}\right] \tag{29}$$

NOTE The terms included in brackets generally are negative signed.

7.8.14.3 The minimum tension calculation in Equation (28) is illustrated in Figure 9. Although the form of this equation is similar to Equation (26), the values of the terms may be different. In particular, the loading condition and configuration corresponding to the most probable minimum tension conditions are different than those corresponding to the maximum tension conditions. For example, the positive tide and surge term will be different from the negative term, and the minimum tension will generally come from the minimum rather than maximum slowly varying offset which is associated with an extreme wave event.

7.8.14.4 The combinations of wind, wave, and current that yield conservative estimates of maximum tendon tension may not produce conservative estimates of minimum tendon tension. For example, strong currents aligned with severe wind and waves may generate the largest tendon tensions. However the smallest tendon tensions may be generated by severe wind and waves combined with weak currents or with currents that have a heading that is orthogonal to the wind and waves (Forristall, Larrabee, and Mercier, 1991 [141]). See A.3 for a discussion of long-term response analysis and the implementation of response-based design criteria.

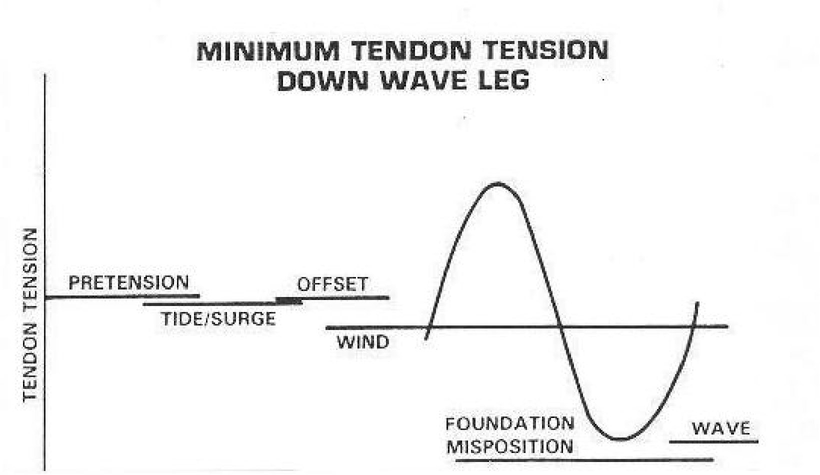


Figure 9—Minimum Tension Components

7.8.14.5 For tendons with positive wet weight, the minimum tension occurs near the lower tendon connection; hence the tendon weight (in water) needs to be subtracted from the minimum tension at the upper flex element. Otherwise, the tension components may be evaluated by a method similar to those described above for maximum tensions.

7.8.15 Minimum Tension Simplified Code Equation

Minimum tension has been formulated differently by various designers, while still achieving acceptable safety in design. One simple formulation which has been used in both preliminary and final design is shown in Equation (30).

$$\begin{aligned} T_{\min} = {} & T_{\mathrm{o}}(at\,LDWL) + T_{\mathrm{setdown}}(at\ min\ drift\ offset) \\ & + T_{\mathrm{wind,\ wave\ drift,\ current\ moments}} \\ & \quad + T_{\mathrm{wave\,+\,springing\,+\,ringing}} \end{aligned} \tag{30}$$

where

the last two terms in Equation (30) are negative valued; and

min drift offset is the (offset due to current, one-hour wind, and steady wave drift) – (significant value of wave and wind slow drift).

NOTE The minimum tension can occur in up-wave or down-wave tendons, depending on the system configuration.

Other formulations which define reasonable combinations of response and which can be shown to give reasonable estimates of the expected minimum tension are also acceptable for design. The use of full simulations which include all major contributors to tension variation is also acceptable for predicting design values of minimum tension.

7.8.16 Minimum Tension Criteria

7.8.16.1 The design check for minimum tension is intended to ensure that there is sufficient tension to maintain the structural integrity and restraint to motions that are provided by the tendon system to the TLP.

7.8.16.2 The fundamental design philosophy in today's TLP concepts is that the tendon system provides deterministic structural restraint of the structure in heave, pitch, and roll. The objective is to prevent unrestrained motions which may lead to tendon disconnect or excessive loads in the structure or tendon system. This implies, for some systems, that individual tendons may go slack.

7.8.16.3 Because the sensitivity of a given configuration to the environment may vary from configuration to configuration, or from environment to environment, limiting minimum tension response is best evaluated at a survival level environment.

7.8.16.4 For Category A and Category B, the minimum tendon tension in at least one tendon per corner should remain non-negative. For Category S, minimum tension in at least three corner groups of tendons shall maintain non-negative tension in the survival environment.

7.8.16.5 For Category S, if non-negative tension is not maintained in all corner groups in the survival environment, then a comprehensive coupled analysis of the tendon system performance under loss of tension shall be performed to demonstrate proper reengagement of the bottom connector with the foundation receptacle and adequate robustness against subsequent snatch loading. The analysis shall examine detailed load sequences induced in all components (top and bottom) on all tendons to ensure load capacities are not exceeded and components function as intended in order to prevent tendon disconnect. See Section 9 for detailed guidance.

7.8.17 Tendon Angle

7.8.17.1 Maximum tendon angle at the upper and lower flex assemblies is closely tied to maximum surge and yaw, with the addition of any tendon motion effects. Accuracy of fabrication and of foundation installation should also be considered. The maximum value is used for design of the flex assembly, for hull and foundation clearance allowance, and for calculating bending stresses in the tendon.

7.8.17.1 The maximum angles may be calculated using the maximum surge and yaw calculation methods together to predict a maximum excursion for the upper flex joint. This can be used as input to an analysis of the tendon motion response that provides the angle responses. Due consideration of the consequences of exceeding the predicted extreme should be included when calculating the response.

7.8.17.3 In addition to maximum angle, the flex joint designers generally require the envelope of load range and angle for completing the flex joint design. Minimum load at high angles is likely to be of as much concern as maximum load. Joint statistics of wind, wave, and current are needed to properly estimate the load/angle envelope. Frequency domain methods can be used if phase information between offset and tension is retained. Time domain and model test methods are also suitable.

7.8.18 Minimum Deck Clearance

7.8.18.1 The minimum deck clearance for a TLP is governed by a combination of increasing water level and decreasing deck height. The increasing water level is caused by incident wave elevation, tide, storm surge, and radiation/diffraction effects from the platform. In very steep sea conditions, the diffraction effects can be considerable. The decreasing deck elevation is caused by platform setdown with offset. Platform setdown increases nonlinearly at high offsets, leading to a rapid decrease of clearance with increasing environmental severity.

7.8.18.2 The radiated or diffracted waves generally cause the wave to impact the deck locally. In some cases, local impacts may be accounted for in design, and may result in both local stiffening and increased weight of the deck as well as tendon ringing, which affects the peak loads in the tendons and porch structure. Increased tendon load response will also affect the minimum tension, which will in turn affect the design pretension.

7.8.18.3 The deck height has a significant effect on the vertical position of the center of gravity and, in turn, on the maximum and minimum tendon tensions. The deck elevation also affects the wind load and wind overturning moments. In general, a higher deck has adverse effects on tendon tension responses. However, large tendon tension variations may result if the deck is too low and waves strike the lower deck.

7.8.18.4 In determining the deck clearance, one should consider the following:

a) wave crest elevation,

b) storm and astronomical tides,

c) platform setdown due to platform offset and yaw,

d) local wave modifications due to the presence of the hull,

e) dynamic vertical motion of platform,

f) air gap,

g) phase angle between wave crest and platform position.

7.8.19 Minimum Deck Clearance Criteria

7.8.19.1 The design check for minimum deck clearance is intended to ensure that there is sufficient deck height to prevent inundation of the deck by wave crests, thereby preventing damage to equipment and preventing excessive loads to the deck and total TLP system.

7.8.19.2 The deck clearance criteria apply to deck structure that is not intended to be immersed. There have been concepts proposed, such as bare wellhead support structures, where the deck is intended to be inundated by wave crests in extreme conditions, and in which the deck and overall TLP system are designed for such occurrences to “extreme” load safety factors. The minimum airgap criteria do not apply to such structures.

7.8.19.3 Because of the increased setdown with storm severity, traditional design approaches such as the specification of a nominal clearance in the design level 100-year storm may not be adequate. The designer should consider both the consequences of deck impact, and the rapidity with which clearance is being diminished.

7.8.19.4 The recommended minimum deck clearance criteria requires a 1.5 m (5 ft) clearance to main steel in extreme conditions (100-year return period), combined with zero or greater clearance in survival (1000-year minimum return period) conditions with no margins. Local wave effects in these conditions can be dealt with by local strength design.

7.8.19.5 If the designer chooses to design for deck impact rather than ensure sufficient clearance to avoid impact, the TLP system, including deck, hull, tendons, and foundations should be designed for the anticipated local and global wave forces (including slamming) and resulting responses.

7.8.19.6 Given recent Gulf of Mexico large storm observations, it may be good practice to provide tripping brackets on major deck girders even with designs meeting the criteria described in this section.

7.8.20 Maximum Acceleration

7.8.20.1 The lateral accelerations of the platform are used in the design of the structure and in the design of equipment and equipment supports. In addition to the in-service condition, other conditions during fabrication, transportation, and installation phases of the platform life should be considered. The response of interest is generally the extreme horizontal acceleration, although operating condition accelerations may be important in the design of process equipment and deck drainage systems.

7.8.20.2 Global lateral accelerations are governed by the dynamic horizontal offset forces acting on the platform. These are dominated by first-order wave forces and nonlinear high-frequency wave forces, but may also include wind and wave-drift components. Local lateral accelerations are also produced by the rotational responses of pitch, roll and yaw.

7.8.20.3 The wave frequency and high-frequency motions and accelerations are estimated by frequency or time domain solutions to the equations of motion supplemented by model tests. Deterministic or short term probabilistic methods can be used to predict the maximum acceleration response.

7.9 Responses for Fatigue Analysis

7.9.1 Introduction

This section provides guidance in the prediction of the response histories for fatigue calculations. The prediction of fatigue life or damage is by nature a statistical procedure. Historically, the standard procedure for fatigue calculations involved deterministic analysis with high safety factors. However numerous investigators have developed more accurate probabilistic approaches (see Wirsching, 1983 [249]). These methods inherently furnish the designer with more information on the fatigue properties, but the probabilistic approach requires more input data than is often available. The three methods described in 7.9.1 through 7.9.1.3 are in order of increasing complexity and data requirements.

7.9.1.1 Method 1—Discrete Wave Height and Period

The joint frequency statistics of wave height and wave period (as described in a wave scatter diagram) are operated on by appropriate transfer functions to produce corresponding force and motion statistics. Due to the sensitivity to wave period, traditional methods using a mean period for each wave height are not applicable. Wave-drift, wind, and current response statistics can be estimated using similar methods.

7.9.1.2 Method 2—Frequency Domain

The joint (H_S, T_P) wave spectrum statistics are operated on by appropriate response amplitude operators (RAOs) to produce corresponding force and motion spectra statistics. The response statistics to wave-drift force, current, wind, and platform loadings are estimated using Method 1. The RAOs can be generated on the basis of regular wave or random sea inputs, and with frequency or time domain simulations. Regular wave or random sea model tests can also be used to generate the RAOs.

7.9.1.3 Method 3—Random Time Domain

A time domain simulation is performed for each sea state in the wave scatter diagram. The response statistics generated from each time domain simulation are combined with the corresponding frequency of occurrence of that sea state to generate the force and motion statistics.

7.9.2 Tendon and Foundation Loads

The tendon and foundation loads can be calculated using one of the above methods. However the results should be modified to include the following effects, if present:

a) springing and ringing;

b) wave slamming on the deck, if this will be permitted;

c) setdown caused by surge, sway and yaw, the tides, and the platform loading.

7.9.3 Surge Offset/Tendon Flex Joint

The offset/tendon angle can be calculated using one of the above methods. The effect of the tide, storm surge, and platform loading on the offset should be considered.

7.9.4 Hull Forces

The hull forces can be calculated using one of the above methods. Forces generated by tendon springing and ringing and wave slamming should be considered.

7.9.5 Single Event Fatigue

Components that are susceptible to low-cycle/high-stress fatigue should be analyzed to assess damage accumulation during rare extreme events that may be of extended duration, such as a 48-hour rise and fall of the 100-year storm. Such discrete events may be found to induce more fatigue damage accumulation over the service life of the platform than is captured by applying the probabilistic wave scatter diagram for these low probability events.

Refer to 9.2.5.4 for specific guidance on single event fatigue analysis for tendon components.

8 Platform Structural Design

8.1 Introduction

8.1.1 Purpose and Scope

This section addresses the structural design and analysis of the hull and deck for all pre-service and in-service condition loading combinations. Discussions of fabrication, inspection, and maintenance are addressed in Section 14.

8.2 General Structural Considerations

8.2.1 Project Phases

The hull and deck structures should be designed for loadings that occur during all project phases including construction, transportation, installation, and in-place phases, including operations (see 5.6.3).

8.2.2 Damage Conditions

The structural design should consider the possibility of accidental events (see 5.4 and 8.3.). Accidental events include, but are not limited to collisions, dropped objects, fire, explosion, or flooding. Special cases associated with mechanical devices, such as riser tensioners, shall be evaluated for maximum stroke conditions. Generally these devices do not have stress conditions proportional to wave height and therefore an overload can occur with waves marginally greater than the selected design wave.

8.2.3 Redundancy

The capability of the deck and hull to redistribute loads under damaged condition should be considered when selecting the structural configuration. The results from the redundancy analyses can be used in conjunction with HAZIDs for the selection of critical elements to be selected for fireproofing and blast.

8.2.4 Interfaces with Other Systems

The structural design of the deck and hull should consider critical interfaces with other systems, such as tendons and risers, installation equipment, moonpool requirements, drilling and production equipment, hull systems, and foundations. (See Sections 9, 10, 11, and 12.)

8.2.5 Safety

The arrangement of the main structural deck elements should be coordinated with topside facilities, equipment, and operational requirements. The influence of the structure on proper ventilation of hazardous areas, access for fire fighting, fire protection and escape routes should be considered (see Section 12.)

8.2.6 Deck Clearance

8.2.6.1 The lower deck elevation should be established based on 7.8. If local wave impact on the underside of the lower deck is anticipated, local strengthening of the deck structure may be needed.

8.2.6.2 In general, the design should minimize platform components, piping or equipment located below the lower deck in the designated air gap. However, when it is unavoidable to position such items as minor subcellars, sumps, drains, production piping, or other secondary structures in the air gap, provisions should be made for the wave forces acting on these items. These wave forces may be calculated using the crest pressure of the design wave applied against the projected area. Local wave diffraction effects due to the hull columns should be incorporated into the wave crest velocities used to calculate the loads. This includes the influence of increased wave kinematics and surface elevation. These forces may be considered on a “local” basis in the design of the item. These provisions do not apply to vertical members such as deck support posts, hull columns, risers, etc., which normally penetrate the air gap. If the cumulative load on the items in the designated air gap is sufficient to influence the global performance, they should be included in the global model. See 8.3.3.10 for wave and current loads.

8.2.7 Weight Engineering

Because of their effect on the platform buoyancy and tendon tension requirements, all weights and centers of gravity should be accurately and continuously monitored throughout the design, construction, and in-place project phases. Particular attention should be to the application of contingency in the design at the various project phases. In the earlier phases adjustments in the design either by proper contingency to design loads or reductions to allowable stresses should be made to accommodate the growth predicted by the weight growth predicted in the weight engineering estimates. See 5.4.4 for weight verification.

8.2.8 Corrosion

8.2.8.1 The steel materials should be protected from the effects of corrosion by the use of a corrosion protection system (see Section 13). Corrosion protection system components include coatings, cathodic protection (sacrificial anodes or an impressed current system), corrosion allowance, and corrosion monitoring, or combinations of any of these.

8.2.8.2 Internal hull corrosion may be mitigated by multicoat painting systems, provided they are regularly inspected and maintained. The paint system should be supplemented by a cathodic protection system, particularly for installations with an anticipated field life longer than five years. Protection of voids may be achieved by evacuation and actively maintained and monitored dehumidification of each void compartment.

8.2.8.3 The material selection process and corrosion control procedures should be made with consideration of the interaction of these issues. The method(s) of corrosion protection may have a direct bearing on materials selection. High hydrogen overpotential from the cathodic protection system, for example, may aggravate stress cracking of high strength steels or accelerate coating damage through cathodic disbondment mechanisms. Material and corrosion control selection should also include consideration of any special requirements such as compatibility with internal fluids or unusual site-specific conditions. Care should be taken that any chemicals injected for antifouling purposes are fit for purpose, as overuse of chlorine can cause pitting corrosion or other structural issues, especially in sea chests.

8.2.8.4 The design of structural details is important for producing a complete structure that will be free of severe localized corrosion during the life of the platform. For example, intermittent welds should not be used where corrosion is likely. Unless specified otherwise, all faying surfaces should be sealed against corrosion by continuous fillet welds. Seal welds need not exceed 3.2 mm ($^1/_8$ in.) but should conform to AWS minimum fillet weld sizes. Attachments to the exterior of the hull should be designed to eliminate the possibility of water entrainment, in order to minimize corrosion.

8.2.9 Coatings

Unless specified otherwise by the designer, the applications of coatings should conform to the guidelines provided in Section 13. Any coating system subject to cathodic protection should have a proven history of resistance to cathodic disbondment.

8.2.10 Antifouling

In geographical areas where marine fouling is significant, organisms are active and the use of antifouling coatings may be considered to reduce the effects of marine growth.

8.2.11 Cathodic Protection

The cathodic protection system components should be in accordance with drawings and/or specifications and the guidelines provided in Section 13. Overprotection, which may cause hydrogen embrittlement or coating disbondment, should be avoided. The design life of the cathodic protection system shall be commensurate with the platform's design life.

8.2.12 Corrosion Allowance

A corrosion allowance appropriate for the environment and design life of the platform should be provided on all members. The corrosion allowance should be based on the guidelines provided in Section 13. Unprotected steel, including plates with stiffeners and girders, in drillwater tanks should also be provided with a corrosion allowance. Coatings and cathodic protection should be considered to help provide additional corrosion protection to these components. Corrosion allowance should not be included in the plate thickness used in stress or buckling analyses.

8.2.13 Splash Zone

External surfaces exposed in the splash zone region should be protected with special corrosion protection systems. Guidelines are provided in Section 13 regarding corrosion protection systems and corrosion allowances. The splash zone is based on the astronomical tidal range, the maximum wave height in the 1-year storm, and any anticipated foundation subsidence. The upper limit of the splash zone is 65 % of this wave height above high astronomical tide (HAT) plus the maximum expected subsidence, and the lower limit is 35 % of this height below low astronomical tide (LAT). Subsidence is not considered in determining the lower limit of the splash zone.

8.2.14 Vibrations

The effect of machinery vibrations should be included in the design. Reinforcing of the structure may be needed to reduce the level of local stresses. Structural details in areas of high vibration should be designed to reduce the effect of resonance and local member fatigue.

8.2.15 Ultimate Instability Stresses and Fabrication Control

Instability stress algorithms are based on structural components meeting API-recommended fabrication tolerances to keep the residual stresses introduced during fabrication to a reasonable level. Component configurations and structural details should be developed to preclude fabrication complications so that tolerance requirements are achieved and residual stresses limited. When tolerance requirements are not met, corrective measures should be taken either to meet the requirements or to downgrade the ultimate instability stresses by accounting for the deficiencies.

Generally, in the final design phases the construction methodology and/or details are not known. Appropriate load cases should be assumed to incorporate the expected construction methodologies, until the methodologies are finalized, to ensure that the design will be able to tolerate the actual construction methods.

8.3 Design Cases

8.3.1 General

A design case is a combination of loads due to the project phase, system condition, and environment with the appropriate safety criteria as described in 5.6. Some design cases given in 5.6 may not be required for a specific concept, while others not listed may be required. The designer should review the proposed concept to be sure that all appropriate design cases are considered.

8.3.2 Safety Criteria

The safety criteria for Category A, Category B, Category S and Category C are defined in 5.2. Specific recommendations for safety factors for platform design are given in 8.6 for categoriy A and Category B, and in 8.5.5 for Category C. In accordance with 5.2.3, inclusion of hull structural strength checks in survival conditions is not explicitly recommended, but is at the option of the operator.

8.3.3 Design Loading Conditions, Intact

8.3.3.1 General

8.3.3.1.1 For each design case, the platform should be designed for the loading conditions that will produce the most severe effects on the structure. Environmental loads, with the exception of earthquake loads, should be combined in a manner consistent with the probability of their simultaneous occurrence during the design case being considered. Earthquake loads should be imposed on the platform as recommended in 5.6.

8.3.3.1.2 Loads for structural analysis may be derived from various data sources. Gravity loads may be taken from the weight budget for various operating cases required to drill and complete the wells. Variations in consumables and the locations of movable equipment such as a drilling substructure or riser completion equipment and the resulting loads should be considered in order to determine the maximum design stress in the platform members. Production riser loads should be applied in combinations of worst-case scenarios for the locations of the loads. Lateral loads due to environmental conditions may be developed in conjunction with other analyses. Load combinations may be derived by superposition of the individual loading effects at each structure component.

8.3.3.1.3 Contingency and an allowance for future growth should be included in all loads. Contingency, with the exception of riser contingency, is considered a permanent load since it represents potential increases of fixed equipment. All allowances for growth should be included in the design loads.

8.3.3.1.4 Loads resulting from construction, transportation, and installation should be considered in the design and are further defined in Section 14.

8.3.3.1.5 The loads in 8.3.3.2 through 8.3.3.19 should be considered as a minimum.

8.3.3.2 Permanent Loads

Permanent loads are the fixed gravitational loads that can be varied only by major alterations to the structure and/or the installed equipment. They include the weight in air of the entire structure and associated equipment and machinery, fixed packages and modules, and all piping and electrical distribution systems.

8.3.3.3 Variable loads

Variable loads represent the weights and positions of variable items required for each operation performed on the platform. These loads include, but are not limited to the following:

a) self weight of the riser tensioner units and the riser pretension,

b) export risers and flowline loads,

c) ballast required to trim the platform for each operating case, and

d) fluids for drilling and production operations.

Drilling loads, such as drill pipe, hook, setback, etc. and consumables, personnel, and spares would also be included in this category.

8.3.3.4 Hydrostatic Loads

Hydrostatic loads represent the buoyancy of the hull and the associated static forces due to pressure on the hull at the specific drafts.

8.3.3.5 Open Area Live Loads

Uniform area loads may be prescribed for all areas that do not have specific loading requirements. Typically, these areas are walkways, landings, lower deck equipment space, ladders, stairways, and ladder rungs. These area loads may be used to size local deck framing and will generally not be included in the global analysis.

Generally open area live loads are not included in the weight budget estimates, but should be considered in the structural analysis. Consideration should be given for the appropriate “knock down factor” for the open area live loads. For the overall analysis of the hull and deck, a reduction in the open area live loads may be appropriate considering that 100 % of the load will not be on the structure at the same time. These knock down factors will vary depending on the area of the structure to be evaluated from 100 % for the local design of the tertiary structure to 0 % for global analysis of the hull and deck. The global weight database should include all components which may compose the live load.

8.3.3.6 Platform Cranes

Design loads and moments for local structural framing in the vicinity of platform cranes may be twice the maximum rated capacity of the crane. Movement of the crane may also result in significant fatigue loads in the crane pedestal. Typically on TLPs, the cranes have long booms and the boom weight is a significant portion of the design pedestal moments. As the crane rotates without load this high boom weight adds significantly to the fatigue stress of the pedestal. It is recommended that for large boom cranes the additional cycles for the boom rotation be added to the working load cycles in API 2A-WSD for fatigue calculations. See API 2A-WSD and API 2C for additional design considerations.

8.3.3.7 Drilling Rig

Variability of the drilling rig substructure and skid base should be adequately addressed in the structure design. Location of the rig over a range of well slots will have an impact on the deck structure design, as well as on the global system requirements, as a result of the rig CG changes and changes in the rig wind loads and moments. Drilling rig structure design and applied loads from drilling rigs should meet TLP design criteria. See API 4F for additional design considerations.

8.3.3.8 Local Design Loads

Maximum support reactions during loadout and transportation and maximum reactions for modules, utility cranes, snubber units, and other equipments may be utilized to size local structural supports. These reactions shall be selected to be the maximum for all conditions including all phases of construction and operations.

8.3.3.9 Wind Loads

Lateral and overturning moments due to local wind loads for each component should be applied to the structural model at the components support points for each approach direction. Loads associated with the three-second gust should be used for extreme conditions to ensure that local framing in the structure is appropriately sized. For a large deck, the one-minute wind should be used for the overall design of the deck primary structure and the overall global structural analysis of the deck and hull should use the one-hour wind. The stresses associated with gust loading should be combined with stresses due to global deformations of the system due to wave and current loading, but should not be combined with global deformations due to other sustained wind loading. Global wind loads will have an impact on the system structural performance.

8.3.3.10 Wave and Current Loads

8.3.3.10.1 Distributed wave loads may be calculated based on 3D radiation/diffraction theory. Local wave and current drag loads for production risers, catenary risers, pipelines, and appurtenances should be calculated and combined appropriately with static loads for stress checks of the local structures. The maximum lateral and vertical water particle velocities near to the hull structure are generally substantially higher than in an undisturbed wave away from the hull.

8.3.3.10.2 Local design of tertiary and secondary structures and deck modules designed utilizing isolation bearings isolating direct wave loads from the immersed hull are generally designed for the inertial effects only ignoring the effects of the wave loads on the hull.

8.3.3.11 Wind, Current and Wave-drift Load Combination

TLP structures will laterally move (i.e. excursion/offset) due to quasistatic wind, current and wave-drift forces. Such structures shall be analyzed for loading combinations at no offset, minimum, and maximum offset conditions.

8.3.3.12 Zero Offset Condition

The structure and its components shall be analyzed for a combination of functional and environmental loads associated with both the extreme and the routine operating conditions. Applied environmental loads on the structure shall be due to wave alone.

8.3.3.13 Minimum/Maximum Offset Conditions

8.3.3.13.1 The structure and its components shall be analyzed for a combination of functional and environmental loads associated with the extreme condition. Local design of tertiary and secondary structures and deck modules designed utilizing isolation bearings isolating direct wave loads from the immersed hull are generally designed for the inertial effects only ignoring the effects of the wave loads on the hull. Applied environmental loads on the structure shall be due to wave, current and wind.

8.3.3.13.2 Applied stresses used in design shall be compatible with the maximum offset condition that results in a set-down and an increase in both applied external pressure on hull components and an increase in overall buoyancy and, thereby, tendon tensions.

8.3.3.13.3 For TLPs with integrated hull and deck structures, two drafts should be considered. The first one, the minimum draft determined at the mean offset minus the wave-induced hull motions, generally controls the lower hull structures, since the center of pressure on the columns is nearer the pontoons. The second one, the maximum draft determined at the mean offset plus the wave-induced hull motions, maximizes the loads in the deck.

8.3.3.14 Wave Loads for Appurtenance Design

The calculation of wave loads shall be based on the relative velocity of the member to the water particle, including the effect of platform-induced motions. Wave pressures may be calculated based on a Morrison drag formulation using an appropriate drag coefficient. An example of procedures for such calculations can be found in DNV-RP-C205.

Impact loads due to wave slamming need to be properly checked. Since wave impact is an impulse loading, a dynamic amplification factor of at least 2.0 should be used, unless an analysis, which considers the duration of the impulse loading and natural frequency of the structure, demonstrates that a lesser value is appropriate. Impact loads determined from appropriate model tests may also be used.

8.3.3.15 Hull Compartment Loads

Watertight plating in the hull will be subjected to loads resulting from the type of compartmentation on either side of the structure including ballast, void, and storage tanks. The most critical combinations of the above tank load conditions and hull external pressure should be investigated. Additional information is found in ABS 6.

8.3.3.16 Load Combinations for Hull Design

Special load combinations shall be used for hull design where local hydrostatic and hydrodynamic pressures are an important component of the total state of stress. Due to the different nature of internal and external structures, different load cases shall be used for each. Conditions with less than the maximum hydrostatic and hydrodynamic loads on the hull, compatible with maximum tendon loads, should also be considered. Static and dynamic stresses from the global TLP analyses shall be included, where appropriate.

8.3.3.17 Impact Loads Due to Fluid Sloshing

Lateral and angular motions of the TLP will generate wave motions within the ballast tanks in the pontoons and columns. Depending upon the size of the tanks, the amount of water in the tanks, and the motions of the TLP at the resonant sloshing period of the water, local impact loads should be generated. These loads may be significant from a static strength and a fatigue standpoint.

8.3.3.18 Transport Loads

During transport to the installation site, the platform will be subjected to transport loads. Depending upon the location and length of the transport, certain members may experience loads that exceed the in-place design loads. Fatigue during transport should be combined with in-place fatigue when determining allowable fatigue damage.

8.3.3.19 Construction and Installation Loads

Loading conditions during construction and installation should be considered. Provisions for loading during the construction phase are provided in Section 14 and shall be evaluated for acceptance based on the requirements of this section. Additional fatigue checks may be needed if the actual installation period or conditions experienced are substantially different than analyzed in the original design.

8.3.4 Design Loading Conditions, Damaged

8.3.4.1 General

The platform shall be analyzed for several damaged conditions under the extreme environment, reduced extreme and normal environmental conditions as follows.

- The platform shall be analyzed with the normal environment in the damaged condition with no compensating ballast water added. Use Category B safety factors.
- The platform shall be analyzed with the reduced extreme environment after the necessary ballast has been added to equalize tendon loads. Use Category B safety factors.
- At the option of the operator, the platform may be analyzed with the extreme environment after the necessary ballast has been added to equalize tendon loads. Use Category S safety factors.

The loads addressed in 8.3.4.2 through 8.3.4.4 shall be considered as a minimum.

8.3.4.2 Compartment Flooded

The platform shall be analyzed for accidental flooding of the worst hull watertight compartment, or the number of hull compartments that could be flooded by damage 1.5 m (5 ft) deep, 3m (10 ft) high, running from 5 m (16.4 ft) above to 3 m (10 ft) below the still water line, as outlined in 5.4.2 and 5.6.4.3. In addition, damage should be considered up to 5 m (16.4 ft) above the 10-year reduced extreme quasistatic water line. Flooding due to dropped objects or fatigue cracks should also be considered in the TLP design cases.

8.3.4.3 Collisions and Dropped Objects

The design event should include the largest liftable items that may be expected on a repeatable basis. The direct loads and consequential damage due to collisions and dropped objects should not cause complete structural collapse or loss of platform stability. It may not be possible to design the platform to survive a collision with a very large object such as a tanker.

8.3.4.4 Load Combinations for Hull Design

Special load combinations shall be used for hull design where local hydrostatic and hydrodynamic pressures are an important component of the total state of stress. Due to the different nature of internal and external structures, different load cases shall be used for each. Static and dynamic stresses from the global TLP analyses shall be included, where appropriate. Certain hull component designs may be controlled by maximum tendon loads compatible with less than the maximum hydrostatic and hydrodynamic loads on hull components. Such load combinations should not be ignored.

8.3.5 Design Loading Conditions, Tendon Removed

Tendons are designed for the life of the platform. However, tendon disconnection/replacement shall be considered and the platform should be analyzed for removal of one tendon at the most critical location in the reduced extreme environment. This condition is a planned maintenance or construction condition, and would include appropriate ballast to maximize performance in this condition.

8.4 Hydrodynamic Loads for Hull Design

8.4.1 Introduction

8.4.1.1 Some of the most significant environmental loads for TLP design are normally those induced by wave action. The characteristics of waves may be described by deterministic design wave methods or by stochastic methods applying wave energy spectra. Deterministic methods are used when the sea state is represented by regular waves, defined by wave height and wave period. Stochastic methods are used to represent the irregular nature of the sea. The sea state is represented by a wave energy spectrum that is characterized by a significant wave height and peak spectral period.

8.4.1.2 Stochastic methods for the response analysis of a large body marine structure are, in principle, recognized as the best methods for simulating the irregular nature of wave loads. Computer methods for such analysis are today available, and global performance is normally evaluated by stochastic methods. Stochastic stress analyses may also be carried out.

8.4.1.3 For structural design evaluation, however, engineering judgment and knowledge of structural behavior is vital for a sound and optimal structure. For this purpose, stochastic stress results are not well-suited, as simultaneous internal force/moment and stress distribution is lost, making it difficult to optimize the structural design. A regular wave analysis will, however, show the force/moment and stress distribution diagrams and is therefore popular for engineering applications.

8.4.1.4 To satisfy the need for obtaining simultaneous relationship of the response, a design wave approach is often adopted for maximum stress analysis. Using the extreme stochastic values of some relevant characteristic response parameters described in 8.4.3 retains the merits of the stochastic approach. The procedures of development of the stochastic equivalent design wave cases for structural analysis are described in 8.4.4.

8.4.1.5 The effects of column wave run-up, and green water overtopping the column top, and the dynamic loads transmitted by the tendons, such as ringing, springing, and VIVs, shall be analyzed if model test results indicate that such phenomena will occur. The effects of wave inundation shall be included.

8.4.2 Hydrodynamic Pressure Load Generation

8.4.2.1 The wave forces acting on a TLP consist of four components, first-order forces at wave frequencies, second-order forces at frequencies lower than the first-order frequencies, a steady component of the second-order forces, and high-frequency forces due to loads transmitted from the tendons. These tendon loads include ringing and springing loads, VIV-induced loads, changes in pretension due to seafloor slope, differential settlement, and changes in the center of gravity of the TLP.

8.4.2.2 The first-order wave forces are the governing loading for structure design. For hull shapes composed of large members, wave loads are generally calculated with 3D diffraction, integrating the total pressure field on an immersed body. This method is appropriate when the body is large relative to the water motion amplitude and wavelength so that the wave field is modified through diffraction and radiation.

8.4.2.3 For the local tertiary and secondary steel design and the case where the deck modules are isolated from the hull, the actual accelerations associated with these hydrodynamic loads are required for structural design. In these cases, the accelerations from the first-order predictions may need to be adjusted for higher-order effects. These accelerations can be taken from the global rigid body analysis. For integrated decks, the first-order effects included in the diffraction analysis are sufficient since the primary loads are from the dynamic pressures on the hull.

8.4.2.4 Wave radiation/diffraction solutions do not include viscous forces. When body members are relatively slender or have sharp edges, viscous effects may be important and wave load may be expressed as the sum of a drag force and an inertia force. Morison’s equation is an empirical formula for calculating forces on a member for a given water velocity and acceleration condition. It is based on the assumption that the presence of the member does not appreciably alter the waveform.

8.4.2.5 The dynamic pressure at a point on the immersed surface of a structure is expressed as the superposition of the pressure associated with the following:

- incident and scattered waves;
- six degrees-of-freedom radiation potential due to the motion of the structure in still water;
- the varying hydrostatic pressure due to heave, roll and pitch displacement of the structure from its mean position, as well as seafloor settlement and other factors which may modify the mean draft;
- variation in the gravitational moment due to pitch and roll displacement.

8.4.2.6 In addition to dynamic pressure, hydrostatic head on each submerged structural member is the main contribution to the total loading on the structure. The total pressure acting on the immersed surface is written as:

$$P = P_s + P_d \tag{31}$$

where

P_s is the hydrostatic head associated with the mean position of the structure;

P_d is the dynamic pressure including the variation of the hydrostatic pressure on the immersed surface due to the vertical displacement of the point and the water surface.

P_s is calculated as follows:

$$P_s = \rho_w\, g\, (z + t) \tag{32}$$

where:

ρ_w is the unit mass of seawater;

g is the acceleration of gravity;

z is the vertical distance from mean water level (MWL) to point of applied pressure (positive down);

t is the height of tide above MWL.

8.4.3 Characteristic Global Hydrodynamic Loads/Responses

8.4.3.1 General

Characteristics loads discussed in this section primarily refer to a typical TLP configuration consisting of multiple columns, pontoons, and integrated decks. For other configurations, critical maximum loads compatible with each configuration shall be determined.

Characteristic loads and the associated specifications are different for different hull configurations and shall be verified to be appropriate as outlined in 8.4.4. Typical characteristic loads are provided below and any combination will generally provide the desired maximum stress as prescribed in 8.4.4. Additional guidance is provided in ABS 6, DNV-RP-C103, and DNV-OS-C103.

8.4.3.2 Squeeze-pry Loads between Columns

Squeezing and prying action of the hull affect major joints and braces of the hull and the trusses and lateral bracing systems of the decks. A squeeze condition is defined as one where lateral loads from a wave are maximum inward toward the center of the platform, effectively “squeezing” the columns towards each other. A prying condition occurs when the lateral loads act outward away from the platform center, having the opposite effect. The critical value for this response generally occurs with the waves approaching along the platform diagonal axis, with a wavelength slightly more than twice the diagonal column centerline spacing. This response will normally give the maximum moment on the connection between the pontoons (or braces) and columns and the interconnection between the hull and deck. A second important squeeze-pry load case is with beam seas and a wavelength slightly more than twice the column centerline spacing in that direction. This response will normally give the maximum axial force in the transverse horizontal bracing or pontoon members.

8.4.3.3 Torsion Moment About a Transverse Horizontal Axis

The critical value for this response will occur with quartering seas and a wavelength approximately equal to distance between the outer corners of pontoons. This response will normally give the maximum axial force in the diagonal horizontal and vertical bracings.

8.4.3.4 Longitudinal Shear Force Between the Pontoons

The critical value for this response will occur with quartering seas and a wavelength of approximately 1.5 times the distance between the outer corners of the pontoons. This response is normally the governing load case for all horizontal bracings. This response introduces opposite longitudinal displacement for each pontoon, and thus, introduces the bending moment on the pontoons or transverse bracings.

8.4.3.5 Longitudinal Acceleration of Deck Mass

The critical value for this response will occur with head seas. This response introduces:

a) longitudinal racking due to acceleration of the mass in the deck,

b) shear force and corresponding bending moments for the vertical columns, and

c) axial forces in the pontoons or longitudinal diagonal bracings.

8.4.3.6 Transverse Acceleration of Deck Mass

The critical value for this response will occur with beam seas for the transit condition. This response introduces:

a) transverse racking due to acceleration of the mass in the deck,

b) shear force and corresponding bending moments for the vertical columns, and

c) axial forces in the vertical diagonal bracings.

8.4.3.7 Vertical Acceleration of Deck Mass

The critical value for this response will occur with beam and/or head seas for the primary deck structure.

8.4.3.8 Vertical Wave Bending Moment on the Pontoons

The critical value for this response will occur with beam and/or head seas for a wavelength slightly larger than the pontoon length.

8.4.4 Procedures to Determine the Design Wave Cases

A design wave approach is recommended for maximum stress analysis of TLP hulls. This design wave approach preserves the merits of the stochastic approach by using the extreme stochastic values of some characteristic response parameters in the selection of design wave parameters. This approach should be performed for the TLP at “zero” offset and repeated at “maximum” offset with the compatible hull set-down. Multiple drafts at the offset condition may be required to find the appropriate characteristic loads for both the hull and the deck.

The sequence of major steps in this design wave approach is as follows.

1) Select and define the characteristic loads, which are summarized in 8.4.3, and the corresponding wave headings for the specific platform design. This may be developed according to experience gained from a similar structure or experience derived from the stochastic design approach.

2) A series of design waves should be generated for the structure design. In order to develop the design waves, a set of wave frequencies and amplitudes are assembled in order to provide upper bounds to 100-year (or required return period) stresses, as computed by normal techniques. For example, the calibration process usually includes picking wave frequencies that correspond to wavelengths that are equal to one-half of the distance between columns. This results in the maximum prying load.

3) Develop the transfer function of the chosen design characteristic loads.

4) Derive the most probable characteristic loads using the stochastic long-term or short-term response analysis.

5) Calculate the characteristic wavelength (or period) for each of the design wave cases. Normally, the wavelength should correspond to the peak-wave-length or slightly higher. Compare the results by varying the design wavelength, as the one exactly corresponding to the peak-wave-length, in some cases, may yield unreasonably conservative results.

6) Calculate the characteristic wave amplitude. Divide the most probable largest response amplitude by the value of the transfer function corresponding to the selected wavelength (or wave period).

7) Derive the detailed hydrodynamic loads for the selected design wave cases (pairs of characteristic wave amplitude and period). The methods of generating detailed hydrodynamic loads are described in 8.4.2.

8) Each load case corresponding to one wave length (or period) and one wave heading should be calculated at two time instances with the proper phase angles, one may correspond to a wave crest amidships and the other to a wave zero-crossing at the same point. Alternatively, a single wave position, corresponding to the maximum stress, may be used for each element of interest.

8.5 Structural Analysis

8.5.1 General

The basic objective of developing computer models and analyzing these models is to ensure that all structure components are analyzed and designed to have adequate capacity against failure due to both rare extreme loads and the repeated operating loads.

The natural periods referred to in this section are those of the elastic vibration of the platform hull and deck and do not refer to the rigid body periods of the platform and tendon system. The natural periods are expected to be small enough in comparison with periods with significant wave energy that structural dynamics need not be considered. This assumption should be verified for each specific platform design.

Environmental loads applied to the platform are time varying and can be calculated using two different methods, frequency domain or time domain, as described in 7.5 and 7.6 respectively.

8.5.2 Analysis Methods

The platform may be analyzed for the applied loadings using a variety of computational methods such as a plate and beam finite element model or a linear, elastic space frame computer analysis. Detailed finite element analyses may be necessary to more accurately determine the local stress distribution in complex structures. Supplementary manual calculations for members subjected to local loads may be adequate in some cases. If a space frame model is used for hull global strength analysis, detailed finite element analysis should be carried out for complex joints and critical connection areas.

The objective of the analysis is to determine TLP hull and deck stress distributions to preclude component failure. Computer models shall be developed to determine

a) applied excitational loads on the unit and its motions,

b) hull component stresses compatible with excitational and platform inertial loads to be used to determine component strength/buckling adequacy, and

c) peak stresses for both extreme and operating environments to determine adequacy of the components against yielding and fatigue damage.

8.5.3 Modeling

8.5.3.1 Global Space Frame Model

A space frame model generally consists of beam elements, plus other elements needed to model specific structural characteristics. All primary structural elements should be modeled in the space frame analysis. The effects of secondary members (if not included in the space frame model) should be accounted for in detailed local analysis. The effect of joint eccentricities and joint flexibility should be accounted for in the model, as should the in-plane stiffness of the deck plating.

8.5.3.2 Global Finite Element Model

A global finite element model generally consists of plate elements to model the major hull structural elements, including the outer shell, bulkheads, and flats. Beam elements, in combination with plate elements for stiffened plate structures within the deck, are typically used to model the deck. Other elements may be incorporated to model specific structural characteristics. The global stiffness should be adequately modeled. Beam elements are suitable only for members having small cross-sectional dimensions compared to their length.

8.5.3.3 Detailed Finite Element Models

Finite element analysis is recommended for complex joints and other complicated substructures to determine local stress distributions more accurately and to verify the stiffness of the space frame model. The loads applied to the detailed finite element models should come from the global finite element analysis or space frame analysis and from local loads acting on the structure. Columns and pontoons with complex stiffeners, flats, or bulkheads will require finite element analysis unless manual calculations are sufficient to accurately determine stress distributions.

8.5.3.4 Manual Calculations

Manual calculations may be performed where a detailed finite element analysis is not needed, and may use empirical formulas or basic engineering principles. The loads used for these calculations should come from the global space frame analysis and from local loads acting on the structure.

8.5.3.5 Peak Stresses (Stress Concentration Factors)

Peak stresses are determined to obtain the peak-to-nominal stress ratio (i.e. stress concentration factor) to assess fatigue lives. Stress concentration factors shall be used, where appropriate, to be utilized in fatigue analyses. The stress concentration factors should be determined by detailed finite element analysis, by physical models, by other rational methods of analysis, or by published formulas.

8.5.3.6 Structural Stability Analysis

Formulas for the calculation of both the buckling strength of structural elements (i.e. instability stresses) and applied stresses are presented in API 2A-WSD, API 2U, and API 2V. These documents also provide design guidelines to achieve hierarchical order of instability stresses so that the steel is distributed effectively between the plate and the stiffening system. As an alternative, buckling and postbuckling analyses or model tests of specific shell or plate structures may be performed to determine buckling and ultimate strength loads.

8.5.3.7 Transportation Model

8.5.3.7.1 Dry Transport

The transportation vessel should be modeled in sufficient detail to accurately estimate the motions and hydrodynamic loads for the platform during the dry transportation condition. A simple hydrostatic data computation should be executed to ensure that the hydrostatic data derived from the diffraction model is consistent with the data derived from the stability program.

The transport vessel structural model should be in sufficient detail as well, such that it provides the correct stiffness interaction between the transport vessel and the TLP to correctly include the internal stresses from the deformations of the transport vessel.

8.5.3.7.2 Wet Transport

The TLP should be modeled in sufficient detail to accurately estimate the motions and hydrodynamic loads for the platform during wet tow and platform installation conditions. The TLP hull should be modeled for the following draft variations, as applicable:

a) wet tow draft,

b) float over draft,

c) tendon/hull installation draft,

d) several intermediate drafts.

A thorough verification should be done to ensure that the hydrostatic data derived from the diffraction model are consistent with the data derived from the stability program.

8.5.3.8 Tolerances and Residual Stresses

The model should be revised to determine the effects of fabrication tolerances on residual stresses should the set limits not be met.

8.5.3.9 Pre-service Conditions

8.5.3.9.1 Dry Transportation Analysis

The TLP load-out, float-on, and discharge from the transportation vessel should be analyzed to ensure that these operations can be carried out while maintaining adequate vessel and TLP stability and structural integrity. The ballast arrangement should be developed to ensure that the transportation vessel has adequate longitudinal strength, intact and damaged stability, draft, and freeboard.

Vessel motion analysis may be performed using the frequency-domain approach. Vessel motion and acceleration RAOs may be used to estimate extreme statistical responses for the worst environmental conditions during dry transportation. These results provide the basis to assess the structural integrity of the topsides, hull, and deck structure during the dry transportation condition.

Local wave impact on the TLP and hull submergence/emergence should be considered in the system analysis.

Seafastening loads should be developed for the specific placement of the TLP on the transportation vessel. Care shall be taken to ensure that the combined TLP/vessel model includes a close representation of any planned cribbing elements, so hull stress concentrations are identified. The seafastening forces include the inertial loads due to accelerations, the gravity components due to motions, the loads due to structural flexure, the dynamic wind loads, the nonlinear instantaneous buoyancy loads due to the hull submergence into the waves, and the vertical and horizontal wave slamming loads.

8.5.3.9.2 Wet Transport Analysis

Structural and intact and damaged stability analyses of the wet transport should be performed. Any temporary stability modules installed on the TLP and the associated connection to the TLP hull should be designed to provide adequate strength for the draft, trim, and wind heeling conditions considered in the wet transport stability analyses.

Vessel motion analysis results for the wet tow condition provide the basis to assess the structural integrity of the topsides, hull, and deck structure during the wet-tow phase. The analytical tools used to develop motions during the wet tow should be validated with model test results.

8.5.3.9.3 Platform/Tendon Installation

8.5.3.9.3.1 A platform/tendon installation analysis should be performed to determine the TLP free-floating motions relative to the top of the tendons and the TLP motions while the tendons are “latching down” to the final connection draft, if applicable. The system loads with the tendons “hanging” should also be analyzed, if applicable. The objective is to simulate the TLP and tendon motions and to assess the dynamic tendon loads, including the tendon “snap loads” during this critical stage. Installation of a partial number of tendons should also be considered.

A structural analysis should be performed to evaluate the stresses in the hull and deck structure throughout the platform/tendon installation phase for normal, extreme environmental, and associated damage conditions applicable to the platform/tendon installation operation. Procedures to remove any temporary stability modules should also be analyzed.

8.5.3.9.4 Topsides Integration Analysis

The required analyses for the installation and hookup of topside modules on a floating TLP hull include assessments of the orientation, ballast requirements, stability, hydrostatic, and structural characteristics of the system as the topsides modules are sequentially installed on the hull. This applies to a free-floating TLP hull as well as a preinstalled TLP hull condition.

The required analyses for the installation and hookup of topside modules on an onshore or grounded TLP hull include assessments of the orientation and structural characteristics of the system as the topsides modules are sequentially installed on the hull.

Topside integration structural analyses should be performed to evaluate the stresses in the deck and hull structure throughout the topsides module installation and integration process. For multiple topside module installations, which could result in residual stresses, these residual stresses should be explicitly included in the structural model. Refer to API 2A-WSD for module lift design considerations.

8.5.4 Component Strength/Stability

TLP deck components consist primarily of plate/box girders, WF sections, and small tubular elements. The hull structure primarily consists of complex systems (i.e. both flat plate and cylindrical shell with orthogonal stiffening). Strength and stability of small diameter tubular elements and WF sections can be determined through the use of formulas and tables provided by API 2A-WSD and AISC 360-05, respectively.

Complex systems are redundant in nature and require determination of several instability modes. It is desirable to establish a hierarchical order of instability so that the critical stress (i.e. failure stress) for the least important instability mode (i.e. local instability) is always smaller than the critical stress for the most important instability mode (i.e. general instability). API 2U and API 2V provide guidance for the design and analysis of cylindrical shell and flat plate structures. Commentary to these bulletins present adequate information on the formulations used to determine critical stresses for each instability mode, their comparison with test data to justify their validity. These bulletins also provide guidance on the use of finite element methods compatible with the appropriate use of both applied and instability stresses in determining component adequacy/integrity to resist individual loads and load combinations.

8.5.5 Fatigue Analysis and Design

8.5.5.1 Fatigue Life Requirement

The allowable fatigue life is a function of inspectability, repairability, redundancy, the ability to predict fatigue damage, and the consequences of failure of a structural element. In general, it is recommended that the design fatigue life of each structural element of the platform be at least three times the intended service life of the platform. For critical elements whose failure could be catastrophic and for elements not easily accessible for inspection or repair, use of an additional margin of safety should be considered. For example, critical, noninspectable elements, such as tendon porches, should be designed with a fatigue life at least ten times the intended service life. This corresponds to safety criteria Category C as defined in 5.2. The use of fracture mechanics approach, instead of S-N analysis approach may allow a reduction in the required fatigue life margin. Guidance for the tendon porch fatigue design is further addressed in B.2.

Fatigue should be checked not only at joints, but also at any details with high-stress concentrations, such as doubler plate welds, thickness transitions, etc. Structural details should follow good design practice as described in 8.6. Fatigue life computations should include damage experienced during all phases of the system life, including fabrication, transportation, installation, and operation.

8.5.5.2 Fatigue Loading

Cyclic environmental loads and machinery vibrations acting on the in-place platform can cause fatigue. Transportation and installation can also contribute to fatigue damage. Other sources of fatigue damage are current and VIV contributions.

The main cause of platform fatigue is cyclic wave loading. The wave climate should be derived on the best available basis. The wave environment description can be established from recorded data and/or hindcasts. The wave climate is the aggregate of all sea states expected over the long term, including the heading of the sea state, and may be condensed into discrete sea state blocks. Each sea state block may be characterized by a spectral description. Also refer to 7.9.5 for fatigue due to extreme events.

Stress ranges can be associated with the sea state description. Histories of cyclic stresses due to other types of loads should be calculated and included with the wave induced stresses for the fatigue analysis.

An analysis should be performed to obtain stresses for each wave frequency applied to the structure. An inertial load set corresponding to platform motions should always be included. Structural vibration dynamic effects should be taken into account when it is believed that they make a significant contribution to the response of the structure. The short-term stress response and number of wave cycles can be developed for each sea state.

Fatigue is a localized problem; therefore, detailed structural models of complex joints and other complicated structures may be needed to develop local stress distributions.

8.5.5.3 Fatigue Analysis

8.5.5.3.1 General

Fatigue life estimates are made by comparing the long-term cyclic loading in a structural detail with the resistance of that detail to fatigue damage. Two different approaches have been developed for determining fatigue damage:

- the S-N approach,
- the fracture mechanics approach.

8.5.5.3.2 S-N Approach

The S-N approach uses an S-N curve, which gives the number of cycles to failure for a specific structural detail or material as a function of constant stress range, based on the results of experiments.

The damage ratio is the ratio of the actual number of cycles to the available number of cycles using some fatigue curve for a particular stress level. Miner's rule may be used to add damage from each stress level.

Fatigue curves other than suggested by API 2A-WSD may be used if used in an appropriate manner (e.g. BS 7608). For example, “in air” fatigue curves may be used if the inside and outside surface is protected with thermal spray aluminum or other appropriate sealing methods. Misalignment and the effects of weld grinding should also be considered in selecting a fatigue curve.

The long-term stress distribution is used to calculate the cumulative fatigue damage ratio, D_x, as shown in Equation (33).

$$D_\text{x} = \sum \frac{n_i}{N_i} \tag{33}$$

where

n_i is the number of cycles within stress range interval i;

N_i is the number of cycles to failure at stress range i as given by the appropriate S-N curve;

D_x is the damage ratio for each phase of the system life.

It is suggested that Equation (34) be applied to the combined effect of damage.

$$D = \sum F_x D_\text{x} \tag{34}$$

where

D is the total damage ratio evaluated for the service (design) life of the structural component considered. D should not exceed unity for the design fatigue life;

F_x is the factor of safety for a specific phase, i.e. transportation, installation, or in-service phase, during its service life (e.g. 20 years);

D_x is calculated damage ratio for a specific phase, i.e. transportation, installation, in-service phase, during its service life (e.g. 20 years).

8.5.5.3.3 Fracture Mechanics Approach

The fracture mechanics approach can be used to predict the growth rate of a fatigue crack and the crack length at which failure will occur, thus giving the fatigue life. The fatigue strength of a particular model being analyzed can be calculated using the Paris law expression:

$$\frac{da}{dN} = C\left(\Delta \text{K}\right)^m \tag{35}$$

where

da/dN is the crack growth rate;

K is the range of stress intensity factor occurring at the crack tip;

C and m are constants for a particular material, loading, and environmental condition.

These material constants depend on material, structural, and environmental conditions. By integration and proper calculation for ΔK, a relationship can be established between the cyclic stress and the number of cycles to failure taking into account initial defect sizes and material toughness.

This method can also be used to help establish inspection intervals by predicting the time necessary for a crack to grow from an undetectable size to failure. Fracture mechanics analysis can be used to determine required material toughness, maximum allowable initial flaw size (for in place inspection), and inspection intervals.

Any fatigue analysis should account for material properties in seawater or air, frequency of loading, ratio of minimum to maximum stresses (including any residual weld stresses), temperature, level of oxygenation, and cathodic protection effects.

Refer to API 2A-WSD for a more detailed discussion of fatigue analysis techniques.

8.6 Structural Design

8.6.1 Design Basis

The design basis adopted in this publication is the working stress design method, whereby stresses in all components of the structure are not allowed to exceed specified values. Design guidelines and detailed design algorithms to be used in determining ultimate stresses for each instability mode and the applied stresses are presented in API 2U and API 2V.

The structural components of the deck and hull should be designed in accordance with the applicable provisions of API 2A-WSD, AISC 360-05 and API 2U and API 2V. In general, cylindrical shell elements should be designed in accordance with API 2U, flat plate elements in accordance with API 2V, and all other structural elements in accordance with API 2A-WSD or AISC 360-05 as applicable. Applicable class society codes may be used for buckling design.

In cases where the structure's configuration or loading condition is not specifically addressed in API 2A-WSD, AlSC 360-05, and API 2U and API 2V, other accepted codes of practice can be used as a design basis. Where alternative codes are followed, the designer shall ensure that the safety levels and design philosophy provided in this publication are adequately met.

In API 2A-WSD and AISC 360-05, allowable stress values are expressed in most cases as a fraction of the yield stress or the buckling stress.

In API 2U, allowable stress values are expressed in terms of critical buckling stresses.

In API 2V, the allowable stresses are classified in terms of limit states. Two basic limit states are considered: ultimate limit states and serviceability limit states. Ultimate limit states are associated with the failure of the structure. Serviceability limit states, such as material yield, local buckling, excessive deformations, etc., are associated with the adequacy of the design to meet its functional requirements. While an ultimate limit state, if reached, leads to structural failure, reaching the serviceability limit state implies that the structure's ability to serve its intended purpose has been impaired, but the structure is still capable of carrying additional loads before reaching an ultimate limit state.

Careful selection of the overall structure configuration, the layout of its members, the degree of redundancy, the availability of alternate load paths, and the adequate design of foundation and support conditions shall avoid the loss of equilibrium of a part or the whole structure. Design judgment shall be used to ensure that the possibility of this type of failure is minimized.

8.6.2 Allowable Stresses

For structural elements designed in accordance with API 2A-WSD or AISC 360-05, the safety factors recommended in API 2A-WSD and AISC 360-05 should be used for normal design conditions associated with Safety Criteria A. For extreme design conditions associated with Safety Criteria B, the allowable stresses may be increased by one-third.

The safety factors for structural elements designed in accordance API 2U and API 2V, are provided in the respective documents.

For shell structures designed in accordance with API 2U, a factor of safety equal to 1.67ψ is recommended for all buckling modes for safety criteria A. For Safety Criteria B, the corresponding factor of safety is equal to 1.25ψ. The parameter ψ varies with the buckling stress and is defined in API 2U. It is equal to 1.2 for elastic buckling stresses below the proportional limit and reduces for inelastic buckling from 1.2 at the proportional limit to 1.0 when the buckling stress is equal to the yield stress.

For flat plate structures designed in accordance with API 2V, the allowable stress depends on the limit state under consideration (ultimate or serviceability). For each limit state, the allowable stress is obtained by dividing the limit state stress by an appropriate factor of safety. Factors of safety for different service conditions and limit states are shown in Table 7.

The parameter ψ is dependent on the buckling stress and is defined in API 2V. The value of ψ is 1.20 when the buckling stress is elastic, 1.00 when buckling stress equals the yield stress, and varies linearly between these limits.

Table 7—Allowable Stress Safety Factors

Safety Criteria	Factor of Safety	
	Serviceability	Ultimate
A	1.67	1.67 ψ
B	1.25	1.25 ψ

If both limit states are checked, the lower of the two allowable stress values should be used. In the case of serviceability limit states associated with deformation, the allowable deformation criteria are defined in API 2V.

8.6.3 Design of Deck Structure

The design of the deck structure should conform to the provisions of API 2A-WSD, AISC 360-05 and API 2V.

The design of stiffened flat panels and grillages should comply with the provisions in API 2V. Deep plate girders should be designed to AISC 360-05.

API 2A-WSD and AISC 360-05 should be used for the design of truss elements, rolled beams, shallow plate girders, and built up members such as open box type beams.

Alternate rational methods may be used where necessary.

8.6.4 Design of Hull Structure

The design of the hull structure components should comply with the applicable provisions of API 2A-WSD, AISC 360-05 and API 2U and API 2V. The design of circular cylindrical columns and pontoons should comply with the provisions in API 2U. The design of stiffened and unstiffened tubular braces against local buckling should comply with the provisions of API 2U. For other design considerations, the applicable provisions of API 2A-WSD and AISC 360-05 should be used.

The design of stiffened flat plate hull components should comply with the provisions in API 2V.

Alternate rational methods may be used where necessary.

NOTE Class rules, as applicable, may determine scantling requirements.

8.6.5 Design of Nodes and Connections

8.6.5.1 Tubular Joints

The design of small, unstiffened tubular-to-tubular joints should comply with the provisions of API 2A-WSD.

Tubular-to-wide-flange, wide-flange-to-tubular, and wide-flange-to-wide-flange stiffened joints should comply with the provisions of AISC 360-05.

Complex intersections should be verified by finite element analyses.

Stiffened tubular joints should be designed according to 8.6.5.2.

8.6.5.2 Pontoon-to-Column and Deck-to-Column Joints

Joint designs should be checked by using a finite element analysis to determine the load path through the joint. Joints should be designed to provide a continuous transfer of loads from the pontoons and decks through the columns. Primary stresses in the joint shell and internal stiffening may be compared to the limit state strength formulas for curved and flat structural elements. Tensile limit states should be checked to guard against fracture of node material or welds. Model tests may be useful to determine the stress distribution in complex joint geometries.

Cast insert pieces may be used to reduce stress concentrations at these joints.

8.6.5.3 Transition Joints and Stiffened Plate Intersections

The same general principles described in 8.6.5.2 apply in the case of transition joints and stiffened plate intersections. Whenever the complexity of the geometry justifies, a finite element analysis should be performed and may be complemented by model testing.

8.6.6 Design of Structural Details

The design of structural details is important for producing a complete structure that will be free of local cracks, buckles, and severe localized corrosion during the life of the platform.

Details and penetrations in main structural members should be checked for compliance with 8.6.2. The platform designer, to ensure that the design has not been compromised, should review the details incorporated in the final construction drawings.

Special consideration should be given to the design of structural details for any top of hull equipment and access structures into the hull such as flush hatches or watertight doors that can experience hydrodynamic and hydrostatic loads, leakage, and corrosion.

Guidance for sizing beam brackets and spacing of panel stiffeners can be found in the rules of the major classification societies such as ABS and DNV.

References SSC 266, SSC 272, and SSC 294 should be consulted by the designer. These references provide some history of service performance of structure on oceangoing ships.

The tendon porch strength design loads are from the global analyses, performed to obtain the maximum tendon loads. Tendon porch fatigue design should also be based on tendon loads, rather than hull global fatigue analyses. Guidance on tendon porch design is further addressed in Annex B.

8.6.7 Design for Accidental Loads

8.6.7.1 General

Structural design should consider the possibility of accidental events. The term “accidental event” is a collective term for exceptional conditions, such as collisions, dropped objects, fire, explosion, or flooding.

8.6.7.2 Design Philosophy

Satisfactory protection against accidental damage can be obtained by a combination of two means:

— low damage probability,

— acceptable damage consequences.

8.6.7.3 Energy Absorption Capability

The structure should behave in a ductile manner to absorb energy caused by impact loads. Measures to obtain adequate ductility are:

a) make the strength of connections greater than the strength of the members;

b) provide redundancy in the structure, so that alternate load redistribution paths may be developed;

c) avoid dependence on energy absorption in slender struts with a limited degree of postbuckling reserve strength;

d) avoid pronounced weak sections and abrupt changes in strength or stiffness;

e) use materials that are ductile in the operating temperature range.

8.6.7.4 Damage Tolerance

A damaged platform should resist functional and reduced extreme environmental loads (see 5.6). This implies that the platform should maintain its structural integrity and be stable with no immediate need for conducting repairs. The residual strength of a damaged member may be included provided its magnitude can be assessed by rational analysis or tests. If such residual member strength is not proven, damaged members should not be considered effective.

8.7 Fabrication Tolerances

Guidance on fabrication tolerances is given in Section 14. Any change in these tolerances as a consequence of specific fabrication methods should be considered in the design. Structural configuration and details should be developed to avoid fabrication complications so that tolerance requirements can be achieved and the residual stresses limited.

8.8 Structural Materials

8.8.1 General

8.8.1.1 Purpose and Scope

The purpose of this section is to define materials appropriate for use in design and construction of TLPs. Material selection should be done in conjunction with consistent requirements for performance, welding and inspection. Steels are covered in some depth; cement grout, concrete, and elastomers are discussed in less detail. Fracture and fatigue considerations are indicated for all critical components with yield strength of 50 ksi (345 MPa) or greater. Also refer to API 2A-WSD.

8.8.1.2 Specifications

Steel should conform to a definite specification and to the minimum strength level, group, and class in accordance with the design. In situations where an appropriate ASTM, API, or class society specification does not exist, a material specification should be developed, subject to reproduction qualification (see API 2Z) and used as appropriate for each situation.

Certified mill test reports or certified reports of tests made by the fabricator or a testing laboratory in accordance with ASTM A6, ASTM A450, or equivalent constitutes evidence of conformity with the specification.

8.8.2 Manufactured Steel

8.8.2.1 Structural Shape and Plate Specifications

Unless otherwise specified by the designer, structural shapes and plates should conform to one of the specifications listed in API 2A-WSD, Table 8.2.1-1. Steels above the thickness limits stated may be used, provided applicable provisions are considered by the designer. In situations where an appropriate ASTM or API specification does not exist, a materials specification should be developed, qualified, and used for each situation.

8.8.2.2 Structural Steel Pipe

8.8.2.2.1 Specifications

Unless otherwise specified, seamless or welded pipe should conform to one of the specifications listed in the in API 2A-WSD, Table 8.2.1-1.

Structural pipe should be fabricated in accordance with API 2B, ASTM A139, ASTM A381, or ASTM A671 using grades of structural plate listed in the API 2A-WSD, Table 8.1.4-1, except that hydrostatic testing may be omitted. Refer to API 2A-WSD.

8.8.2.2.2 Selection for Service

Consideration should be given to the selection of steels with toughness characteristics suitable for the conditions of service. For tubes cold formed to D/t less than 30, and not subsequently heat treated, due allowance should be made for possible degradation of notch toughness, e.g. by specifying a higher class of steel or by specifying notch toughness tests run at reduced temperature.

8.8.2.2.3 Steel Forgings and Castings

In situations where an appropriate ASTM specification does not exist, a detailed specification should be developed and qualified for the specific application. Certified mill test reports and mechanical property tests should be in conformance with the appropriate ASTM A6 or ASTM A370 specifications.

8.8.3 Special Applications for Steel

8.8.3.1 Tubular Nodes

Welded tubular joint intersections are subject to local stress concentrations that may lead to local yielding and plastic strains at the design load. During the service life, cyclic loading may initiate fatigue cracks, making additional demands on the ductility of the steel, particularly under dynamic loads. These demands are particularly severe in heavy wall joint cans designed for high brace loads.

8.8.3.2 Underwater Joints

Group I and Group II steels for underwater joints, such as tubular joint cans or through members in overlapping joints, should meet the criteria provided in API 2A-WSD. Guidance on toughness selection for Group III and Group IV steels is given in 8.8.4.

8.8.3.3 Abovewater Joints

For abovewater joints exposed to lower temperatures and possible impact from boats or dropped objects and for critical connections at any location in which brittle fractures are to be prevented, the tougher Class A steels should be considered, e.g. API 2H. Special attention should be given in developing welding procedures for higher strength steels to ensure that the required mechanical and toughness properties are maintained throughout the welded joint. Additional guidance for Group III and Group IV steels is given in 8.8.4.

8.8.3.4 Brace End

Although the brace ends at tubular connections are also subject to stress concentration, the conditions of service are not quite as severe as for joint cans. For critical braces, for which brittle fracture would be catastrophic, consideration should be given to the use of stub ends in the braces having the same class as the joint can, or one class lower. Similar considerations may apply where stress risers are encountered along the member between joints.

8.8.3.5 Critical Joints and Plate Intersections

Joints formed by the intersection of stiffened plates may form areas of high restraint, through-thickness shrinkage strains, and high residual stresses and may be subjected to through-thickness tensile loads in-service. Special care should be given to the design of stiffened intersections or terminations to minimize or avoid the formation of stress intensifiers, notches, etc. For these and other highly restrained critical joints, consideration should be given to the use of castings, forgings, or steel having improved through-thickness (Z-direction) properties.

8.8.4 Fracture and Fatigue Considerations

8.8.4.1 Group I and Group II Steels

The recommendations in API 2A-WSD should be followed for these steels.

8.8.4.2 Group III and Group IV Steels

The operator should select materials and fabrication processes that lead to adequate levels of toughness and fatigue properties under service conditions. Fatigue properties of tendon materials should be defined with appropriate mean tensile stress.

8.8.4.3 Toughness Testing

8.8.4.3.1 General

The materials and fabrication methods used should have sufficient toughness to avoid brittle failure. For Group I and II materials, this can be achieved by specification of Charpy V-notch toughness requirements at prescribed temperatures. Steel with increased thickness or increased strength may require alternate means for assessing toughness requirements.

8.8.4.3.2 Crack Tip Opening Displacement (CTOD)

Testing together with rational target toughness values may be used. This approach involves testing of specimens of full thickness in the parent plate, heat affected zone (HAZ) and weld metal. The target value of CTOD should ensure that readily detectable (and rejectable) fabrication flaws will not propagate unstably under service conditions. Effects of stress (or strain) concentration, residual stress, and loading rate should be incorporated into the selection of target values. See API 2Z for prequalification requirements for CTOD-qualified steels.

Application specific threshold thicknesses for requiring CTOD properties and the target levels should be selected by the designer.

Charpy V-notch impact values achieved on procedures passing the CTOD requirements can be used as a quality control indicator in production plate testing and routine qualifications.

8.8.4.4 Fatigue Resistance

This publication recommends fatigue analysis based either on the Palmgren-Miner S-N approach or the fracture mechanics approach. API 2A-WSD provides recommended fatigue S-N curves that may be applied when utilizing materials specified therein. However, when moving to higher strength material it is recommended that sound justification be established before accepting an S-N curve for design purposes. Such curves should be based on tests carried out on specimens of the appropriate material having microstructures and weld profiles or notch effects (where appropriate) that model the general characteristics to be found in prototype components. Testing should be carried out under conditions consistent with the actual prototype operating environment with respect to loading frequency, area of application (in air, splash zone, submerged), level of cathodic protection, temperature, bioorganic environment, and stress level. Curves should cover the range of variables where they have significance to design.

The fracture mechanics approach to fatigue analysis should have reliable and pertinent fatigue crack growth data. As with S-N curves, the data should be gathered from the tests appropriate to the design situation on specimens having similar

- material chemistry and microstructure,
- environment,
- loading frequency,
- cathodic protection,
- temperature, and
- mean stress.

In particular, data should be collected at cyclic stress intensity levels pertinent to design. Testing should be carried out on specimens with known KI calibrations. Standard compact and three-point bend specimens should be considered.

8.8.5 Structural Welding

8.8.5.1 General

Welding should be done in accordance with applicable provisions of API 2A-WSD, the AWS D1.1, and other applicable AWS documents, and shall be consistent with the requirements in 8.8.4 and the general provisions in Section 14. Supplementary requirements, as outlined in these codes and otherwise, shall be specified for the effects of dynamic loading on the structural welding requirements.

8.8.5.2 Inspection

The degree of inspection required should be specified by the designers to be consistent with service requirements and material selection. As a minimum, inspection requirements of welded joints should conform to the appropriate requirements of Section 14, API 2A-WSD, and AWS D1.1. Supplementary requirements for inspection, as outlined in these codes and otherwise, shall be specified for the effects of dynamic loading on the structural requirements. Every effort during design should be made to ensure that all welds are easily inspectable. Welds that are difficult to inspect may have been as difficult to weld properly. The use of 3D modeling in the design phase is recommended for this review.

8.8.6 Elastomeric Materials

Deck structures may be designed as structurally independent modules supported by elastomeric bearing pads. These pads effectively isolate the deck modules from wave loads acting on the hull while adequately restraining the modules from platform lateral accelerations and wind loads.

Elastomeric bearings should function normally while experiencing design vertical and horizontal loads simultaneously. Bearing design should include rotations due to all applicable service loads and movements, maximum rotations caused by fabrication and installation tolerances, and allowances for uncertainty. Special consideration should be given for tension conditions since bearings are free to separate under tension loads. Tensions ties that do not restrict the movements and rotations should be added for tension conditions. Local damage without catastrophic failure may be acceptable for certain survival loading conditions.

Steel rotational elements (e.g. pots and pistons) should be machined from single pieces of steel. The pot should be deep enough to permit the seal and piston rim to remain in full contact with the vertical face of the pot wall under all design loads, movements, and rotations. Contact between metal components shall not prevent further displacements or rotation. The pot walls should be designed to withstand both the internal pressures caused by vertical loads (considering the elastomer behaves as a fluid) and horizontal loads.

Guide bars for directional bearing pads should be welded to the slide plates. Bolted connection should not be permitted. Guide bars should be designed to the specified horizontal loads, but not less than 10% of the vertical capacity of the bearing. Guided bearing pads should have their contact area within the guide bars for all operating conditions.

Elastomeric pads (typically neoprene) should be individually molded in one piece. The elastomer should be plain and not laminated or fiber reinforced. No layering or stacking should be permitted. Cuts, gouges, or nicks from machine cutting or flash trimming are cause for rejection. Sealing grooves should be molded integral to the pad and should be square to the pad top surface.

Each elastomeric bearing should be sampled, tested, and inspected to determine the following.

a) The bearing should be loaded to 100 % of its design vertical load and simultaneously cycled to its design displacement by means of a horizontally placed actuator. Coefficient of friction values should be determined from measurements taken on the first and last cycles.

b) The bearing should be cycled between 50 % and 150 % of its design vertical load while simultaneously under maximum design rotation. The bearing should then be loaded to 150 % of its design vertical load and held for a duration of at least 30 minutes. The bearing should be inspected for evidence of proper elastomer performance (e.g. no leakage). The bearing should be disassembled after the test for inspection of all inner components.

c) The bearing should be loaded to 100 % of its design vertical load and 125 % of its design horizontal load. Guided bearings should be loaded such that the guide bar is situated perpendicular to the direction of load application. The bearing and guide bar should be inspected for proper performance. The bearing should be disassembled for inspection of the pot wall and piston face.

d) Installation procedures should include an allowance for tops of columns being slightly out of level and flatness. This may be compensated by injecting epoxy between the bottom plate of the elastomeric bearing and the top of column.

9 Tendon System Design

9.1 General

9.1.1 Purpose and Scope

This section addresses the analysis and design of TLP tendon systems. Discussions of fabrication, transportation, installation, materials, inspection, maintenance, and operational considerations are included. The tendon system consists of the entire vertical mooring system between (and including) the top connection to the platform and the bottom connection to the foundation.

Determination of tendon tensile loads induced by platform motions is addressed in Section 7 with references and further description in this section. Determination of tendon bending loads induced by platform motions and by direct hydrodynamic forces is addressed in this section. Additional information on tendon system design can be found in Annex C.

9.1.2 Description of Tendons

An individual tendon is composed of three major parts: an interface at the platform, an interface at the seafloor, and a main body that links between the two. Each part may contain several components, with each component taking a variety of forms depending on the specific design. Specific designs may require individual pieces of equipment for each function or combine two or more functions into one unit. The functions of the three major parts are described below:

9.1.2.1 Platform Interface

Components at the platform interface shall perform the following functions:

a) apply and adjust a prescribed level of pretension to the top of a tendon,

b) connect a tensioned tendon to the platform,

c) react lateral loads and control the bending stresses of a tensioned tendon.

9.1.2.2 Foundation Interface

Components at the seafloor interface shall perform the following functions:

a) provide a structural connection between the tendon and foundation,

b) react side loads and control the bending stresses of a tensioned tendon.

9.1.2.3 Main Body

The main body of a tendon may take a variety of forms including tubulars; solid rods or bar shapes; stranded construction such as parallel or helical wire rope; or any other configuration that meets the tendon service requirements. In the case of tubular tendons, the bore may be considered for use in routing umbilicals between the seafloor and surface, or as a fluid flow conduit.

To date, steel tubulars have been the preferred material for tendons. Nonmetallic materials and composites, such as aramid or graphite fibers in a composite matrix, have been proposed and may be considered as a tendon material.

Regardless of material or configuration, all tendons will have top and bottom terminations. In most cases, tendons will have intermediate connections along their length. Tendon connections may take the form of mechanical couplings (threads, clamps, bolted flange, etc.), girth welded joints, or any other type of structural connection meeting the service requirements.

9.1.2.4 Specialized Components

The tendon design may incorporate specialized components, such as the following:

a) corrosion protection system components, which may include coatings, sacrificial anodes, elements of an impressed current system, or combinations of any of these;

b) buoyancy devices such as air cans or foam modules to offset a portion of the tendon's submerged weight;

c) devices intended to suppress vortex induced vibrations and/or reduce hydrodynamic drag;

d) sensors, tattletales, or other forms of instrumentation intended to provide information about the performance or condition of the tendons;

e) auxiliary lines, umbilicals, or similar conduits, for tendon service requirements, or for some function not related to the tendons;

f) ancillary parts for the tendons to be used as guidance structures for running other tendons, or equipment packages to be used in support of other operations;

g) elastomeric elements, as described in 9.3.4.

9.2 General Design

9.2.1 Tendon Removal

Tendons may be designed either to be permanent or to be removable for maintenance and/or inspection. Regardless of whether the tendon is permanent or not, the tendon system should be designed for the possibility of one tendon removed. The allowable stresses recommended in 9.6 should not be exceeded when one tendon is missing. An appropriate environmental condition should be selected taking into account the expected frequency of tendon removal and the length of time for which one tendon is likely to be out of service.

9.2.2 Service Life

The tendon system should have a specified service life. The nominal tendon life should meet or exceed the design life of the platform. Cost or risk incentives may extend or shorten the tendon design service life criteria depending on factors such as initial tendon cost; the cost of tendon replacement; the ability to inspect the tendon in-place; and the risks associated with tendon retrieval and reinstallation.

9.2.3 Design Procedure

A tendon design procedure should be developed to ensure that a tendon system satisfies operational, installation, material, inspection, stress and fatigue requirements. An example of these steps is shown in the form of a flow chart in Figure 10. In general, the sequence of major activities in the design process is as follows.

a) Platform Sizing—Determine overall TLP configuration.

b) Preliminary Tendon Design—Estimate pretension and other input required for platform sizing.

c) Coupled Analysis Check—Determine whether a coupled response analysis is necessary.

d) Response Analysis—Develop vessel motions and maximum and minimum tendon loads.

e) Tendon Horizontal Response—Calculate tendon bending loads and horizontal motions.

f) Minimum Tension—Establish minimum allowable tendon tension.

g) Preliminary Stress Analysis—Check preliminary maximum stress level, fatigue life, and hydrostatic collapse.

h) Operational Limits Check—Check for acceptable vessel offsets, tendon motions and displacements.

i) Fatigue Life—Calculate fatigue life under combined axial and bending loading.

j) Final Design Check—Check for maximum stress; minimum tension; fatigue life; fracture mechanics and inspection replacement strategy; hydrostatic collapse; and VIVs.

k) Model Test (Optional)—Verify tendon motions and loads.

Procedures for tendon installation, including special equipment requirements and limiting environmental conditions, shall be developed. These generally follow selection of the final platform and tendon design configurations. Depending on the type of tendon and tendon top attachment, the installation requirements could influence the platform and tendon design. It may be advisable to develop the tendon installation design, including some tendon analysis, in parallel with the platform/tendon design procedure.

The flow chart in Figure 10 illustrates the iterative interaction between the platform sizing, global response analysis (see Section 7) and the tendon design analysis. Tendon loads and maximum angles also influence the design of the foundation (see Section 10).

9.2.4 Design Data Requirements

9.2.4.1 Environmental Data

The tendon loads depend on platform response to wind, waves, current, and tide, and possibly to marine fouling, seismic activity, floating ice, and platform snow or ice accumulation. The extreme environmental conditions as well as other return period conditions might be pertinent for damage conditions, for less than a full complement of tendons, during installation, or for other specified operational events. Wind and wave spectra and directionality data are valuable for assessing tendon fatigue. Current profiles, sea state probabilities, and weather persistence data help establish the design of equipment and the techniques needed for tendon installation and retrieval. Water temperature, salinity, and oxygen content can be used to establish cathodic protection requirements. See 5.5 for a more complete discussion of environmental data requirements.

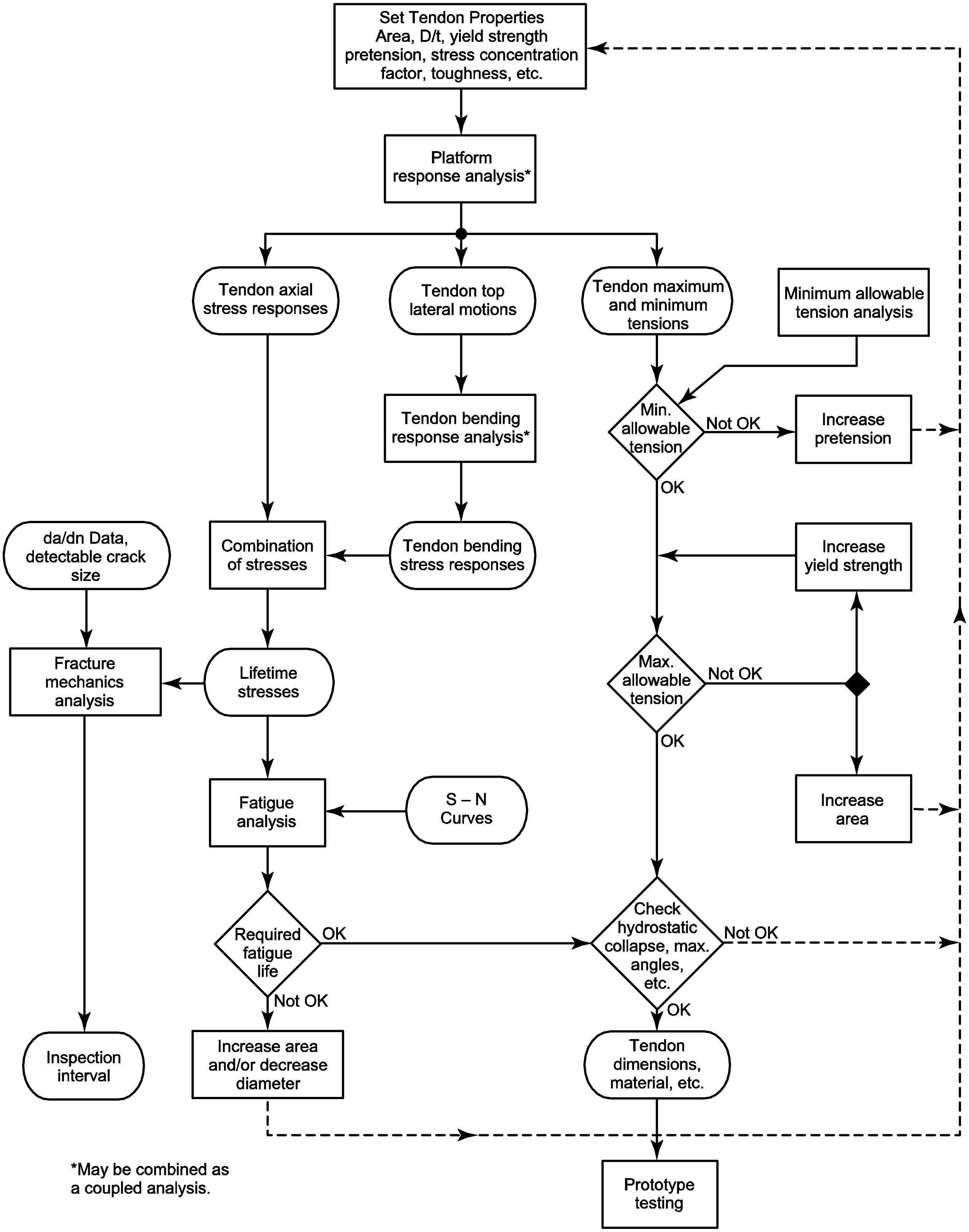


Figure 10—Tendon Design Flow Chart

9.2.4.2 Platform, Tendon, and Foundation Characteristics

The properties of the tendons affect platform displacement and response, and vice versa.

Tendon pretension (tension in still water) is established to satisfy the maximum platform offset limit and to control minimum tendon tension. Tendon pretension has a direct effect on platform displacement and tendon maximum tension.

Tendon cross-sectional area establishes tendon axial stiffness that is a major factor in the platform natural periods of heave, pitch and roll vibration. These periods should be kept low enough to limit fatigue damage due to wave excitation.

The diameter-to-thickness ratio for air-filled tendons is also important because it establishes the tendon weight in water that, in turn, establishes the difference between the top and bottom tensions in the tendons. These tensions influence platform displacement and offset.

The number of tendons, their pattern and their loading also affects the foundation system design. If separate foundations are used, the tendon load is affected by the placement accuracy of the foundation system.

The size of the platform’s columns determines the space available for handling and installing tendons. The number of tendons per corner might be determined in part by this available space. The column structural arrangement should accommodate the localized tendon loads and the possible presence of tendon access tubes.

9.2.4.3 Operating Limits and Other Design Considerations

Other limits that may be imposed on the tendon design include the following.

a) Flexure Limits—The flex element shall accommodate the maximum tendon angles at top and bottom due to platform surge/sway motions.

b) Interference—Interference between tendons and platform or foundation template structure is governed by flex element angle and the height of the flex elements above or below the platform keel or foundation top of steel.

c) Tendon Centerline Spacing—Minimum spacing is set by equipment space requirements, by possible interference among tendons during deployment, by column fabrication space requirements and potentially by tendon foundation interaction. Large spacing may cause differences in loading among tendons at a corner due to pitch/roll platform motions.

9.2.5 Fatigue Design

9.2.5.1 Safety Factors

Tendon fatigue safety factors shall be selected to be commensurate with the service life, in-service inspection plans, analytical methods, quality of data for S-N curves, quality of data for environmental loading, unique properties of the component, or unique characteristics to the anticipated loading.

In general, tendon components that will not be regularly inspected, or for which repair is difficult or impractical, a minimum safety factor of 10 should be applied to the design service life. For components that cannot be inspected, higher safety factors should be considered. For components that will be regularly inspected and are repairable or replaceable, a lower factor of safety may be considered.

Additional guidance on selection of safety factors for specific tendon components is provided in 9.6.

9.2.5.2 Analysis Methods

Methods for estimating fatigue life are covered in 9.6 for each major tendon component.

9.2.5.3 Environmental Conditions

Tendon fatigue analysis is generally conducted by calculating cumulative fatigue damage over all anticipated sea states over the design service life. A scatter diagram of anticipated environments with associated probabilities is typically used.

Care should be taken to appropriately consider unique metocean situations such as sustained currents that may induce VIV of tendons over a sustained period of time, and cyclonic storms that may produce sustained exposure—i.e. where sufficient data is available, hurricanes/typhoons should be directly included in the wave scatter diagram used in fatigue analysis.

9.2.5.4 Single Event Fatigue

In addition to the conventional scatter diagram fatigue life calculation, the tendon components should demonstrate robustness against low-cycle/high-stress fatigue due to more prolonged events that exceed the probabilistic predictions. The intent is to screen for components that may incur excessive fatigue damage in large sea states to the extent that a reasonable exceedence of the scatter diagram predictions can lead to catastrophic failure.

In order to insure a reasonable level of robustness in this regard, tendon fatigue damage should be assessed for all components over the duration of a single event based on the 100-year extreme storm, including the ramp-up and ramp down before and after the storm. The duration to consider is to be determined by the designer based on the data available and the response characteristics of the components. The unfactored damage accumulated during this event should be equal to or less than 0.01.

Other 100-year return period events that may induce substantial tendon fatigue, such as loop currents in the Gulf of Mexico, should also be considered in the same manner.

Damage calculated for single event fatigue should not be added to the damage predicted in the scatter diagram fatigue analysis, nor compared to the associated safety factors. It is intended only as a robustness check. See C.1 for more discussion.

9.2.6 Robustness of Design

Section 5.2.4 describes Safety Category S for survival conditions. Table 1 describes the load cases to which this category should be applied. Section 9.6 gives specific criteria for this safety category with respect to different tendon components.

Meeting these criteria will in principle insure a robust design for components that have nonbrittle failure modes. Material selection and fabrication procedures described in this RP are intended to insure ductile behavior of structural components. For example, tendon pipe should have a very ductile failure mode. So overloading the tendon to or beyond storms associated with Safety Category S should not lead to catastrophic failure.

Some mechanical components can have unusual failure modes for which, going beyond a certain load may cause movement of mechanical pieces, and/or complete or partial disengagement of the component. Care should be taken to prevent such failure modes from occurring in Safety Category S conditions.

An important example of such a component for a TLP is a typical tendon bottom connector, which is designed to connect or disconnect by stroking the tendon downwards beyond the in-service load shoulder. The design should be such that the connector does not disconnect in Safety Category S conditions (see 7.8.16). All components in the tendon string should be examined for robustness of design, with particular attention paid to any interactions. For example, a mechanical latch on the bottom connector to prevent stroke-out could be used to remove the risk of unlatching; however, such a design change may lead to a potential unseating of the tendon top connector, depending on its design.

With regard to potential for unlatching or unseating of various components, a margin of safety should be built into the design to insure against disengagement under Safety Category S conditions. For example, if a bottom connector is allowed to stroke downwards, the length of stroke and the consequences of reloading the connector should be carefully considered to insure a robust design.

Care should be taken in the design of such components to insure that the device will indeed re-engage properly under actual service conditions. Consideration should be given to corrosion and sedimentation and their potential effect on the connector's mechanical performance. Consideration should also be given to the speed at which the mechanical parts are able to move with respect to the movement of the tendon.

Specific measures should be taken to demonstrate the robustness of the design to overload, including prototype testing and analytical modeling as appropriate. Mechanically securing the connector in place may also be considered as a means of ensuring robustness.

Furthermore, a means should be provided for positively verifying that the connector has been properly engaged after tendon installation.

See C.2 for additional information.

9.3 Material Considerations

9.3.1 Purpose and Scope

Tendon systems generally are fabricated from components made from steel pipe, forgings, castings, and elastomeric bearings. A tendon system utilizing a configuration other than steel pipe is not precluded and may offer design advantages in certain situations. Alternate materials may be used provided they are designed with an equivalent philosophy as described in this publication and keeping in mind the critical performance and longevity requirements for tendons.

9.3.2 Overview

9.3.2.1 Initial Material Selection

Materials used for tendon main body sections, connectors and end termination mechanisms are chosen by geometric considerations (e.g. dimensional control relating to collapse resistance), fatigue resistance, fracture toughness, ease of machining, weldability, etc. Material availability (strength, diameter, wall thickness, length, etc.) should be taken into consideration during tendon design so that the resulting design may be practically achieved.

Selection of materials and the tendon fabrication method should be made with consideration of the serial assembly of individual tendons and the need to avoid potential localization of failure in the event of overload.

9.3.2.2 Additional Considerations

Tradeoffs between material selection, fabrication methodology, inspection requirements and long-term installation exposure, should be considered. In-place exposure to seawater may preclude contact of dissimilar metals.

Performance specifications for fabrication, manufacture and inspection of each tendon system component should be developed and implemented to ensure the successful application of prescribed materials. Specifications should be based upon relevant industry standard specifications, with modifications as appropriate to the unique performance requirements of the tendon system.

9.3.2.3 Existing Practice

Typical state-of-the-art tendon systems have incorporated main body sections utilizing UOE pipe (for dimensional control) formed from TMCP steel (for strength and weldability). Pipe grade has ranged from X52 to X70. Forged material selection has been dominated by high strength, high toughness alloys, without requirements for post weld heat treatment, that are compatible with TMCP steel pipe. Forged material yield strength is selected to overmatch the tendon pipe. Cast materials have successfully been used in both tensile and compressive load applications.

9.3.3 Steel Components

9.3.3.1 Specifications

Steel should conform to a definite specification and to a minimum strength level and performance in accordance with the design. In situations where an appropriate ASTM, API or ABS specification does not exist, a materials specification should be developed, subject to preproduction qualification (e.g. refer to API 2Z) and used as appropriate for each situation. Certified mill test reports or certified reports of tests made by the fabricator or a testing laboratory in accordance with ASTM A6, ASTM A450, or equivalent, or as required by design, constitutes evidence of conformity with the specification.

9.3.3.2 Tubular Tendon Materials

Tubular material may be either seamless or welded. Tubular material shall, as a minimum, conform to API 5L, with preference to TMCP formed material. The tendon material should possess optimum mechanical properties including

- tensile and yield strength,
- fatigue strength,
- toughness, and
- ductility.

Material selection should consider design applications such as all-welded tendons; tendons joined by connections integral to the pipe ends; and tendons joined by mechanical connectors welded to the pipe ends.

9.3.3.3 High Strength Steels—Yield Strength 52 ksi to 70 ksi (360 MPa to 480 MPa)

The following considerations should be considered for these steel applications:

a) weldability and special welding procedures that may be required;

b) fatigue problems that may result from the use of higher working stresses;

c) toughness in relation to other elements of fracture control, such as service stress, service temperature and environment;

d) steel cleanliness to ensure the absence of internal discontinuities, whose presence could otherwise give rise to unacceptably short times to crack initiation and growth.

9.3.3.4 High Strength Steels—Yield Strength in Excess of 70 ksi (480 MPa)

Steels in this classification are generally forged materials; quenched and tempered; often joined to the tendon main body by welding. The following considerations should be considered for these steel applications in addition to those specified in 9.3.3.3:

a) heat treatment procedures necessary to meet mechanical property requirements, including fracture toughness requirements;

b) welding procedures that might require preheat and postweld heat treatment (with full consideration to consequences on selected tendon tubular material);

c) susceptibility to hydrogen embrittlement and/or stress corrosion cracking in seawater and other possible environments that might be present.

9.3.3.5 Steel Castings—Yield Strength 50 ksi to 80 ksi (345 MPa to 550 MPa)

Use of steel castings should consider the following:

a) requirements for welding to other portions of the tendon system,

b) critical regions requiring enhanced NDE,

c) repair requirements and procedures.

9.3.3.6 Fracture Considerations

The operator should select materials and fabrication processes that lead to adequate levels of toughness and fatigue properties under service conditions. Fatigue properties of tendon steel materials should be defined with appropriate mean tensile stress levels.

Materials and fabrication methods should have sufficient toughness requirements as specified as a function of the application (e.g. operating temperature, operating environment, criticality of design, etc.). Depending on application, toughness may be specified by the following.

a) Charpy V-notch toughness requirements at prescribed temperatures.

b) Crack tip opening displacement (CTOD) testing with target toughness values developed as part of the design process. This approach involves testing of specimens of full thickness in the parent material, heat affected zone (HAZ) and weld metal.

c) Application specific threshold thickness for requiring CTOD properties and the target levels should be selected by the designer.

d) Charpy V-notch impact values achieved on procedures passing the CTOD requirements can be used as a quality control indicator during production material testing, if specified by the designer.

Data should be gathered from tests on specimens having similar

— material chemistry and microstructure,

— environment,

— loading frequency,

— cathodic protection,

— temperature, and

— mean stress.

In particular, data should be collected at cyclic stress intensity levels pertinent to design. Testing should be carried out on specimens with known KI calibrations. Consideration should be given to standard compact and three-point bend specimens.

9.3.4 Elastomeric Materials

9.3.4.1 Function

Elastomer compounds may be used in the articulating flex element of the tendon system. Selection of a material is highly dependent on the user specifications and the design of the flex element.

9.3.4.2 Typical Materials Used in Flex Element Design

Selection of elastomers for use in flex elements is dependent upon the laminated structure design approach employed by the flex element manufacturer. Although many of the specific compounds used are proprietary to the manufacturer, they typically fall within general types including synthetic and natural rubbers. Synthetic rubbers include nitriles, neoprenes, SBRs, butyls, polysulfides and blends of two or more polymers.

9.3.4.3 Selection Criteria

The flex element contractor normally performs material selection; design, manufacture and testing of flex elements. The selected material should have sufficient successful use history to demonstrate to the user's satisfaction its adequacy for its intended purpose.

A specification should be supplied to the flex element supplier to ensure the best combination of flex element design and material is selected. This includes the following as applicable:

a) tendon loads as a function of local tendon rotation, including normal operating and design maximums and minimums;

b) maximum rotation at design load;

c) design life;

d) long-term stress histogram of tension loads and rotations;

e) fatigue resistance;

f) external environment considerations (e.g. external pressure, seawater temperature);

g) internal conduit pressures;

h) diameter and weight constraints;

i) maximum rotation spring rate at operating conditions;

j) minimum axial stiffness;

k) corrosion protection requirements;

l) proof loads.

9.3.4.4 Contractor Requirements

The flex element contractor should provide specifications for approval that include the following:

a) the type of elastomer to be used;

b) material mechanical property testing requirements such as:

   - ASTM D412;
   - ASTM D429;
   - ASTM D624;
   - ASTM D2240;

c) shear modulus requirement at a particular set of strain conditions;

d) bonding agents and surface preparation methods.

The flex element contractor should demonstrate appropriate controls of materials, processing and testing to ensure uncured green rubber is delivered to the molding operations. Age and storage controls should be documented.

The flex element contractor should have suitable molding process specifications for molding techniques; mold design: cure time, temperatures and pressures.

The flex element contractor should provide in-depth analysis of design, material selection (including documented history of successful application of similar designs), operational, and environmental situations.

9.3.4.5 Acceptance Criteria

Acceptance criteria for the molded elastomer should include the following:

a) normal dimensional requirements,

b) nondestructive examination,

c) proof loads and rotation angles,

d) inspection techniques to ensure proper location of reinforcements and adequate rubber coverage,

e) specific criteria for voids and surface blemishes,

f) local interfacing with corrosion protection coatings,

g) repair methods and limitations.

Acceptance criteria for reclamation of metal components from rejected moldings should be defined. Reclamation processes (chemical, thermal or cryogenic) should have no deleterious effect on the metal.

Acceptance criteria for flex element assembly testing should include the following:

- hydrostatic testing (if applicable),
- axial and rotational spring rate testing,
- static proof loads (required),
- fatigue testing (as appropriate).

9.4 Design Loads

9.4.1 Load Types

Tendon loads include axial, bending, shear, torque, radial and hoop loads. Axial loads may be determined by superposition of the load components described in 7.8.12 through 7.8.15. Bending and shear loads may arise from:

a) dynamic response due to platform motions,

b) bending induced by flex element stiffness,

c) hydrodynamic drag and inertial forces,

d) vortex induced vibrations,

e) unusual loading during installation,

f) manufacturing alignment errors,

g) gravity when platform is offset (catenary effect).

Hoop loads result from a difference between internal and external hydrostatic pressure. Torque may be induced by platform yaw motion.

While axial tension loads characteristically dominate tendon design, the other load types should be evaluated as appropriate to ensure adequate design margins. Buoyant tendon designs in deepwater could be controlled by hydrostatic collapse, and large diameter tendon design could be dominated by bending.

9.4.2 Loading Conditions

9.4.2.1 General

Tendon structural analysis should consider as a minimum load cases associated with the following:

a) maximum tension and allowable stress,

b) minimum tension,

c) maximum flex element angle,

d) lifetime fatigue conditions,

e) installation loads,

f) hydrostatic collapse,

g) maximum loading on specific components.

Maximum tension, minimum tension, and maximum angles are discussed in 7.8.12 through 7.8.17.

9.4.2.2 Extreme Event

Selection of environmental conditions and a TLP configuration for each load case should account for the likelihood of joint events occurring which could lead to an extreme load occurrence.

For any selected survival load case, specification of the design wave should include a spectral representation or a range of wave heights and frequencies. The design should not be based exclusively on a single “most probable maximum” wave height and an associated period since this single wave representation might not correspond to the maximum loading condition.

The consequence of minimum tension should be considered. Loss of tendon tension could result in tendon buckling and/or damage to flex elements. If tension loss is permitted, tendon dynamic analysis should be conducted to evaluate its effect. See 7.8.14 and 7.8.15 for a more complete discussion of minimum tendon loads.

9.4.2.3 Normal Conditions

Lifetime operating load conditions for the tendons should consider a range of combinations of wind, wave, and current conditions that will commonly occur. Lifetime operating loads are particularly important in the evaluation of tendon fatigue life and inspection interval.

Cyclic loads in the tendon can lead to fatigue crack initiation and growth, thus these loads should be considered. The combined effect of primary and secondary wave effects, including high-frequency axial responses (e.g. springing and ringing), plus vortex shedding should be evaluated. Derivation of life cycle tendon loads should be based on long-term climatic and oceanographic data that includes data on the joint occurrence of waves and factors that result in static platform offset (wind and current).

9.4.2.4 Installation

Loads during tendon installation can result from any of the environmental conditions discussed. Tendon dynamics prior to and during latch-up should be considered to minimize the risk of tendon damage. Pre-installation conditions to be considered include free-hanging and/or free-standing, partial or complete tendons. Tendon latching conditions to be considered should include relative motions with respect to the tendon prior to latching, as well as resonant response of the TLP with a limited number of tendons latched, and any other conditions during pre-installation and latching activities.

As in the case of operational loads, spectral sea state criteria for installation should be based on site-specific spectral measurements or hindcast estimates.

9.4.2.5 Damaged Tendon

Over the structure life, tendons might become damaged. Hence, tendons should be designed to be removable and replaceable.

Structural damage to a tendon may be detected either by in-service inspection (e.g. NDT), tendon leaking or loss of load carrying capability (e.g. from damaged bottom connector or failure of foundation). The operator may elect to leave such a tendon in place for a period of time prior to replacement. The designer should consider appropriate load cases with a damaged tendon in place to determine the effects of such conditions as increased or reduced pretension on a damaged tendon, or complete or partial flooding of an air-filled tendon. Once damage is detected, the operator should consider whether the source of the damage may have affected other tendons, or may indicate a systemic problem, and determine what additional inspections may be prudent for the other tendons on the platform.

9.4.2.6 Seismic

Seismic loads on the tendons should be based on site-specific geotechnical conditions. The design spectra should include the vertical and two orthogonal horizontal components of ground acceleration.

Either the response spectrum method using response spectra presented in API 2A-WSD or the time history method may be used. If the response spectrum method is used, suitable adjustments should be made to the response spectra to account for the best estimate of damping. Also, the response spectra should be extended to cover periods corresponding to lateral (bending) mode vibrations of the tendon in the surge and sway directions. If the time history method is used, ground motion time histories should also include energy contributions in this frequency range (typically up to 12-second periods).

9.5 Load Analysis Methods

9.5.1 General Considerations

Tendon loads consist of both static and dynamic components. Static loads arise from tendon pretension; tide; platform offset due to steady environmental forces; platform vertical set-down due to uncompensated changes in platform loads (e.g. rig loads); and foundation position errors during installation. These loads may be determined from the equilibrium conditions of the platform, tendons and risers as discussed in 7.8.12 through 7.8.15.

Dynamic tendon loads arise from platform and seismic motions, wind gusts and direct hydrodynamic forces. Calculation of these loads and forces is described in 9.5.2.

9.5.2 Dynamic Analysis Considerations

9.5.2.1 General

Dynamic analysis of tendon loads should take into consideration the possibility of platform heave and roll/pitch resonant excitation due to primary and secondary wave effects. Care should be exercised in interpreting model test results for resonant responses since damping may not be accurately modeled.

Dynamic analysis may be performed using either time domain or frequency domain techniques, although each has its advantages and disadvantages as discussed below.

9.5.2.2 Frequency Domain Analysis

Frequency domain analysis requires the modeling of hydrodynamic drag as a linear damping term and assumes small excursions from the mean position. The solution is in the form of a transfer function relating tendon response (tension, bending, displacement, etc.) as a function of frequency. The forcing function will be from platform motions and direct hydrodynamic forces. Therefore, a linear relationship, including phase relationships, between these forces and primary wave height and frequency needs to be determined from the motion analysis as input to the tendon load analysis.

Frequency domain analysis is well suited for fatigue and operational analysis since the transfer functions may be applied directly together with sea spectra to arrive at exceedence statistics for tendon loads and stresses. In order to do this, it is best to combine the results for tension, bending, and shear loads to arrive at a response amplitude operator for total combined stress prior to application of spectral techniques. Otherwise, the phase relationships for the combined load cases are not taken into account properly.

The linearization required for frequency domain analysis may lead to inaccurate results for extreme conditions. In this case, calibration of results to model tests through design recipes or use of time domain analysis should be carried out.

9.5.2.3 Time Domain Analysis

Time domain analysis offers the advantage of directly including many nonlinear effects and the determination of the phase relationship for combined loadings (tension, bending, and shear) under a maximum design condition.

Uncoupled time domain analysis of tendon loads requires as input the time history of top tendon loads and platform offsets, hence, a time domain platform motion is required. A simulated time history of platform motions and top tensions can be constructed from frequency domain platform motion solutions if appropriate phase relationships are maintained between the incident wave profile, motions, and tension and shear components

To determine the extreme values for key parameters (e.g. tension or angle), cases should be run for several wave frequencies at amplitudes consistent with expected maximum wave heights. Nonlinear waveforms should be investigated to examine the possibility of tendon responses at resonant frequencies other than the primary wave frequency. Ideally a random time series representing the waveform in the design storm should be used to develop a histogram of peak loads. A sufficient number of complete cycles should be computed in order to obtain a distribution of peaks.

9.5.2.4 Instabilities and Resonance

The tendon system may possess certain dynamic characteristics that should be given special consideration (e.g. axial forces caused by platform heave and roll/pitch oscillations at resonance). Other effects that should be considered include VIVs and seismic loads. In considering these dynamic responses, the design should include an approximate damping model accounting for both mechanical and hydrodynamic effects.

Transverse vibration modes for the tendons can have natural periods in the range of primary wave periods. Analyses should include a sufficient number of nodes (and time step intervals for time domain analysis) to capture modes with natural frequencies in the range of primary waves. Refer to Section 7 for guidance on computation of global TLP motions and tendon loads.

9.6 Structural Design and Fabrication

9.6.1 General Considerations

This section pertains to the strength and fatigue design of the steel tendon components and its relation to fabrication and actual performance. Recent practice has seen tendons fabricated from tubular strings made of large diameter steel pipes containing a series of girth welds and, in some cases, welded-on mechanical connectors. Tendons manufactured from forgings with integral mechanical connectors have also been used. In the case of tendons fabricated from girth-welded pipe segments, the string may be assembled offshore from joints girth welded onshore in the horizontal position and having connectors at each end. Alternatively, tendon strings may be entirely welded onshore, floated out to site, and upended. The complete tendon is anchored at the bottom to a tension pile or template via a latching mechanism and connected to the hull at the top via a mechanical connector. Typically, elastomeric flex joints are used at the top and bottom connections to ease the transition of the bending moment; however, tapered stress joints may also merit consideration.

Alternatively, tendons can be fabricated of composite materials, such as continuously bundled carbon fiber strands with only one metallic connection interface at the top and bottom ends of the tendon proper. Likewise, tendons may also be fabricated of metallic materials other than steel and in configurations other than tubular. If alternate configurations or materials are used for the design of tendons, similar procedures as defined in this section should be followed to justify their performance.

Tendons are fracture-critical, serial components that require high structural performance. Given the serial nature of the tendons, failure of any its components constitute a failure of the tendon. Hence, the tendons should be reliably designed to sustain dynamic and extreme loads without losing structural integrity. This requires detailed evaluation of the acting stresses and use of robust design criteria.

The criteria provided in this section pertain exclusively to steel tendons in tubular configuration. For composite tendon design, designer should demonstrate by analytical and experimental means that the composite tendon design is at least as safe as its steel counterpart, when the uncertainties of the composite behavior associated with its novelty and lack of operational experiences have been taken into consideration. The same applies to the design criteria to be used for tendon components made of metallic materials other than steel and in configurations other than tubular.

9.6.2 Tendon Pipe

9.6.2.1 General

The tendon pipe cross-section should be designed to safely resist the combined effect of global static loads arising from pre-tension, tension and bending, which react to the environmental loads acting on the hull, and external hydrostatic pressure. When local discontinuities are present in an otherwise straight and continuous pipe body, local secondary bending stresses through the thickness of the pipe section are introduced and the tendon pipe should also be designed to locally resist the resulting membrane and bending stresses.

The tendon pipe body is not as susceptible to cyclic loads as compared to pipe-to-pipe or pipe-to-connector girth welds, provided that no damage is inflicted to inner or outer diameter pipe surfaces (ID or OD). One means of protecting the OD is by using robust protecting coatings. Corrosion (pitting) on the ID should be prevented during storage, fabrication, and service or allowed for in the design.

9.6.2.2 Pipe Acting Stresses

9.6.2.2.1 General

The global loads obtained according to the safety criteria defined in 5.2 should be used to generate global net section stresses. If changes in diameter or wall thickness are present, then local through-thickness bending stresses will also act on the pipe.

9.6.2.2.2 Global Net Section Stress

The net section stress at a cross-section results from axial load and general bending moments. The global axial stress should be calculated as the normal stress acting on the gross cross-sectional area. Global bending stress should be obtained as the extreme-fiber normal stress due to the bending moment acting on the pipe cross section.

9.6.2.2.3 Local Stresses

Local stresses developed in tendons at diameter and thickness transitions should be quantified as described in 9.6.2.2.4 and 9.6.2.2.5.

9.6.2.2.4 Diameter Transitions

Sectional transitions may be included in the pipe body where a reduction in the tendon diameter-to-thickness ratio is required. However, the presence of sectional transitions in the tendon pipe body in conjunction will result in local through-thickness bending stresses due to eccentricity of the global section load path, as well as hoop stresses due to unbalanced radial loads at the junctions between the transition piece and the pipes. The magnitude of these stresses depends on the transition piece configuration. Bell-shaped forgings, as depicted in Figure 11, minimize the local additional stresses. Care should be taken to size the length of the “straight sections” at the top and bottom such that the local stress levels have essentially returned to the nominal pipe body stress at the locations where circumferential girth welds are to be made. Otherwise an additional secondary local stress will be present at the weld, adversely affecting the fatigue life of the girth weld.

The additional bending (f_b') and hoop (f_h') stresses may be calculated via finite element analysis (FEA) or conservatively estimated according to Equation (36) and Equation (37), per API 2A-WSD, Section 3.4.

$$f_{b}' = \frac{0.6t\sqrt{D_{o}(t+t_{c})}}{t^{2}}(f_{a}+f_{b})\tan\alpha \tag{36}$$

$$f_h' = 0.45\sqrt{\frac{D_o}{t}}(f_a + f_b)\tan\alpha \tag{37}$$

where

t is the tendon thickness;

t_c is the cone thickness;

f_a is the mean tensile stress, T/A_s ;

f_b is the outer fiber bending stress, $M D_o/2I$;

α is one-half of the cone apex angle;

T is the tendon wall tension, $T_e - pA_o$;

T_e is the tendon effective tension;

p is the hydrostatic pressure outside the tendon at bottom elevation (positive);

D_o is the tendon outside diameter;

D_i is the tendon inside diameter;

A_o is the tendon outside cross-sectional area, $\pi D_o^2/4$;

A_s is the tendon steel cross-sectional area, $\pi (D_o^2 - D_i^2)/4$;

I is the tendon steel moment of inertia, $\pi (D_o^4 - D_i^4)/64$.

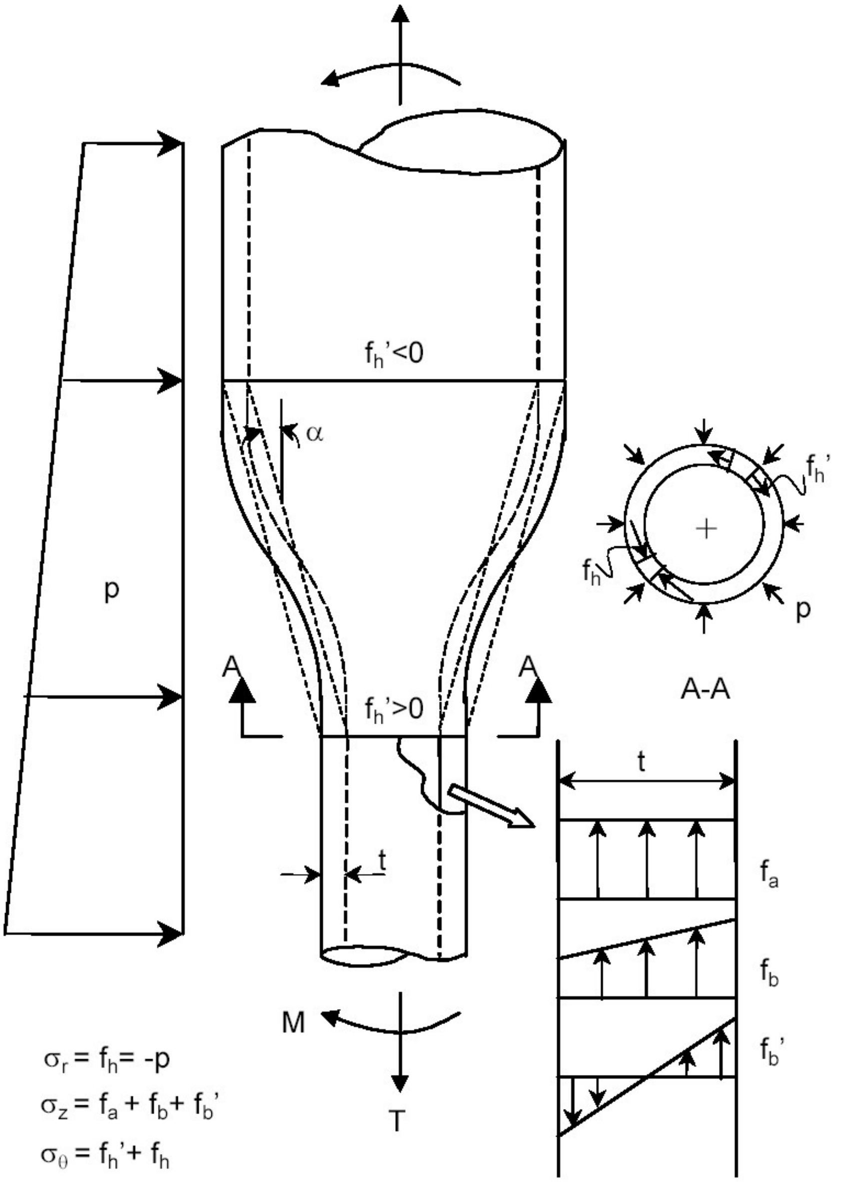
When ($f_a + f_b$) is tensile, the hoop stress f_h' is tensile at the smaller-diameter junction and compressive at the larger-diameter junction.

Referring to Figure 11, the acting radial, longitudinal and hoop stresses to enter the design criteria should be taken as:

$$\begin{aligned} \sigma_r &= f_h = -p \\ \sigma_z &= f_a + f_b + f_b' \\ \sigma_\theta &= f_h' + f_h \end{aligned} \tag{38}$$

9.6.2.2.5 Thickness Transitions

Figure 12 depicts a typical thickness transition where local bending and membrane, or net section stress, developed locally through thickness. For strength checks, these stresses should be obtained from linearization, as detailed in C.5.1.



$$\sigma_r = f_h = -p$$

$$\sigma_z = f_a + f_b + f_b'$$

$$\sigma_\theta = f_h' + f_h$$

$$\sigma^{e}_{mem+bend} = .707[(\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2]^{1/2} \leq \frac{\sigma_y}{SF}$$

Figure 11—Local Stress Check at Tendon Section Transitions

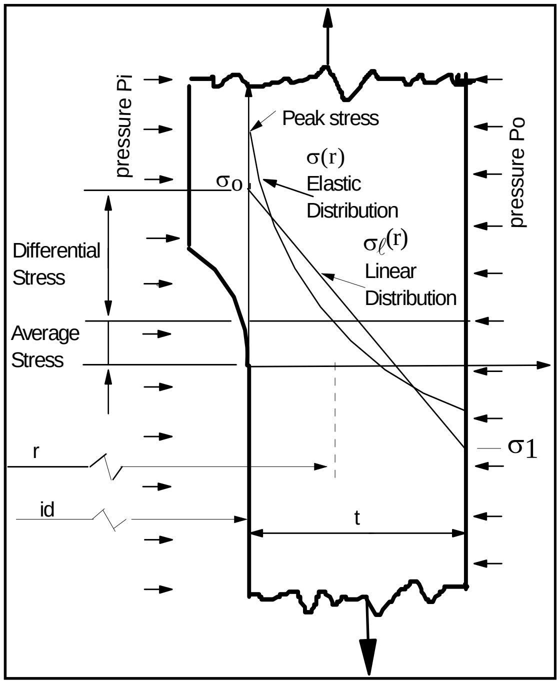


Figure 12—Typical Section, Applied Loads, and Stress Distributions Through-thickness

9.6.2.3 Pipe Strength Criteria

9.6.2.3.1 General

The tendon pipe should be designed to meet both the global and local strength criteria set forth below.

The industry practice includes use of tension/collapse interaction equations developed for API 2A-LRFD, D.3.3, but with either WSD or LRFD safety factors. See C.3 for additional information.

For designs using the working stress designs (WSD) and load and resistance factor design (LRFD) approaches, the recommended criteria are described in 9.6.2.3.2 and 9.6.2.3.3 respectively.

9.6.2.3.2 Global Tension-collapse Strength Criteria with WSD Safety Factors

The tendon pipe subjected to longitudinal tensile stresses arising from the combined action of tension and bending acting in conjunction with hydrostatic pressure should satisfy the following interaction equations.

$$A^2 + B^{2\eta} + 0.6\left|A\right|B \le 1.0 \tag{39}$$

$$A = \frac{(f_\mathrm{t} + f_\mathrm{b})SF_\mathrm{t}}{F_\mathrm{y}} \tag{40}$$

$$B = \frac{f_\mathrm{h}SF_\mathrm{c}}{F_\mathrm{hc}} \tag{41}$$

$$\eta = 5 - 4\frac{F_\mathrm{hc}}{F_\mathrm{y}} \tag{42}$$

where

f_t is the axial tensile stress due to wall tension;

f_b is the outer fiber bending stress due to bending moment;

f_h is the hoop stress due to hydrostatic pressure;

F_{he} is the elastic hoop buckling stress;

F_{hc} is the critical hoop buckling stress.

The elastic and critical hoop buckling stresses, F_{he} and F_{hc} respectively, are defined as follows:

$$F_{he} = 0.88E\,(t/D)^2 \tag{43}$$

where

D is the tendon pipe outer diameter;

t is the tendon pipe wall thickness;

E is the modulus of elasticity;

If $F_{he} < 0.55F_y$ (elastic buckling),

$$F_{hc} = F_{he} \tag{44}$$

If $F_{he} > 0.55F_y$ (inelastic buckling),

$$F_{hc} = 0.7F_y \left[\frac{F_{he}}{F_y} \right]^{0.4} \leq F_y \tag{45}$$

The safety factors for tension, SF_t , and for hydrostatic collapse, SF_c, used in the interaction check are listed in Table 8 (see C.3).

Table 8—Safety Factors for Tension-collapse Check

Safety Criteria	**Tensile** SF_t	**Hoop** SF_c
A (operating)	1.67	1.63
B (extreme)	1.25	1.38
S (survival)	1.05	1.25

Tendon pipe subjected to compressive wall stresses and hydrostatic pressure should use the appropriate analysis methods and safety factors provided in API 2A-WSD or API 2A-LRFD.

9.6.2.3.3 Global Tension-collapse Strength Criteria with Load and Resistance Factors

The tendon pipe subjected to longitudinal tensile stresses arising from the combined action of tension and bending acting in conjunction with hydrostatic pressure should satisfy the following interaction equation, which is repeated from Equation (39):

$$A^2 + B^{2\eta} + 0.6\left|A\right|B \leq 1.0 \qquad (46)$$

In the LRFD approach, the terms are defined as:

$$A = \frac{(f_\mathrm{t} + f_\mathrm{b})}{\phi_\mathrm{t} F_\mathrm{y}} \qquad (47)$$

$$B = \frac{f_\mathrm{h}}{\phi_\mathrm{h} F_\mathrm{hc}} \qquad (48)$$

$$\eta = 5 - 4\frac{F_\mathrm{hc}}{F_\mathrm{y}} \qquad (49)$$

where, in the LRFD approach

f_t	is the axial tensile stress due to the *factored* wall tension;
f_b	is the outer fiber bending stress due to the *factored* bending moment;
f_h	is the hoop stress due to the *factored* hydrostatic pressure;
F_he	is the elastic hoop buckling stress;
F_hc	is the critical hoop buckling stress.

The elastic and critical hoop buckling stresses, F_he and F_hc respectively, are defined as follows:

$$F_\mathrm{he} = 0.88\mathrm{E}(t/D)^2 \qquad (50)$$

where

E	is the modulus of elasticity;
t	is the thickness of the unstiffened tendon pipe;
D	is the thickness of the unstiffened tendon pipe.

If $F_\mathrm{he} < 0.55\,F_\mathrm{y}$ (elastic buckling) $F_\mathrm{hc} = F_\mathrm{he}$ (51)

If $F_\mathrm{he} > 0.55F_\mathrm{y}$ (inelastic buckling) $F_\mathrm{hc} = 0.7F_\mathrm{Y}\left[\frac{F_\mathrm{he}}{F_\mathrm{y}}\right]^{0.4} \leq F_\mathrm{Y}$ (52)

The load factors for TLP tension response are defined relative to static loads (pretension and hydrostatic pressure), environmental tension effects, and tension margins. The load factors L_1, L_2 and L_3 and resistance factors ϕ_t and ϕ_h used in the interaction code check are listed in Table 9.

Table 9—Load and Resistance Factors for Tension-collapse Check

Design Condition	Load Factors			Resistance Factors	
	L_1	L_2	L_3	ϕ_t	ϕ_h
Operating	1.00	1.30	1.50	0.95	0.8
Extreme	1.00	1.10	1.35	0.95	0.8
Survival	1.00	1.00	1.00	0.95	0.8

where

L_1 is the load factor for the design margin;

L_2 is the load factor for the static pretension;

L_3 is the load factor for the environmental and inertia loads;

ϕ_t is the resistance factor for the axial, bending and shear strength;

ϕ_h is the resistance factor for the hoop buckling strength.

In the analysis, the inertia loads are not factored separately from environmental loads because tendon tension responses are part of an overall dynamic system response, which includes both environmental and inertial components. It is not feasible to separate applied environmental loads from dynamic inertia loads in a general response model.

The level of uncertainty of inertia loads is considered similar to that of applied environmental loads in TLP analysis.

The factored loads are defined in Equation (53) through Equation (55).

The factored wall tension is defined as:

$$T = L_1 \times T_{\mathrm{margin}} + L_2 \times T_{\mathrm{pre}} + L_3(T_{\mathrm{tide}} + T_{\mathrm{mean}} + T_{\mathrm{dyn}}) \tag{53}$$

where

T_{margin} is the total of tension margins added external to the response simulation;

T_{pre} is the pretension;

T_{tide} is the tendon tension increase due to the tide and storm surge;

T_{mean} is the mean tension due to the mean environmental loads (including setdown effects);

T_{dyn} is the dynamic tension response induced by the environmental, including the inertia portion of the response.

The factored bending moment is defined as:

$$M = L_3(M_{\mathrm{mean}} + M_{\mathrm{dyn}}) \tag{54}$$

where

M_{mean} is the mean bending moment;

M_{dyn} is the dynamic bending moment.

The factored hydrostatic pressure is defined as:

$$P = L_2 \gamma_{\text{w}} H_{\text{z}} \tag{55}$$

where

γ_{w} is the density of seawater;

H_{z} is the submerged depth of the tendon section.

In the LRFD factor approach, tendon pipe net section stress utilization ratio shall be checked separately using Equation (39). The A ratio in the equation shall be no greater than 1.0 based on the factors of safety defined in Table 8.

9.6.2.3.4 Local Stresses

Local stresses developed due to diameter or thickness transition in the tendon should be checked according to the following criteria.

a) Diameter transitions—When the hoop stress f_{h}' is tensile, a local check based on a von Mises equivalent stress at the outer fiber should be made according to the following stress criteria:

$$\sigma^{e}_{\text{mem+bend}} = .707[(\sigma_{\text{r}} - \sigma_{\theta})^2 + (\sigma_{\theta} - \sigma_{\text{z}})^2 + (\sigma_{\text{z}} - \sigma_{\text{r}})^2]^{1/2} \le \frac{\sigma_{\text{y}}}{SF} \tag{56}$$

σ_{y} is the nominal strength of the material and SF is the safety factor given in the Table 10 according to the safety criteria.

When the hoop stress f_{h}' is compressive, f_{h}' should meet the criteria for F_{hc} given in 9.6.2.3.2 or 9.6.2.3.3, except that, in Equation (40) and Equation (47), ($f_{\text{t}} + f_{\text{b}}$) becomes ($f_{\text{t}} + f_{\text{b}} + f_{\text{h}}'$), and in Equation (41) and Equation (48), f_{h} becomes ($f_{\text{h}} + f_{\text{h}}'$).

b) Thickness transitions—The radial and hoop components of stress approach zero such that the von Mises equation reduces to the following checks for local membrane or net section stress (σ_{mem}) and combined membrane plus bending stress ($\sigma_{\text{mem+bend}}$).

$$\sigma_{\text{mem}} \le \frac{\sigma_{\text{y}}}{SF_{\text{mem}}} \tag{57}$$

$$\sigma_{\text{mem+bend}} \le \frac{\sigma_{\text{y}}}{SF_{\text{mem+bend}}} \tag{58}$$

The safety factors for local pipe strength may be taken according to Table 10.

Table 10—Local Pipe Strength Safety Factors

Safety Criteria	Safety Factors	
	Membrane	Membrane + Local Bending
A (operating)	1.67	1.11
B (extreme)	1.25	0.83
S (survival)	1.05	0.83

9.6.3 Tendon Girth Welds

Satisfying the strength criteria stipulated in 9.6.2 for the tendon pipe body ensures the strength performance of the girth weld as long as the welds are overmatched in strength relative to the actual maximum pipe material properties. Loss of pipe wall thickness resulting from dressing the weld reinforcements should be considered in the design for local fatigue. Girth welds, however, are especially susceptible to cycling loads due to the presence of flaws inherent to the welding process.

9.6.3.1 Girth Weld Acting Stresses

The cyclic loading acting on the welds to be considered here are the same as those acting on the pipe body generated via the load analysis methods discussed in 9.4. Additionally, secondary local stress at the weld resulting from the attachment of mechanical connectors, section transitions, pipe misalignment, or local thin spots resulting from dressing of the weld reinforcement should be considered.

9.6.3.2 Girth Weld Fatigue Design

9.6.3.2.1 General

The reliable fatigue design of the tendon girth welds requires the interaction between analysis, fabrication considerations, and qualification and/or confirmation testing as needed. Figure 13 shows an example of elements to be considered in the fatigue design process for fracture-critical tendon girth welds, which is complementary to that described in 9.2.5 for the overall design process.

9.6.3.2.2 Girth Weld Fatigue Damage Analysis

Based on the stress histories acting on the tendon girth welds, conventional Miner’s rule cumulative fatigue damage should be conducted. The resistance side of the damage calculation should use a design S-N curve consistent with the type and quality of weld sought.

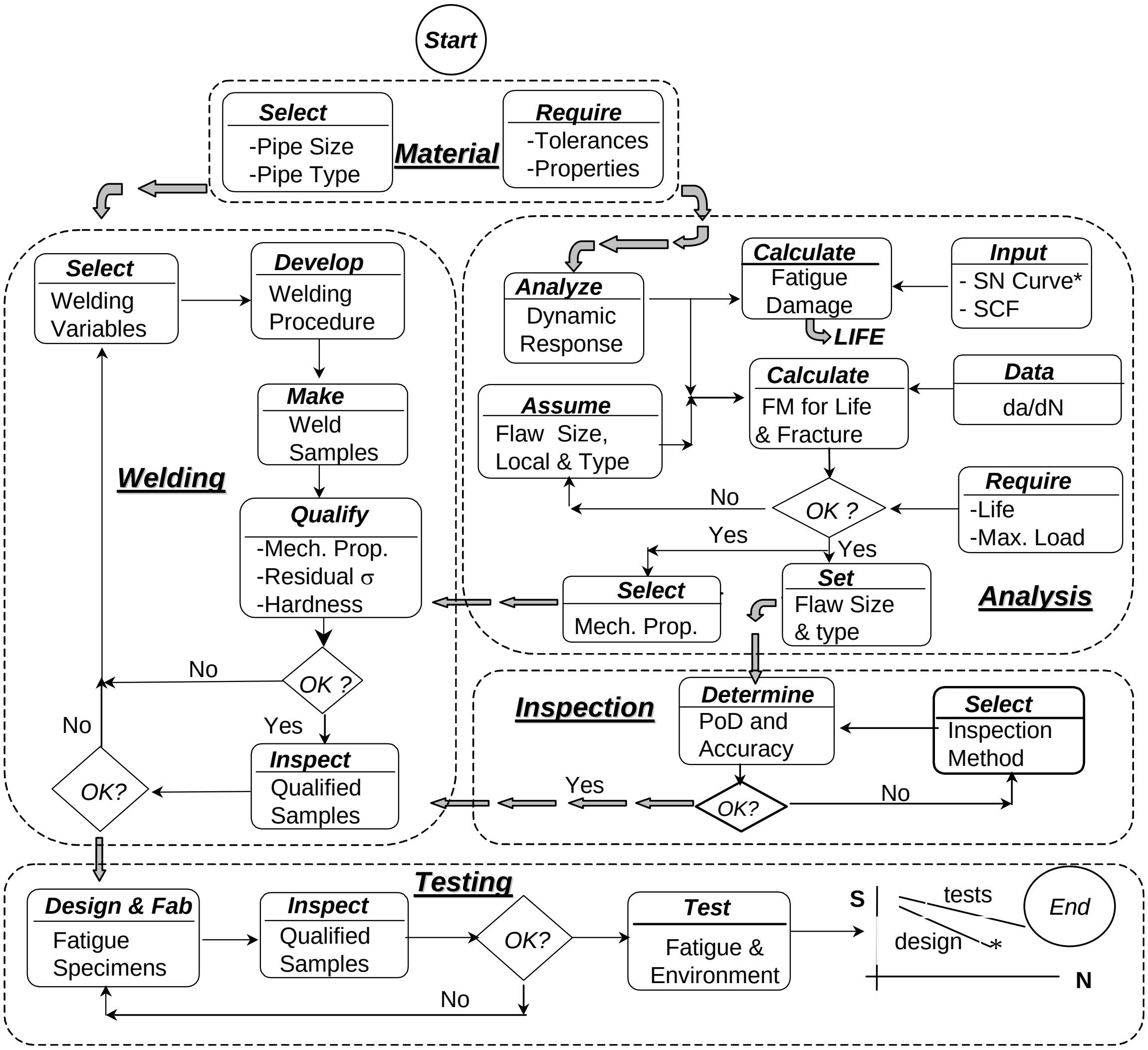


Figure 13—Design, Fabrication, and Verification Process for Fracture-critical Tendon Welds

For tendon welds designed not to be inspected for fatigue cracks in-service, the calculated S-N fatigue life should be at least 10 times the planned life of the facility. A lower life design factor may be used when:

a) a proven, reliable in-situ inspection/crack detection method and an expedient replacement or repair plan are to be employed, or

b) the uncertainties of the variables entering the damage calculations are reduced (Wirsching, 1986 [250]). In no case, however, should the fatigue life of the weld be less than three times the planned life of the facility.

S-N design curves given by BS 7608, Table 7, for circumferential butt welds in tubes are recommended in accordance with the manufacturing requirements, special inspection requirements and notes stipulated. Welds made from one side but which otherwise meet all other requirements stipulated for Class C can also be assessed with the Class C curve. Any other pertinent curve may be used, provided it is relevantly justified on the basis of pertinent data. Invoking an endurance limit or change in slope, such as in BS 7608, should be based on data that includes variable amplitude loading effects. If welds are ground properly (see 9.6.3.3) a correction for thickness effect on fatigue may be waived. A thickness effect may also be waived if the S-N is based on actual component size data (see C.4.1).

For cases where the S-N curve selected does not already embody local stress concentration effects of misalignment expected for the tendon welds, a stress concentration factor (SCF) should be applied to the nominal pipe stress to account for local wall misalignment as the tubulars join at the girth weld. The SCF is an exclusive function of the dimensional tolerances of the joining tubulars. The SCF can be estimated by (Buitrago and Zettlemoyer, 1998 [108]) by Equation (59):

$$SCF = 1.0 + 2.6\frac{e}{t_{\text{thin}}}\left[\frac{1}{1+0.7\left(\frac{t_{\text{thick}}}{t_{\text{thin}}}\right)^{1.4}}\right] \quad (59)$$

The centerline offset (e) can be expressed as a function of the specified hi-lo mismatch (h) at the ID of the weld as follows:

$$e = h + \frac{t_{\text{thick}} - t_{\text{thin}}}{2} \quad (60)$$

The specified hi-lo can be deduced as a function of the out-of-roundness (OOR) from pipe fabrication fit-up as follows:

$$h = \frac{OOR}{2} \quad (61)$$

A correction to the calculated SCF is necessary to account for the fact that tendon analyses use nominal pipe sizes, whereas actual pipes are delivered within a range of dimensional tolerances. This correction factor, which multiplies the calculated SCF, can be taken as the ratio of the analyzed thickness to t_{thin} of the pipes meeting at the weld.

As mentioned in 9.6.2.2, the presence of a conical transition in the tendon pipe generates an additional SCF due to secondary bending induced by the section change. In this case, the total SCF at the cone-pipe junction is the product of the SCF due to the local thickness misalignment given above and the SCF due to secondary bending given in 9.6.2.3.4.

For the case of in-situ inspection, the inspection interval should be established via fracture mechanics based on an initial crack size no smaller than that likely to be missed by the inspection method. In no case, however, should the in-situ inspection interval be longer than one-fifth of the time necessary for the crack to grow through thickness.

9.6.3.3 Girth Weld Fracture Mechanics Analysis

9.6.3.3.1 General

Fracture mechanics (FM) analyses are intended to establish the following:

a) fracture toughness level to be achieved through the weld qualification process to sustain the extreme loads without fracture;

b) critical initial defect sizes at various locations through the weld thickness;

c) in-situ inspection intervals, if applicable.

One important input to the FM analysis is the crack-growth rate (CGR) of the material through which the crack is assumed to propagate. In the absence of specific CGR data for the specific weld, general guidance may be used such as that given in BS 7910:1999. However, no advantage should be taken of crack threshold behavior (see C.4.2).

For the case of no in-situ inspection, the critical initial defect size in the weld, as obtained via fracture mechanics, should be reliably found during inspection after welding and should not propagate to its through-thickness condition in a period shorter than five times the planned life of the facility. Subsurface defects should also be considered in the analysis given the ease of access to the tendon weld surfaces and the high reliability of the inspection methods used for the detection of surface-breaking defects during fabrication.

Care should be exercised in applying the leak-before-break (LBB) approach to tendon design, due to the uncertainty in achieving the flooding rates upon which the design may be based (see C.4.2).

9.6.3.3.2 Girth Weld Fabrication

The manufacturing process of the basic pipe material restricts the tubular size, thickness, and dimensional tolerances. Tolerances play an important role in the local SCF that may ultimately control the location of fatigue failures. Tendons made with UOE pipe may be less oval than conventional rolled tubulars used in offshore structures, thereby improving the fit-up and the SCF.

The welding process is crucial in establishing the fatigue design basis for the welds. The process determines not only the type but also the size and frequency of occurrence of weld flaws. A reliable and consistent welding method is recommended to improve the quality of the weld. The weld qualification process should ensure that the mechanical properties required by the analyses are met, in particular fracture toughness.

The weld reinforcements at the ID and OD may be ground flush with the pipe walls to improve fatigue performance by eliminating the weld toe defects and to facilitate inspection. Attainment of better fatigue performance by grinding requires that the grinding procedure be qualified as to location and amount of material to be removed, surface finish, inspection of the ground surfaces for surface-breaking defects, and evaluation of the significance of the acceptable internal defects via fracture mechanics, as discussed at the top of this section.

9.6.3.3.3 Girth Weld Inspection

In order to link the fracture mechanics analyses to fabrication and to ensure the expected S-N fatigue performance, the inspection system should reliably detect, locate, and size the critical welding surface-breaking and embedded defects during production. Given the uncertainties of the fracture mechanics analyses and inspection process, care should be exercised when setting acceptable flaw size limits, taking into consideration the maximum flaw size likely to be missed during inspection (see C.4.3).

The defect acceptance criteria to be enforced during inspection, in terms of maximum allowable defect heights for given circumferential lengths, should take into account not only the inspection method’s sensitivity and flaw sizing accuracy but also its probability of detection characteristics. In reducing the calculated critical flaw size, account should be taken of the maximum undersizing accuracy error expected for the NDT method.

9.6.3.3.4 Girth Weld Testing

Full-scale girth weld testing may be required when essential welding parameters or tendon pipe material are significantly different from those -with proven practice or when there are significant differences between the welds to be used in practice and the manufacturing or inspection stipulations specified for the invoked S-N fatigue curve. When necessary, the primary objective of testing is to confirm that, for the actual pipe size and material, welding process, inspection method, and defect acceptance criteria employed during fabrication, the girth welds can indeed achieve the required fatigue performance. Small-scale specimens, in the form of strips taken from girth welds, may also be used. However, in selecting the size and number of strips to be tested account should be taken of the potential variability of girth welds with respect to presence of acceptable flaws around the circumference and the total length of sample weld to be tested as well as differences between residual stresses in full-scale girth welds and removed strip specimens. The results of full-scale and/or strips can also provide a basis to upgrade the fatigue criteria and to confirm defect acceptance criteria for inspection.

9.6.4 Tendon Connectors

9.6.4.1 General

Besides the pin-and-box type of connectors used to assemble tendon segments offshore, other types of mechanical connections at the top and bottom of the tendon should also be considered in the tendon design process. The guidance provided here applies to both end and intermediate mechanical connections in the tendon string, except for the flex elements.

9.6.4.2 Connector Acting Stresses

9.6.4.2.1 General

The acting stresses in the tendon mechanical connections are those induced at the connection critical sections or characteristic geometric features (e.g. notches) as a result of assembling the connector (i.e. make-up stresses) and sustaining the tendon pipe nominal loads (i.e. without SCF) due to the extreme or fatigue environments.

Connectors are acted upon by external pressure and axial loads and moments acting on the nominal pipe. Each of these loads may act alone or in concert with others to result in stresses in the connector. Connectors typically can be represented by an axi-symmetric model that facilitates application of axial and pressure loads, but not bending moments. To obviate this problem the axial load (P) and the bending moment (M) can be converted to an equivalent load (P_{eqv}). The concept of the equivalent load is simple and slightly conservative for relatively thin pipes ($D/t > 20$). The design load (P_{design}) can be expressed as:

$$P_{\text{design}} = P + P_{\text{eqv}} \quad (62)$$

$$P_{\text{eqv}} = \frac{Mc}{I} A = M \frac{32t\left(D-t\right)^2}{D^4 - \left(D-2t\right)^4} \quad (63)$$

where

c is the outside pipe radius, which equals $^1/_2\ D$;

A is the pipe cross-sectional area;

I is the pipe cross section moment of inertia;

D is the pipe outside diameter;

t is the pipe wall thickness.

A simpler expression may be used for P_{eqv} when $D/t \geq 20$:

$$P_{\text{eqv}} = 2M/R \quad (64)$$

where

R is the mid-radius at the section of interest;

M is the bending moment.

9.6.4.2.2 Connector Acting Local Stresses

Connector stresses should be obtained via FEA that includes the effect of dimensional tolerances on local stresses, as well as the pipe and pressure loads. Elastic FEA is typically sufficient and conservative. When performing FEA to arrive at stresses to be used for fatigue analysis, consideration should be given to performing mesh density studies in order to ensure peak stresses near structural discontinuities, e.g. notches, thread roots, etc. have been accurately captured. As such, an increase in peak stress of less than 10 % when going from one mesh density to a finer mesh density is typically desired as an indicator that further refinements in mesh density are not required. Typically, there should be a minimum of seven to eight elements in any 90° arc of a critical radius.

9.6.4.2.3 Connector Acting Section Stresses

Prior to conducting strength checks, each of the stress component distributions (axial, hoop, radial, and shears) across the section of interest should be obtained via linear analysis (or measurements in the case of surface values) and then linearized, as illustrated in Figure 12. Membrane stresses and bending stresses can then be obtained from the linearized distributions. Alternatively, peak surface stress values may be used directly to calculate the von Mises equivalent stress without linearization. For details on linearization of stress components see C.5.

In general, the membrane and membrane plus bending von Mises equivalent stress can be calculated in polar coordinates as follows with r, θ, and z being the radial, hoop, and longitudinal directions, respectively:

$$\sigma^{e}_{\mathrm{mem}} \text{ or } \sigma^{e}_{\mathrm{mem+ben}} = .707\left[\left(\sigma_{r}-\sigma_{\theta}\right)^{2}+\left(\sigma_{\theta}-\sigma_{z}\right)^{2}+\left(\sigma_{z}-\sigma_{r}\right)^{2}+6\left(\tau^{2}_{r\theta}+\tau^{2}_{\theta z}+\tau^{2}_{zr}\right)\right]^{1/2} \tag{65}$$

where

$\sigma^{e}_{\mathrm{mem}}$ is the membrane von Mises equivalent stress;

$\sigma^{e}_{\mathrm{mem+ben}}$ is the membrane plus bending von Mises equivalent stress;

σ_r, σ_θ, σ_z are the membrane or membrane plus bending component of linearized normal stresses;

$\tau_{r\theta}$, τ_{zr}, $\tau_{\theta z}$ are the average shear stresses.

9.6.4.3 Connector Strength Criteria

Connectors should be designed to sustain the stresses and deformations arising from assembly, external loads applied to the pipe body, and pressure without exceeding the resistance of the connector. Criteria to conduct strength checks are given below. See C.5.2 for additional information.

9.6.4.3.1 Primary Stress Criteria

9.6.4.3.2 General

Primary stresses are those that are induced by applied loads and are required to satisfy equilibrium. The membrane ($\sigma^{e}_{\mathrm{mem}}$) and membrane plus bending ($\sigma^{e}_{\mathrm{mem+ben}}$) von Mises equivalent stresses resulting from applied loads should satisfy the following conditions:

$$\sigma^{e}_{\mathrm{mem}} \le \frac{\sigma_{y}}{SF_{\mathrm{mem}}} \tag{66}$$

$$\sigma^{e}_{\mathrm{mem+ben}} \le \frac{\sigma_{\mathrm{y}}}{SF_{\mathrm{mem+ben}}} \tag{67}$$

where

σ_{y} is the nominal yield strength of the material;

SF is the applicable safety factor according to criteria and stress type as identified in Table 11.

Table 11—Connector Strength Safety Factors

Safety Criteria	**Safety Factors**	
	Membrane	**Membrane + Bending**
A (operating)	1.50	1.00
B (extreme)	1.25	0.83
S (survival)	1.00	0.83

Strains developed under primary stress conditions should also be limited such that the ability to seal, disassemble and/or the function of the tubular string are not adversely affected.

9.6.4.3.3 Primary Plus Secondary Stress Criteria

Secondary stresses are those that are self-limiting and self-equilibrating, such as those induced by makeup. The combined primary and secondary stresses, as calculated by linear analysis under preload and externally applied loads, should also satisfy the following condition:

$$\sigma^{e}_{\mathrm{mem+ben}} \le 2\sigma_{\mathrm{y}} \tag{68}$$

9.6.4.3.4 Shear Stress Criteria

The average shear stress on the gross section, τ_{av}, resulting from the applied loads should satisfy the following condition:

$$\tau_{\mathrm{av}} = \frac{\sigma_{\mathrm{y}}}{2.5} \tag{69}$$

9.6.4.3.5 Bearing Stress Criteria

The average bearing stress, σ_{br}, resulting from the applied loads should satisfy the following condition:

$$\sigma_{\mathrm{br}} = \frac{\sigma_{\mathrm{y}}}{1.0} \tag{70}$$

Connectors should also avoid modes of failure not related to material strength but to maintaining connector engagement (e.g. “jump-out”). Sudden disengagement of a connector may take place due to excessive local deformation at the points of load transfer. One example is the sudden disengagement of the mating surfaces in threaded or grooved connectors.

9.6.4.4 Connector Fatigue Design

9.6.4.4.1 General

Fatigue lives may be computed either by the conventional S-N stress life method, or by the strain life method. Either method requires local elastic stresses at the fatigue critical location in the connector induced by the nominal loads in the pipe body and material- or component-specific fatigue data.

9.6.4.4.2 Connector Fatigue S-N (Stress Life) Method

In the S-N method, fatigue damage is calculated based on an S-N curve qualified by relevant connector or connector material fatigue test data and the nominal pipe stress history. The effect of local SCFs and mean stresses should either be included in the qualified S-N curve or otherwise explicitly accounted for. Notch alleviation, or notch sensitivity effects, on the elastic SCF should be taken into account (e.g. via the Peterson fatigue notch factor). The stress history may be expressed as an occurrence stress range histogram in cycles per year.

Using Miner's rule, the total damage may be calculated by summing, over all the stress ranges included in the tendon response, the ratios of the number of cycles of the response to the number of cycles to failure from the S-N curve for corresponding stress range values. For fracture-critical, uninspectable connectors in series with the tendon pipe, a safety factor greater than 10 should be considered.

9.6.4.4.3 Connector Fatigue Strain Life Method

This method transforms the local cyclic elasto-plastic behavior stress at the critical notch of the connector into equivalent strain amplitude vs reversals to failure curve, with failure defined as the development of an initial crack. The procedure to calculate the strain life for a given stress range is given in C.6. Linear FEA of the connector is needed to generate mean stress and SCFs at the notch, as well as relevant cyclic and monotonic properties of the base material. Once the strain life curve has been generated, it can be converted to a conventional S-N curve referenced to the nominal stress on the pipe, as illustrated in C.6. In this way, the same methodology followed for damage accumulation and life criteria, as given in 9.6.4.4.2, can be used. Typically, damage levels calculated by this method are much less conservative than those obtained via the S-N stress life method. The crack propagation phase is conservatively neglected.

9.6.5 Tendon Flex Elements

9.6.5.1 General

Flexible elements typically are used at the top (hull) and bottom (foundation) ends of the tendon. They consist of stacked laminates of steel and rubber or elastomer enclosed in a spherical steel housing that enables the tendon to rotate while maintaining its axial stiffness. This rotation reduces the bending moment that otherwise would have developed due to the abrupt change of stiffness between the tendon and its structural supporting elements.

The strength and fatigue design of tendon flex elements requires a significant amount of analysis to evaluate the acting stresses on both the rubber and the steel laminates; test data to establish basic static and time-dependent material properties; and overall performance of the full-scale flex element. Experience with the manufacturing process and quality control is also very important for achieving the required performance. For these reasons, flex elements selected for tendon application shall either be of a design having a well established track record of successful fabrication and performance, or having undergone rigorous manufacturability qualification and performance verification (see C.7).

9.6.5.2 Flex Element Acting Stresses

The flex element should be designed to safely sustain short duration extreme stresses and long-term cyclic stresses imparted by the tendons without impairing the rotational stiffness of the elements assumed in the response analysis of the tendons. The design of the flex element should be based on analysis that includes the specific properties of the rubber material and the explicit modeling of the laminates. The model should permit the application of axial force in conjunction with bending moment in one plane.

9.6.5.3 Flex Element Strength Design

The strength check should be performed for both the element laminates and the steel parts of the housing and contact surfaces. The element should be originally designed to provide the rotational stiffness assumed in the tendon response analysis. This stiffness should be confirmed by full-scale testing of a element prototype, as part of the fabrication qualification of the element.

The steel strength criteria should be the same as those used for other tendon steel element design. The rubber strength design should be based on the maximum allowable bulging during compression of the critical rubber layer, maximum shear deformation during rotation and potential tension loading.

9.6.5.4 Flex Element Fatigue Design

The fatigue life of the flex element elastomer may be evaluated by using a cumulative damage approach based on the Palmgren-Miners ratio and a strain-life curve. This curve should be based on data generated using small-scale, strain-controlled tests of the elastomer in question under shear strain conditions. For fatigue calculations using the cumulative damage method, the calculated fatigue life should exceed 10 times the service life.

Alternatively, the fatigue life may be calculated using a tearing energy method in which the extent of crack growth in the elastomer is calculated as a function of tearing energy (T) arising from the annual alternating tension and rotation cycles (Stevenson and Harris, 1992 [228]; Gunderson, et al. 1992 [151]). For tearing energy calculations, the growth of a crack equivalent to 50 % of the radial section of any elastomer layer should be considered the point of functional failure. Calculations by either method should account for the changes in mechanical properties of the elastomer over the service life. For fatigue calculations using the tearing energy method, the calculated fatigue life should exceed five times the service life.

The flex element steel components should also be checked for fatigue damage using the fatigue procedure given for other tendon components in 9.2.5. The required fatigue lives for flex element steel components should be equal to or longer than the greater of the required lives of tendon connectors or the tendon itself. Particular attention shall be given to the fatigue performance of the flex element shims, given their potential increased vulnerability to fracture due to their generally higher strength, as well as their complete inaccessibility.

See C.7 for additional guidance.

9.6.6 Tendon Bottom Receptacle

Tendons may be directly anchored to foundation piles or to a foundation template. In either case, the tendon bottom termination connects, via a mechanical latch, to a receptacle on the template or pile. Receptacles may have geometric features in the form of grooves or internally protruding elements to engage the tendon bottom termination. These features may result in high local stresses that may lead to cracking.

The strength and fatigue design of the bottom receptacle and attachment girth weld should follow the guidance provided in 9.6.3 and 9.6.4. For the case of tendons directly connected to piles, fatigue and damage due to installation should also be accounted for as provided in 10.3.3.4.

9.7 Transportation, Handling and Installation Procedures

Transportation and handling of tendon systems is discussed in 14.5.4. Procedures for the installation of tendon systems are discussed in 14.6.4.

9.8 Operational Procedures

9.8.1 Load Monitoring

The tendon system should be suitably instrumented and monitored to aid in operations and to ensure that the system is performing within design limitations.

Provision should be made to monitor tendon top tension. In addition, it may be desirable to monitor platform mean offset position and tendon upper and/or lower flex joint angles.

9.8.2 Tendon Retrieval and Replacement

The need to retrieve a tendon could arise as part of a scheduled plan for inspection or replacement, in the event of damage or suspected damage, or in removing the TLP from site. Regardless of the reason for retrieval, the equipment, operations, and procedures involved should be carefully preplanned and personnel trained to carry out the procedures.

9.9 Corrosion Protection

9.9.1 General

Steel materials should be protected from the effects of corrosion by the use of a corrosion protection system that is in accordance with NACE SP0176 or DNV-RP-B401. The corrosion protection systems include coatings, cathodic protection, corrosion allowance, and corrosion monitoring. Overprotection that may cause hydrogen embrittlement should be avoided.

9.9.2 Antifouling

In areas where marine fouling is significant, organisms are active and the use of antifouling coatings may be considered to reduce the effects of marine growth.

10 Foundation Analysis and Design

10.1 General

10.1.1 Purpose and Scope

This section addresses the analysis and design of TLP foundations. Discussions of fabrication, transportation, installation, materials, monitoring, inspection, and maintenance as related to the foundation are also included.

10.1.2 Description of Foundation Systems

The term foundation system refers to the foundations used to anchor the tendon legs to the seafloor. A foundation system can consist of structures such as independent leg templates and well templates or an integrated single piece foundation supported or anchored by piles, suction anchors, gravity, mudmats, or combinations of each.

10.1.2.1 Piled-template Foundations

Foundations comprised of piles and template structures (integrated or independent) are addressed. Well templates are also addressed since the well template may be integrated with the leg templates. Figure 14 illustrates an integrated foundation, Figure 15 shows components of an independent template foundation system and Figure 16 shows the concept of a tendon directly connected to the pile.

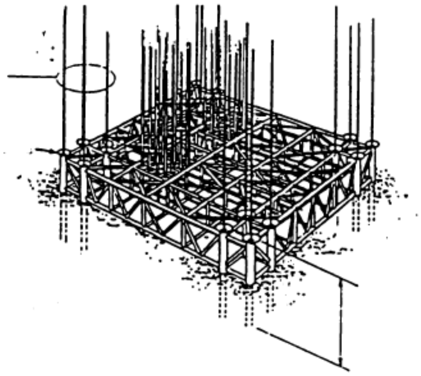


Figure 14—Components of an Integrated Template Foundation System

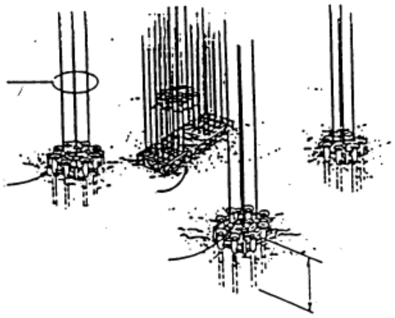


Figure 15—Components of an Independent Template Foundation System

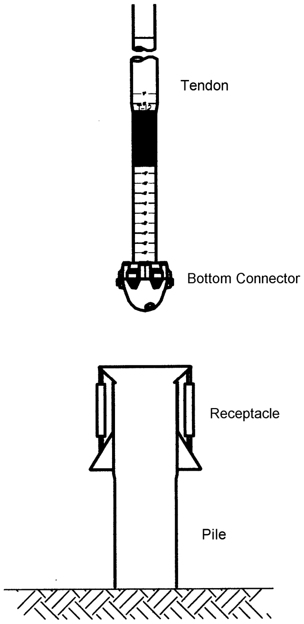


Figure 16—Components for Directly Connecting the Pile to a Tendon

10.1.2.2 Shallow Foundations

Shallow foundations principally address gravity foundation systems but also include the piled template during installation prior to pile placement. Figure 17 is an example of a shallow foundation system. Mudmat design and analysis is covered in the shallow foundation subsection.

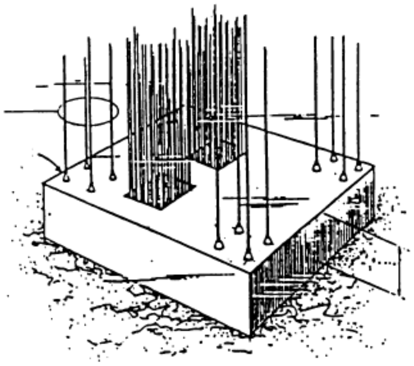


Figure 17—Components of a Shallow Foundation System

10.2 Foundation Requirements and Site Investigations

10.2.1 Foundation Requirements

The primary function of the foundation system is to anchor the tendons.

Load transfer to the soil can be accomplished in a number of ways. For example, through tendons directly attached to piles or suction anchors, through templates, which distribute tendon forces to the soil via piles, or through a gravity base.

The use of a template structure requires consideration of several factors including: template configuration, structural strength, installation feasibility, required positional and alignment tolerances, connections with the tendons, risers, and if applicable, connections between the template and piles.

The design of the foundation structure should ensure that permissible limits of stress, displacement, and fatigue are not exceeded during and after installation. Particular attention should be given to loading eccentricity arising from tendon/riser force variations within a group, tendon/riser installation sequences, and possible tendon/riser retrieval and redeployment during the platform's operational life. The permissible soil stress and displacement should be established considering variations in soil properties resulting from cyclic tensile and lateral loadings, and in the case of pile supported foundations, potential creep due to sustained axial tension loadings. Consideration should also be given to the loss of foundation capacity due to scour or other soil instabilities (e.g. mudslides and liquefaction).

The foundation system above the mud line should include provisions for inspection and maintenance. The extent of inspection, timing of the inspection, and maintenance should be commensurate with the redundancy relative to overall safety and performance.

10.2.2 Site Characterization

10.2.2.1 General

Primarily, the type and function of the platform to be installed, the availability and quality of data from prior site surveys, and the consequences that would result from a partial or complete foundation failure should guide requirements for site investigations. Special problems include deepwater sites and unusual loading conditions. It is recommended that a high-quality, high-resolution geophysical survey, combined with a realistic geological interpretation of that survey be combined with the geotechnical data in order to assess restraints imposed on the design by geological features, to serve as a guide to develop a prognosis for the vertical and horizontal extent of geotechnical investigation and to aid in the interpretation of the geotechnical data obtained during a site investigation. Some examples of these integrated geoscience studies are given by Doyle (1998) [126] and Jeanjean, et al. (1998) [161].

The measured properties of soil samples retrieved from deep waters may be different from in-situ values. Without special precautions, the relief of hydrostatic pore pressure and its resulting effect on any dissolved gases can yield soil properties significantly different from in-situ conditions. Because of these effects, in-situ or special laboratory testing to determine soil properties is warranted. Since installation sites may be remote from areas for which extensive site data are available, regional and local site studies to adequately establish soil characteristics may be required. Previous site investigations and experience may permit a less extensive site investigation. Some of the geotechnical tools available when rotary drilling techniques are employed for deepwater investigations are discussed by Dutt, et al. (1997)[132]. Coring with “jumbo” or “long” coring devices has also been shown in recent studies (Young, et al. 2000 [251]; Borel, et al. (2002) [101]) to provide shear strengths equivalent to those obtained by rotary drilling methods and holds promise as an alternative coring method.

The upward static and dynamic loadings are different from those typically experienced by a jacket-type structure. Piled TLP foundations are subjected to constant and cyclic tensile load components that can result in tensile creep of the foundation and excessive deformations associated with cyclic loading. Tests to ascertain the soil-pile response when subjected to these loadings should be performed.

A site investigation program should be accomplished for each platform location. The program should, as a minimum and preferably in the order listed.

10.2.2.2 Background Geophysical Survey

Regional geological data should first be obtained to provide information of a regional character which may affect the analysis, design and siting of the foundation. Such data should be used in planning the subsurface investigation, and to ensure that the findings of the subsurface investigation are consistent with known geological conditions. Site-specific background data should include a re-examination of the 3D, multichannel data obtained for exploratory purposes and a review of the “geohazard” study used to site the exploratory wells. The 3D data set should be re-processed to enhance its high-frequency content. Suggested reading for further information is given in Doyle and Kaluza (2001) [128].

10.2.2.3 Seafloor and Sub-bottom Survey

A site-specific, high-resolution geophysical information should be obtained relating to the conditions existing at and near the surface of the seafloor. The survey should include the mapping and description of all seafloor and sub-bottom features, some of which may be as follows:

a) contours of the seafloor and shallow stratigraphy;

b) position of bottom shapes, which might affect scour;

c) the presence of sea floor bottom objects such as, slumps, boulders, obstructions, and small craters;

d) gas seeps;

e) shallow faults;

f) slump blocks;

g) the effect of drill cuttings on the foundation installation;

h) previous usage of seafloor;

i) gas hydrates.

The geophysical study should be evaluated within the context of a geological model to determine the existence of any geological feature(s) that might have an effect on the design (i.e. a geological risk assessment shall be performed to assess the affect of geological features on the TLP performance).

The survey should use geophysical equipment and practices appropriate to the water depth of interest and provide high-resolution imaging of the seafloor as well as detailed stratigraphic information to a reasonable penetration below the zone of influence of the structure. In addition, the survey scope should encompass both the lateral and vertical extent of possible geological features that may be a constraint to the design of the foundation. The bedding resolution of the survey should be such that it can be used to interpret the geotechnical data.

10.2.2.4 Geotechnical Investigation

The subsurface investigation should obtain geotechnical data concerning the stratigraphy and the lateral variability of the soil. The sampling and in-situ testing intervals should ensure that a reasonably continuous profile is obtained within each significant stratigraphic layer. The design soil parameters in various soil strata should be determined from a field program that tests the soil in as nearly an undisturbed state as feasible. Because the quality of soil samples can be expected to decrease with increasing water depth, the use of in-situ testing techniques are recommended for deepwater sites. In addition, soil samples will be required to characterize the soil types and provide other basic engineering property data.

The number and scope of the borings will depend on the quality and interpretation of the high-resolution geophysical study. Based on the geophysical survey, significant lateral stratigraphic variability may require that more than one boring be obtained. For pile foundations, the minimum penetration of at least one boring shall exceed the anticipated design penetration. For piled or non-piled gravity foundations, the minimum penetration of each boring should be related to the expected zone of influence of the loads imposed by the base. Appropriate in-situ tests should be carried out, where possible, to a penetration that will include the soil layers influenced by the foundation components. Additional shallow sampling and testing may be necessary to allow accurate predictions of near-surface soil-foundation interaction, and to assess the variation of soil stratigraphy across the site. Recovered samples, which are to be sent to an onshore laboratory, should be carefully packaged to minimize disturbance, changes in moisture content, and temperature variations. Samples should be labeled and the results of the initial inspection of the samples recorded, including soil fabric, color and sample disturbance.

10.2.2.5 Soil Testing Program

The soil-testing program should consist of in-situ and laboratory tests to establish classification properties for all significant strata and initial estimates of the soil's strength and deformation properties. When applicable, testing should be performed in accordance with ASTM or other applicable standards. Additional testing should be performed to define the creep and cyclic behavior of the soil to allow prediction of soil structure interaction due to sustained and cyclic loading. Some examples of the scope of deepwater investigations and the interpretation of data are given in Doyle (1998) [126]; Jeanjean, et al. (1998) [161]; Andersen and Lauritzen (1988) [90]; Andersen, et al. (1988) [89]; Andersen (1991) [91]; Dutt, et al. (1992) [130]; and Pelletier, et al. (1997) [207]. Consideration should be given to the performance of permeability and consolidation tests in order to understand setup effects for piled structures and capacity consideration for suction caissons.

Additional Studies—as applicable, additional analytical studies or scaled tests should be performed to assess the following effects:

a) scouring potential;

b) hydraulic instability and occurrence of sand waves;

c) earthquake ground response studies or analysis;

d) seafloor instabilities in the area where the foundation system is to be placed;

e) setup effects.

10.3 Loading

10.3.1 General

The basic definition of load types and conditions are found in Section 5. These definitions are amplified here as they apply to the foundation design.

10.3.2 Load Types

10.3.2.1 General

The load types defined in Sections 5 and 7.3 through 7.6 need to be considered as either static or cyclic loads when applied to the foundation design.

10.3.2.2 Static

A static load is an externally applied force of constant magnitude or a slow-rate monotonic load that behaves as a force of constant magnitude. Some loads that vary over relatively long time durations can also be considered constant. For example, the forces from movable drilling equipment or the forces due to astronomical and wind-driven tides and currents are considered static.

The long-term, sustained application of loads may induce creep movements in the pile and should be a consideration in the design of piling. These loadings may be due to several sources and include the mean tension load applied to the foundation during normal operations as well as potentially long duration loop current loading such as occurs in the Gulf of Mexico. The effects of these long-term loads on the soil undrained shear strength should be investigated and accounted for, if necessary, in the design of the foundation. Such effects can usually be investigated through creep tests on soil samples or through foundation load tests. See D.1 for more information.

10.3.2.3 Dynamic and Cyclic

A dynamic and/or cyclic load is due to an externally applied force or displacement that can produce time varying loads to the foundation system.

Cyclic forces can be classed as:

— cyclic recurring,

— varying forces induced by waves, and

— wind or earthquake motions.

Dynamic forces can be classed as:

— impact noncyclic forces induced by dropped objects, boat collision, or drill rig hook loads;

— temporary forces induced by an event of short duration such as those due to launching, lifting, placement, or pile driving.

10.3.3 Loading Conditions

10.3.3.1 General

Forces at the connections between the foundation and the tendons, risers and pipelines should be applied as loads. Loads due to the effective weight of the templates, appurtenances, piles, and conductors may be applied as appropriate.

For axial pile design where the weight of the foundation system is less than approximately 10 % of the ultimate axial capacity, the underwater weight of the foundation system may be subtracted from the applied loads in determining the safety factor of the foundations. For other weight-dominated systems, the foundation system weight should be added to the resistance side of the equation.

For the direct connection method, an installation tilt tolerance of at least 1° in lieu of other data shall be considered in developing the maximum loads applied to the pile. The loading conditions in Table 12 represent the minimum requirements for the analysis and design of the foundation system.

Table 12—Factors of Safety

Load Condition	Safety Category	Safety Factor
Normal environment	A	$2.0 \times B$
Extreme environment	B	$1.5 \times B$
Damage (with reduced extreme environment)	S	$1.5 \times B$
One tendon removed (with reduced extreme environment)	S	$1.5 \times B$

10.3.3.2 Extreme

Drilling and/or producing equipment loads appropriate for combining with tendon and riser forces and foundation system loads resulting from extreme environmental events.

10.3.3.3 Normal

Drilling and/or producing loads appropriate for combining with tendon and riser forces and template loads resulting from normal condition environmental events (conditions which occur frequently during the life of the platform).

10.3.3.4 Fatigue Loading

Consider the life cycle effects of cyclic tendon and riser forces and towing loads on the template, if used, and the cyclic tendon and riser forces on the piling. Fatigue damage due to pile driving shall be considered (see D.2).

10.3.3.5 Tendon Removed

A recurrence interval based upon the time required to replace a tendon should be determined. Tendon and riser forces imparted to the foundation system loads should be based upon the environmental conditions established for this case. A safety factor less than the long term is appropriate for this case when exposure is considered. Gulf of Mexico practice usually allows the B-factor (see 10.6.2) to drop to 1.33 for this case.

10.3.3.6 Transportation and Installation

Static and/or dynamic loads are imposed on the components of the foundation system during the operations of moving them on and off a barge, during tow and placement.

Environmental effects on transport vessel or self-floating motions appropriate to the tow route and installation site should be considered in determining the following.

a) Forces produced during lifting, launching, self-floating or lowering of the foundation system components.

b) Forces that result from on-bottom placement and leveling of the structure such as those due to mudmat reactions.

c) Impact forces due to latching and/or stabbing piles, tendons, and risers. The anticipated running rate and the effect of tensioning devices should be considered.

d) For driven piles, the static weight and impact load caused by the hammer should be considered. The effects of ocean currents on the freestanding portion of the pile and hammer assembly should be included if appropriate. In lieu of other data, a lateral load of 5 % of the underwater weight of the hammer shall be applied at the center-of-gravity of the hammer. The penetration of the pile should be calculated accounting for pile/hammer assembly weight, restraint offered by the template, and soil friction and end bearing. The length of the freestanding portion of the pile can then be determined. Guidance for Gulf of Mexico type soils is given by Doyle (1999)[127]. An installation tilt tolerance of at least 1° in lieu of other data shall be applied to column stability checks.

e) For foundation systems utilizing drilled and grouted piles, the effective weight of piles supported by the structure may be included. After grouting to the soil, a pile should not be assumed capable of carrying its own weight until after a suitable setup time. Pile buoyancy should be considered because of differences in internal and external fluid densities.

f) Pipeline pull-in forces on the foundation.

10.3.3.7 Seismic

See 9.4.2.6 and 9.5.

NOTE Vertical excitation is the significant seismic motion component that affects TLPs.

10.3.3.8 End of Construction

After the tendons are hooked into the foundation, pile foundations may not have achieved their long-term axial capacity. In that case, the *B*-factor (see 10.6.2) may be taken as less than the suggested minimum. Gulf of Mexico practice usually allows the *B*-factor to drop to 1.33 for this case. Several methods exist to determine pile setup as a function of time. One empirical method based on Gulf of Mexico data has been suggested by Bogard and Matlock (1990) [102]; Bogard et al. (2000) [103]; and Bogard (2001) [104]. Analytical techniques using finite element methods and complex soil models have also been applied to this problem (e.g. Whittle and Sutabutr, 1999 [243]; Whittle and Sutabutr, 2005 [244]).

At first production of hydrocarbons (i.e. “first oil”), the foundation shall have reached the minimum long-term factor of safety given in Table 12. Environmental loading conditions may be considered in the context of time of occurrence. For the Gulf of Mexico, the hurricane season is assumed to be between June 1 and December 1. If, for example, hydrocarbon production begins April 15, winter storm loading conditions shall be considered for the time period between the last pile installed and April 15, but hurricane loading conditions do not have to be considered until the time period between last pile installed and June 1.

10.4 Analysis Procedures

10.4.1 General

This section presents guidelines for analysis procedures for the response of TLP foundations under the loading conditions detailed in 10.3.2. Analysis is differentiated from design by the range of behavior (response) of the foundation and the need to provide an understanding of the primary factors controlling the interaction between structure, piling and the supporting soil for given geometry, soil characteristics, and loading conditions. Analysis provides the internal member forces and displacements for use in design.

The possible detrimental effects of conductor and well installation on foundation stability shall be considered in the design of the foundation system. However, it is permissible to ignore catastrophic well blowouts and other formation-induced effects if acknowledged in the design premise of the TLP.

10.4.2 Analysis of Piled-template Structures

10.4.2.1 General

Because piled foundation templates are similar to fixed platform foundations, the recommendations given in API 2A-WSD should be considered where appropriate. However, not all practices given in API 2A-WSD may be appropriate for TLP designs. These differences are discussed in this publication.

10.4.2.2 Template Modeling

The foundation template should be analyzed using a model that represents the geometric, stiffness, and damping characteristics of the structure. Normally, a 3D space frame model of the template should be used to predict load distribution and stress levels in members of the template.

Simpler 2D models may be sufficient if the geometry and loading characteristics allow such simplification. 3D analyses may be required to further check the validity and adequacy of any 2D analyses. The interaction between tendon connectors, template, and piles should be considered.

10.4.2.3 Soil Modeling

The manner in which the foundation soil is modeled and the selection of the values (and range) of engineering properties of the soil is important. The soil model should reflect the characteristics and interactive response of the affected soil zones and be consistent with modeling techniques and level of sophistication used for the rest of the structure. For example, the soil may be modeled as a continuum or a set of discrete springs.

Selection of engineering properties of the soil, such as undrained shear strength, effective friction angle, Poisson’s ratio, elastic and shear moduli should be consistent with the soil model, loading condition, and type of analysis. In addition, the designer/analyst should always evaluate possible variations and ranges of the parameters and assess the effects of these variations on the response of individual components and the overall system. Effects of possible earthquake-induced liquefaction, slumps, and other geological processes should be considered where appropriate.

10.4.2.4 Pile Soil Interaction

Where appropriate the pile may be modeled by discrete elements that account for the stiffness and damping characteristics of soil-pile interaction. For foundations with closely spaced piles, the effects of group interaction on response and capacity should be evaluated. The effect of large lateral deflections shall be considered. The effects of lateral load on axial behavior should be considered because of the consequences of large upward foundation movements.

10.4.2.5 Conductor Modeling

For a template with drilling conductor slots (whether separate or integral), the effect of the conductors on the behavior and strength of the foundation system should be assessed. The same analysis, design and installation considerations used for the pile would apply to a conductor, but with the addition of considering hydraulic fracture potential.

10.4.3 Analysis of Shallow Foundations

10.4.3.1 General

Shallow foundation practice is best described by ISO 19901-4. It is suggested that this reference may be the guide for shallow foundation design.

10.4.3.2 Mudmat Modeling

Mudmats, in general, are similar to those for jacket-type structures for analysis purposes. The designer/analyst should generally follow the recommendations in API 2A-WSD, accounting for the expected loading conditions and duration of service.

10.4.3.3 Gravity Template Modeling

Modeling of a gravity type foundation subjected to high eccentric uplift loads should consider the problems of potential suction under the base and lateral stability under the eccentric uplift loads, together with the interaction between foundation, soil, and skirts. Linear or nonlinear analysis methods may be used. Analyses should model the cyclic nature of the loads and pore pressure generation and dissipation under cyclic loads.

10.4.3.4 Suction Caissons

Shallow foundations practice does not specifically address suction caissons (also called bucket foundations and skirted foundations). However, there is sufficient literature to guide the design. The issues surrounding suction caisson design are discussed by Andersen and Jostad (1999, 2002) [92] [93] and Clukey (2001) [117]. A workshop sponsored by the Offshore Technology Research Center of Texas A&M University (Gilbert, et al. 2001 [145]) provides design guidance. In addition, an ongoing API study on suction caisson anchors and vertically loaded anchors is expected to provide additional design guidance for suction caissons and vertically loaded anchors. A future edition of API 2SK also will address vertical load capable anchors.

10.5 Design of Piled Structures

10.5.1 General

For piled-template structures the internal member forces derived by analysis (see 10.4) should be used to determine the required member sizes. Local details and secondary members such as pile guide cones, tendon stabbing cones, padeyes, grouting system attachments and other appurtenances not included in the analysis may be designed by detailed local analysis.

For the design of a steel template structure reference should be made to API 2A-WSD for allowable design stresses and fatigue estimation procedures. Reference should be made to Section 8 for the minimum design fatigue life of the steel foundation components.

10.5.2 Tendon Connection

The tendon attachment should be detailed to ensure all load components are safely transmitted into the main template structure or directly into the piles. Detailed analyses may be required to determine the stress distribution in the region around the connection. The template should be detailed to provide adequate clearance between the tendons and the template structure during the maximum platform offset, considering the effects of marine growth or debris.

10.5.3 Pile-template-tendon Connection

Piles may be connected to a template by grouted pile sleeves, mechanical connectors or other means. The use of shear keys on the pile and pile sleeve can significantly increase grout bond strength. Reference can be made to API 2A-WSD for the design of grouted pile-template connections. Detailed analyses may be required to determine the stress distribution in the region of the pile-template connection.

The piles may be directly connected to the tendons. In that case, the components of the foundation system are the pile top, receptacle, possible wall thickness transition section, main pile body and pile shoe. The pile top should be designed to accommodate possible lifting devices and the application of driving forces, but not allow the tendons to come into contact with the pile top during extreme environmental events. The receptacle should be a sufficient distance above the mud line to ensure that the tendon bottom connector does not touch the soil. Mud plug formation (i.e. a condition caused when the soil rises up inside the pile as the pile is driven) should be considered in the design especially where near-surface silts and silty clays are known to exist.

10.5.4 Installation Aids

Details of the template structure should consider the requirements for installing piles, tendons, and conductors. Appurtenances should be designed to withstand the effect of impact, driving, or other loads during pile installation.

10.5.5 Corrosion Protection

Corrosion protection should be considered for the pile-soil system. Reference can be made to API 2A-WSD for corrosion protection considerations. No coating should be applied to the pile outside diameter below seabed (except locally for penetration marking and weld protection) unless the skin friction of the coated surface is at least that of the uncoated pile. It is noted that coating of the upper 10 % of the pile penetration has been used in Gulf of Mexico TLPs to improve the performance of the pile/tendon cathodic protection system.

10.6 Design of Piles

10.6.1 General

Pile design should conform to the practice given in API 2A-WSD, except as noted in the following sections, for large lateral deflections, some group pile cases, axial pullout loads, and factors of safety.

10.6.2 Axial Capacity

Ultimate pullout capacity should be calculated using Equation 6.4.1-1 from API 2A-WSD.

$$Q = f \times A_\mathrm{s} \tag{71}$$

where

Q is the maximum vertical uplift load at failure;

f is the unit skin friction capacity;

A_s is the side surface area of pile.

The weight of the soil plug cannot be used in the design of piles. The basis for this is the two-way cyclic tests conducted by Doyle and Pelletier, 1985 [125] that showed the plug weight to disappear under two-way cyclic loading. If other publications indicate otherwise, the weight of the soil plug may be used if these data are appropriate to the diameter and loading conditions of the pile being designed. Although conservative, end bearing may not be counted upon unless appropriately related data indicates otherwise.

The design pile penetration, including the appropriate safety factors, shall be sufficient to develop adequate capacity to resist axial loads unique to TLP foundations. Allowance should be made for maximum computed axial tension load, cyclic degradation about a sustained tension load, axial flexibility of the pile, the effects of sustained tension loading, group effects, and the potential of near-surface axial capacity reduction from gapping caused by lateral loading, scouring, or liquefaction.

The minimum axial factors of safety in Table 12 are recommended for use in conjunction with Equation (71) for each pile in a group and to the group taken as a whole, where B is a bias factor modifying API 2A-WSD recommended pile factors of safety for tension pile applications.

Five specific aspects of pile foundation design are considered in the determination of the B-factor, as follows:

a) uncertainties in understanding soil-pile behavior under tensile loadings,

b) lack of residual strength of the soil-pile system,

c) load redistribution capabilities of the foundation system,

d) relative difficulty of foundation installation,

e) relative integrity of soil samples obtained from deepwater,

f) the possible deleterious effects of cyclic and/or sustained loading on soil-pile behavior.

Refer to D.4 for a detailed discussion of these factors.

The minimum value of B is 1.5 and is based on Gulf of Mexico experience and practice. B-factors different than this may be appropriate for other areas of the world. The considerations that make up the B-factor are discussed above and in D.4. Given the experience in the Gulf of Mexico, it appears that the primary consideration in determining the B-factor is the effect of sustained and cyclic loading on soil-pile behavior.

It is possible that the long-term safety factor may exceed the product of the API 2A-WSD safety factor times the B-factor. This can occur if the owner decides that the end-of-construction safety factor should be increased to minimize risk or that the owner decides that the pile should have a sufficiently high axial capacity to ensure that the pile will not fail before the tendons fail.

10.6.3 Laterally Loaded Piles

The ability of the piles to resist lateral loads and moments should be checked using the criteria given in API 2A-WSD.

Because it is a free-head pile, the direct-connect method may result in lateral deflections that exceed the criterion on which API 2A-WSD is based (see Matlock and Tucker, 1961 [186] and Matlock, 1970 [187]) (see D.5). While the load on each pile in a corner (i.e. in a group) is essentially the same, the piles will move independently through the soil experiencing different soil restraints unless the group has a cap or other restraint. For the case of the direct connect method, the piles should be treated as a two-pile group with a lead pile and a trailing pile. The lateral group effects are to be treated as shown in Equation (72).

$$\frac{(LP+TP)}{2} = GE \tag{72}$$

where

LP is the lead pile efficiency factor = 1.0;

TP is the trailing pile efficiency factor;

GE is the group efficiency.

The lead pile efficiency factor is 1.0 because it is considered to be resisted by undisturbed soil. The trailing pile has reduced efficiency because it is considered to be resisted by soil disturbed by the lead pile. Group efficiencies may be calculated by any number of the commonly used empirical and pseudo-theoretical methods in the literature. For piles in clay, the trailing pile efficiency factor may be used as a multiplier to the calculation of the ultimate lateral resistance, P_u.

10.6.4 Installation Method

10.6.4.1 Driven Piles

Refer to API 2A-WSD.

Drivability in clay has been correlated with deepwater field experience. Guidance on appropriate soil parameters is given by Dutt et al. (1995) [131] and Doyle (1999) [127] for Gulf of Mexico conditions.

10.6.4.2 Drilled and Grouted Piles

Refer to API 2A-WSD.

A deepwater environment may require special installation considerations, such as formation (hydraulic) fracturing, inspection and quality control.

10.6.4.3 Belled Piles

Refer to API 2A-WSD.

A deepwater environment requires special consideration of construction, inspection, quality control and formation fracture potential.

10.7 Design Of Shallow Foundations

10.7.1 Soil Characteristics

The ability of the soil to resist loads from shallow foundations should be evaluated by considering the stability against overturning, bearing, sliding, uplifting, or a combination thereof. The foundation load-deformation behavior is generally characterized using the stiffness and damping of the foundation. Soil properties needed for such an evaluation include, but are not limited to, the soil shear strength, moduli, compression index, and unit weight. An understanding of the present and past state of stress (stress history) of the soil deposit is also necessary.

10.7.2 Design of Gravity Template

A gravity template should be designed in accordance with the design practice given by ISO 19901-4.

10.7.3 Design of Mudmats

Mudmats are used to temporarily support the foundation template during installation and should be designed to consider short-term bearing failure, sliding stability and short term deformation in accordance with API 2A-WSD (shallow foundations). In the event mudmats are made a permanent part of the foundation template, their influence on the performance of the foundation should be considered. However, mudmats should not be relied upon to provide long term sliding or uplift resistance.

10.7.4 Site Preparation

Obstructions on the seafloor should be removed prior to template installation. The foundation surface should be prepared to avoid high-localized contact pressures. Voids between the gravity template structure and the seafloor should be considered and may be filled with grout to achieve effective contact during installation. The grout should be designed so that its strength properties are compatible with adjacent surface soil.

10.8 Material Requirements

Section 14 describes general material requirements. Items of special interest are: grout for a drilled and grouted-pile foundation, and the material connecting piles to templates and templates to tendons.

10.9 Fabrication, Installation, and Surveys

For design considerations arising from fabrication and installation requirements refer to Section 13. Monitoring, surveys, and maintenance requirements for the foundation are also provided in Section 13.

11 Riser Systems

11.1 General

11.1.1 Specifications

This section provides an overview of riser systems and their relationship to the overall design of tension leg platforms. API 2RD is presently the most relevant document for the design of risers operated from floating production systems. Sections 9.6.3 and 9.6.4 may be used for the design of riser girth welds and threaded riser connections. Other relevant design guidelines are as follows:

- ASME *BPVC*, Section VIII, Division 2;
- ASME B31:4 for oil export riser systems;
- ASME B31:8 for gas export riser systems;
- API 1111 for export risers systems;
- API 17E and API 17A for umbilical systems;
- API 17J and API 17B for flexible riser systems;
- API 16F for tensioner systems;
- API 17D and API 17A for connectors;
- API 17B for bend restrictors;
- API 17G for completion and workover riser systems;
- API 16Q for drilling risers.

11.1.2 Functions of Risers

A TLP requires risers to provide fluid conduits between subsea equipment and a surface platform. Riser integrity includes not only fluid and pressure containment, but also structural and global stability. Risers may perform the following functions on a TLP:

- export, import, or circulate fluids;
- guide drilling or workover tools to the wells;
- support auxiliary lines;
- serve as or be incorporated in a tendon system;
- other special functions such as well bore annulus access for monitoring or fluid injection.

Risers on TLPs cover the full range of production, injection, drilling, completion, workover, and exporting operations. When the function of risers and tendons are combined, structural design should also consider the requirements specified in Section 9.

11.2 Riser System Types

11.2.1 Top-tensioned Risers

Top-tensioned risers (TTRs) are generally vertically supported concentric tubular assemblies that are supported at the TLP deck level by some form of tensioner system. TTRs are typically manufactured from high-quality pipe utilizing threaded or flanged connections. The use of TTRs allows direct vertical access to a production or injection well for drilling, completion, or workover. Another advantage of TTRs is that wellhead and BOP assemblies can be located at the surface and not subsea.

Alternatively, TTRs may be locked off at the deck or hull pontoon level. In this event the riser design needs to particularly take into account the effects of vertical motion from wave frequency loads and springing (see Section 7).

TLP motions, particularly offset, are mitigated through the use of the tensioner system. Some examples of tensioner systems are hydro-pneumatic cylinders, mechanical springs and elastomeric struts that stroke up and down from a neutral position to maintain the structural integrity of the TTR. External buoyancy, as used for MODU drilling risers, may also be used for reducing TLP deck loads.

Stress joints at the bottom end of the TTR mitigate bending stresses resulting from TLP motions and allows for the connection of the riser to the wells down hole casing string.

11.2.2 Steel Catenary Risers (SCRs)

Steel catenary risers (SCRs) are generally hung off from a TLP in a catenary shape. Hard piping is used to interface between the riser and the host processing facilities. TLP motions are handled at the top end of the SCR through the use of either flex joint or stress joint assemblies. Flex joints alleviate bending stress at the top end of the SCR by allowing it to rotate. This is accomplished through the use of a combination steel shim-elastomeric assembly. By comparison, stress joints mitigate bending stress by changing the geometry and/or material makeup of the riser.

11.2.3 Flexible Risers

Flexible risers are generally hung off from a TLP in a catenary shape similar to SCRs. The principal difference lies in the unique sheathed construction of the flexible risers that allows the riser to bend without inducing significant stress. Bending stress-induced fatigue is similarly reduced. Compared to an SCR, flexible risers can have much simpler connections to the TLP since flex joint or stress joint assemblies may not be required.

Instead, bell mouths or bend stiffeners are used to limit the bending at the top end of the flexible riser. Careful evaluation of the connection arrangement should be considered.

11.2.4 Other Concepts

Other concepts available for risers, albeit not an exhaustive list, include steel lazy wave risers, hybrid riser towers, near-surface jumpers (e.g. production offtake to an offloading buoy) and risers fabricated from composite materials. Control, power, and chemical injection umbilicals also contain dynamic riser sections that shall be carefully engineered.

11.3 Design Considerations

11.3.1 Interface with Platform Structure

Information on riser installation, retrieval, operation, clearance, hydraulic or pneumatic supply, and structural loads is important for the design of the platform. This information will be needed for the design aspects treated in Section 7, Section 8, and Section 12.

11.3.2 Structural Integrity

The design load for each riser component should be based in part on riser response analysis. Such loadings as tension, bending, torsion, pressure, and thermal gradients should be included in component specifications. The resistance of the component to yielding, collapse and fatigue should be demonstrated by analysis and testing. The effect of accidental loadings such as dropped objects and snag loading (e.g. an anchor dragged across a catenary riser) should be included in the design. Such techniques as finite element analysis and strain gage testing may be specified.

A designer should recognize that risers are integral elements to the overall TLP production system and therefore the consequence of riser failure shall be addressed from an overall safety management point of view. The risk assessment process includes the identification of hazards, number of pressure barriers, frequencies of occurrence, assessment of failure consequences, and identification of prevention and mitigation measures.

11.3.3 Operational Considerations

The operator should develop procedures for safe and efficient risers operations that are suitable to the particular application. Such procedures should be developed in consultation with riser designers to ensure that limits established are consistent with the original riser specifications.

Operating procedures should cover all aspects of riser operations including, but not limited to the following:

a) platform motions and environmental limits;

b) storm and contingency operations;

c) manning requirements;

d) control, monitoring, vessel interface and ancillary equipment requirements;

e) riser deployment and retrieval;

f) riser in-service operations;

g) inspection and maintenance.

11.3.4 Effect of Risers on Platform Motions

The presence of TTRs generally leads to a reduction in platform offset. This is a result of increased stiffness of the TLP in surge and sway due to the tensioning of the riser assemblies, which may more than compensate for the effect of riser drag loads on platform offset. The presence of the TTRs also increases viscous damping, resulting in a reduction in low-frequency surge and sway motions.

The presence of catenary risers typically leads to a static offset of the platform. The magnitude of the static offset is dependent on the water depth, the size of the riser and the departure angle of the riser with respect to vertical. Generally, dynamic low-frequency surge and sway motions are decreased due to the increased stiffness of the TLP and due to added mass and damping of the risers.

11.4 Riser Analysis

11.4.1 General Considerations

Riser design requires that riser response-to-platform motions and environmental loads be obtained. Local forces and moments derived from the response analysis are then used for the design of individual riser components.

Riser design should be based on environmental loads and functional performance requirements. The riser loads include hydrodynamic forces of currents and waves, the motions of the platform, and the loads imposed by contained fluids and tubulars. Some functional constraints include top and bottom angles, steady and alternating stresses, and resistance to column buckling and hydrostatic collapse.

Coupled analysis is recommended when the effect of the risers on TLP motions is noticeable. When uncoupled analysis provides suitably conservative TLP offsets and motions for riser design, or when the influence of the riser system on offsets and motions is insignificant, coupled analysis is not required. In this case, the TLP motions can be calculated first and then treated as input for boundary conditions at the upper end termination of the risers.

11.4.2 Environmental Conditions

Analysis of the riser systems requires a thorough description of the environmental conditions that the platform and riser are likely to experience during their service lives. Operating, extreme, and survival sea states need to be defined in order to quantify the relationship between peak and allowable stress estimates for riser components. In addition, environmental parameters and associated probabilities of occurrence need to be defined for a full range of sea states in order to quantify component fatigue damage.

Risers systems are particularly sensitive to riser interference issues and to fatigue damage caused by VIV. As such, it is essential that site-specific current criteria be developed to assess these effects on the design. Current criteria should reflect both the magnitude of the current velocity at various depths and the directionality of the current.

11.4.3 Platform Data

11.4.3.1 Platform Configurations

In analyzing the global response of a riser, various platform configurations should be considered unless a platform configuration is selected that is demonstrably conservative for all cases. As a general rule, platform configurations that lead to larger platform horizontal offsets tend to increase riser stresses. Tendon pretension variations should be included directly in the global platform studies because the tendon pretensions will directly affect the offset predictions.

It is generally conservative to consider the platform to have no risers installed; however, this should be verified with some representative test cases. For operating, extreme and survival load checks, the bounding configuration should be used to ensure that the peak stress estimates are quantified.

11.4.3.2 Platform Response Data

The platform response to environmental loading is transmitted directly to the top end of the riser. Vessel motions constitute the primary source of dynamic loading on the riser. Analytical and/or model test data on platform response should be acquired in accordance with Section 7. Platform response data may be used for translating wave frequency motion into riser top motions. Long-period excursions and set down should be included.

11.4.4 Riser Interference

In general, riser-to-riser and riser-to-tendon interference should be avoided through appropriate selection of riser top tension, initial separation distance, and hangoff (vertical) and heading (horizontal) departure angles. In general, contact between risers should be avoided. Where contact cannot be avoided (i.e. ultradeepwater, in extreme design and survival environments) estimates of the frequency of contact, contact velocity, and resulting damage should be provided to demonstrate that contact will not cause dents, cracks, loss of buoyancy, or other serious consequences.

11.4.5 VIVs

VIV has an important effect on riser fatigue performance and interference. Current velocity, current profile, riser size, riser tension and riser proximity to other risers are all factors that influence VIV and should be taken into account. The fatigue damage due to VIV should be assessed and added to the fatigue damage due to storm action and platform motions, in order to arrive at an overall fatigue life prediction including all damage mechanisms.

It is often necessary to suppress VIV in order to achieve an adequate fatigue life. Suitable suppression devices (e.g. fairings, helical strakes, etc.) and corresponding span-wise coverage extent should be designed to achieve this end. Marine fouling reduces the effectiveness of these suppression devices. If marine fouling is expected, the assumed effectiveness of the suppression devices should be based on the worst expected marine fouling condition. Alternatively, a regular inspection and cleaning program may be instituted in order to keep the suppression devices free of significant marine fouling. The Marine Operations Manual for the host facility should specify the interval for the recommended inspection/cleaning program.

11.4.6 On-bottom Stability

The ability of a catenary riser to remain in-place during extreme environmental conditions is referred to as on-bottom stability. Stability of the riser is governed by its submerged weight and by either its vertical departure angle from the platform or its top tension. Excessive motions of the riser can lead to repositioning the touchdown point to an unfavorable position. As such, catenary riser systems should be designed to limit movement of the on-bottom riser sections to acceptable values such that all other design criteria are satisfied during and after extreme environmental events.

11.4.7 Thermal Growth

Production and drilling riser systems are likely to experience a wide range of temperature variation during their lives. Thermal effects have several consequences that shall be considered in the riser analyses.

The tensioning system shall be designed such that it can incorporate the peak thermal expansion of the riser system.

For concentric tubular riser assemblies, the amount of thermal expansion will differ between strings because individual tubulars are heated to different levels. This effect tends to alter the tension distribution between the individual tubulars even if the correct overall system pretension is maintained. In particular, the inner tubular may lose enough tension that it experiences some compression near the lower interface. Some compression is allowable provided it is shown that the compression does not lead to an increased risk of failure. A detailed analysis, in which the thermal expansion of each individual tubular should be considered during the various operational phases, is required to ensure that the tubular tensions and stroke requirements are adequately defined.

Temperatures of produced fluids should typically be maintained between minimum and maximum values specified by the facility design engineers. The production riser coating should be selected such that produced fluids are delivered at an acceptable temperature. Thicker riser coatings tend to retain more heat in the system and thus increase the temperature of the delivered fluids. Due to variations in fluid properties and/or flow rate, it may be desired to vary the thermal properties of the riser system over time. This can be addressed via varying contents in Annulus B, e.g. brine or nitrogen gas, effectively varying the thermal conductivity between the tubing and the seawater.

11.4.8 Uncertainty Allowances

Aside from capturing all normal variations that occur during the service life of a riser system, allowances should be made for uncertainties associated with the manufacture and installation of the riser system. Where applicable, the following uncertainty allowances should be considered in the assessment of riser system performance:

a) mill tolerance on pipe weight;

b) mill tolerance on pipe wall thickness;

c) pipe out-of-roundness;

d) pipe end machining;

e) pipe end tapering;

f) soil type, stiffness and strength;

g) departure angle misalignment;

h) flex joint angular stiffness;

i) wellhead angular misalignment;

j) wellhead position misalignment;

k) tension factor;

l) pretension uncertainty;

m) tensioner stroke range;

n) tensioner cylinder failure;

o) marine fouling;

p) corrosion.

11.4.9 Tensioner Allowable Stroke Range

For determining the required stroke range for the tensioning system the following effects shall be included:

a) thermal growth,

b) internal pressure,

c) platform offset,

d) storm and tide induced upstroke and downstroke,

e) load-ring space out allowances,

f) uncertainty margin.

The tensioning system design stroke range requirement can be expressed as the sum of these effects.

12 Facilities and Marine Systems

12.1 General

This section contains guidelines for planning, designing, and arranging facilities for a TLP, while recognizing the requirement for safe, environmentally acceptable, efficient production of oil and gas. This section includes hull systems, and addresses drilling and production considerations unique to a TLP.

This section covers the following on facilities and marine systems.

a) Identify interfaces unique to a TLP with regard to:

   — structures,

   — production systems,

   — drilling systems,

   — hull systems.

b) Emphasize and provide recommendations on the need to limit and control weight (dry and operating) and CG when selecting equipment and determining equipment arrangements.

c) Identify unique static or dynamic loads which could affect equipment selection.

d) Identify industry codes, standards, or guides which might be applicable to TLP design and which have acceptance by industry and governmental bodies.

e) Identify regulatory agencies' established requirements and indicate how they might influence design and arrangement of equipment. Provide guidelines for the selection of hull system equipment such as bilge, ballast, machinery, etc.

Detailed specific design guidelines for sizing, ratings, safety factors, etc., for equipment are not provided. The designer should refer to referenced codes and standards.

12.2 Considerations

12.2.1 Structural

The type of deck and hull structures adopted will affect facilities and marine systems design. Plate girder members and bulkheads will impose constraints on type and quantities of penetrations which may result in less than optimum routing of services. Structural design utilizing plate girders and bulkheads require early service routing agreement to assure that penetration requirements are identified in time to allow structural design to proceed.

Deck height limitations, desired to maintain CG as low as possible, can present facilities design with the following unique concerns:

a) restricted height for installation of gravity systems such as vents, drains, separation trains, etc. to allow for slope and required headroom;

b) a mezzanine level having height restrictions more severe than for fixed structure;

c) circumstances can dictate that some equipment be installed on the main deck when optimal locations may be on lower decks.

Weight restrictions can dictate selection of minimum deck area loading criteria (PSF) and maximum total load for a given area. Requirements for higher deck area loading for maintenance (egress, set down and handling of equipment/machinery) need to be established early in design.

12.2.2 Arrangements

The principles of good practice, as applied to any offshore structure, should be observed in the arrangement of equipment. For planning equipment arrangements, the guidelines provided in API 2G (historical) should be consulted for facilities design. The relatively broad column spacing required for stability will probably permit convenient equipment arrangements on the available deck area. In addition to the equipment spacing considerations provided in API 2G (historical), the following items should be considered.

a) A TLP is sensitive to the effects of weight and CG. The effects of equipment arrangement/selection shall be given special considerations during the planning stages.

b) Area classifications and the separation of hazardous and nonhazardous areas need early resolution to minimize the need for additional bulkheads, long vent ducting, or additional structure.

c) In the hull as well as on the deck, adequate escape routes and equipment maintenance access should be given attention since imposed space limitation will require compromises probably greater than those found on fixed offshore structures. Use of fiberglass grating should take careful consideration of ability to exit the hull in case of fire.

d) Installation of production or drilling equipment in hull spaces will provide greater flexibility in CG location, but will require special venting and bilge requirements and will have other design penalties.

e) The hull structure may provide available space for consumable storage. Location of storage tanks upon or under the deck presents additional operating weight, load, and stability concerns.

f) Influent and discharge casings should be located to prevent recirculation. Consideration should be given to whether seachests or long casings are best suited for seawater intake, keeping watertight integrity in mind (see 12.9.3).

g) The benefits provided when enclosing areas should be weighed against structural weight penalties.

12.2.3 Weight and Center of Gravity

Control of weight and CG location are essential during design and should be an initial design consideration. Weight and weight distribution will affect both the steady and dynamic tensions in the tendons.

Preliminary weight estimates should be as accurate as possible and adequate margins should be provided. Margins should be allowed for estimating inaccuracies, design growth, fabrication deviations, and platform operating requirements so that, when completed, the platform will remain within the established design parameters. Equipment, machinery, and tanks which present heavy concentrated loads require early coordination with global response analysis disciplines. Operational fluids should be included in initial weight estimates.

A strict policy of weight control should be implemented throughout design and fabrication and weight margins reduced as verified weight information becomes available.

12.2.4 Dynamic/Static Loads

In addition to the static and dynamic loads encountered on fixed platforms, a TLP is subject to horizontal accelerations throughout its operational life. The designer should become aware of the methods available to determine the effects of these loads on facilities equipment. Section 7 of this recommended practice provides data on what acceleration forces may be expected. In addition, special loading conditions should be anticipated for construction, tow-out and temporary mooring phases.

12.2.5 Construction, Transportation and Installation

Methods of construction, transportation, and installation have a basic influence on facility design. The designer should become aware of the methods planned for construction, transportation, and installation to assure that design criteria selected support the various phases of the project and final integration.

12.2.6 Environmental and Geographical Issues

The degree of environmental protection required is a function of the final geographic location. The personnel and equipment protection options, such as wind walls, enclosed structures, heating, ventilation, and air conditioning requirements and their impact on equipment arrangement, stability, weight, and CG should be considered.

12.2.7 Resupply

Platform location and prevailing weather conditions should be evaluated to establish an acceptable cycle for consumable resupply to minimize required consumable storage. The location and the maximum weight of supplies should be considered in the weight estimate. Regulatory requirements could have an impact on consumable storage requirements and should be investigated. The TLP design optimally will incorporate the effects of resupply so that ballast adjustments during resupply are not necessary.

12.2.8 Simultaneous Drilling and Production

Weight and CG penalties are associated with simultaneous drilling and production. Drilling of wells prior to installation of production equipment could result in a significant reduction of topside loads. However, weight savings achieved may be at the expense of future drilling program requirements.

12.3 Drilling Specific Considerations

12.3.1 General

When establishing a drilling program, attention should be given to the potential effects of this program on weight and center of gravity. Depth and drift angles, along with casing, mud, and completion programs can determine equipment, storage, utility, and consumable requirements. These requirements may have weight and space impact. Early coordination of the drilling program with other design disciplines can minimize storage and equipment size. Design criteria which specify simultaneous drilling live loads for two rigs present weight and CG penalties. Shared utilities (such as electrical power, utility air, fuel, etc.) between production, hull systems, and drilling should be considered to minimize equipment/machinery requirements.

12.3.2 Modular Package

A modular package approach is often used when designing drilling rigs. Alternative approaches such as palletizing equipment and integrated deck design should be considered because of the TLP sensitivity to weight. Minimum equipment size which meets realistic drilling program requirements should be planned.

12.3.3 Pollution Containment

Drilling system discharges (cement slurry, oily water, clean water, solids, bit cuttings, or chemical discharges) should be integrated into the overall pollution containment and drainage system. Care with the arrangement/routing of cement discharges is suggested to avoid coating or blockage of drain lines resulting in additional weight/CG considerations. The close coordination between drilling rig and facility design is recommended to assure efficient interfaces.

The location of discharge casings for cement slurry, bit cuttings and other solids should consider the effect of settlement or cement fouling of Subsea equipment and suction sea chests. Discharges that can contain solids should not be located where they can accumulate on horizontal surfaces.

12.3.4 Tank Sizing and Arrangement

Mud (wet and dry), cement, drill water, and fuel storage requirements should be identified after the drilling program has been established. These consumables require significant space and present concentrated loads on the platform. Their location and effects on CG should be carefully considered since their relocation after final design is in progress could result in extensive redesign or use of ballast adjustment allowances. Horizontal accelerations during operation could require tank baffling. CG or weight sensitivity may require integrating tanks into the deck structure and/or hull. If so, fire and gas system effects should be carefully considered, as air change requirements required by the presence of hydrocarbons may impede the performance of gas and smoke detectors.

12.4 Production Systems Considerations

12.4.1 General

Initial facility design should emphasize the early establishment of firm design premises, equipment sizing, and layouts in order to establish accuracy in weight estimates.

Where the process system design and equipment selection and location should stress weight reduction and low center of gravity, some additional items to be considered are:

a) minimizing surge and storage capacities,

b) use of horizontal vs vertical separators (to minimize retention time),

c) use of centrifugal or vane type pumps and compressors vs. reciprocating units,

d) use of high strength materials and higher equipment operating speeds,

e) use of gas turbine vs reciprocating drivers,

f) use of central electric power plants vs individual engine drivers,

g) shared use of production and TLP utility systems,

h) liquid storage integrated into hull and deck structures,

i) use of plate frame heat exchangers vs tubular heat exchangers,

j) lightweight valves and fittings.

TLPs are subject to vertical, horizontal, and rotational movements which vary in magnitude in both the moored and tow modes. Such movements and the associated forces generated should be considered in the design of support structures for piping, vessels, and other facility equipment as well as in the design of riser connections. Installation of baffles in storage tanks and process vessels should also be considered to restrict liquid movement and stabilize process levels.

Cooler wellhead temperatures and possible hydrate formation due to extreme water depths may require additional equipment considerations. Chemical storage needs should be considered early in the platform design.

The recommended practices of API 14C for design and analysis for surface safety systems should be consulted. API 14E and ASME B31.3 should be consulted for piping systems.

12.4.2 Packaging

Integrated deck construction provides potential weight and space savings but requires close facility/structure design coordination.

12.4.3 Drain System

It is recommended that topsides drains should be kept separate from bilge systems in the hull (see 12.5.1).

The facilities drain system guidelines provided in API 2G (historical) and API 14G should be consulted. Unique considerations for the TLP are:

a) liquid accumulations in drain system should be kept to a minimum,

b) low deck heights could limit gravity drain system capacity within deck spaces,

c) acceleration forces may affect flow of liquids in gravity drain systems.

12.4.4 Area Classification

When determining the extent and boundaries of hazardous areas on production decks, the following should be considered since they will influence design, arrangement, and type of equipment:

- API 14F,
- API 500,
- API 505,
- NFPA 70.

The extent and boundaries of hazardous areas on production decks is covered in API 500 and API 505. The designer should expect the applicable regulatory agency to examine the plans to determine the overall effect on general safety.

12.4.5 Utility Systems

Utility systems account for a large portion of the total topside equipment. Sharing of these utilities between drilling, production, and hull systems will provide opportunities for weight savings.

Utility demands should be controlled with demand margins identified and modified as the information becomes available.

Applicable regulations and codes that apply to individual drilling, production and hull systems could be imposed on the overall shared utilities.

12.4.6 Riser Connection

The production and pipeline risers present special conditions due to the relative motion between the deck and risers. In selecting a flexible connection to accommodate this relative movement, the following should be considered.

a) Vertical pig launcher/receivers may provide a more desirable solution than horizontal, since a vertical launcher can be mounted on the riser structure.

b) Well shutdown sequences should consider subjecting flexible connections to well shut-in pressure.

c) Amount of wellhead spacing required because of space required for flexible connection.

d) Export Oil Pipeline Riser Flex Joints—the designer should consider the effect of temperature on the long term durability of the elastomers.

12.4.7 Vent/Flare System

Vent system design should be studied early in the design. Since these structures will have significant effects on weight, wind loading and center of gravity, it is important to establish realistic relief rates and system sizing criteria in the initial design phase. API 520 (all parts), and API 521 provide guidelines for pressure relief systems. Dynamic loads from platform accelerations should be considered during the design of flares, vent stacks, and booms.

12.4.8 Riser Tensioner Support System

Many tensioning systems utilize high-pressure gases to minimize riser tension fluctuation in response to platform motions. Such tensioners act as air springs maintaining nearly constant tension on drilling, production, and pipeline risers, while the platform moves with the wind, waves, and current. Similar tensioners may be used during tendon installation to apply tendon pretension while also acting as motion compensators. Tension device guidance can be found in API 16Q.

As a minimum, the high-pressure gas supply system should provide a dew point below the temperature realized with expansion cooling from design pressure and minimum design temperature to atmospheric pressure. Pressurization of any tensioner should be possible without recharge of storage. Design of storage volume, standby supply, compression capacity, and redundancy should consider the potential effects and allowable time of response to partial or complete depressurization of any single tensioning device.

Necessary utilities for supply of high-pressure gas should be available during the installation phase.

The potential for ignition or explosion of hydraulic fluid/high-pressure gases should be considered in the design of tensioning equipment and selection of fluids.

12.4.9 Subsea Inspection Support

Plans for subsea inspection and maintenance should be made early in the design process. Space and weight allowances and any utility requirement for diving support/inspection and/or ROV facilities need to be made prior to finalizing equipment arrangements.

12.4.10 Navigation Aids

The platform shall have obstruction lights and fog signals installed. Applicable guidance for these requirements is found in 33 *CFR* Subpart 67.

Depending upon the installation site as it relates to the Outer Continental Shelf line of demarcation, the structure will be classed A, B, or C. Obstruction light and fog signal requirements for these classes are detailed in 33 *CFR* Subparts 67.20, 67.25, and 67.30, respectively.

While being towed to the installation site, the platform is required to exhibit appropriate navigational lights as prescribed by the *International Regulations for Preventing Collisions at Sea*, 1972 (72 COLREGS). Rule 24a is the pertinent section, and it requires a platform being towed to exhibit sidelights, a stern light, and when the length of the tow exceeds 200 m, a diamond shape where it can best be seen.

12.4.11 Accommodation Area

When establishing accommodation needs, the USCG regulations will influence the design. See 46 *CFR*, Subchapter I-A Parts 107 to 109, and in particular Part 108, Subpart B for guidance in U.S. waters.

The accommodation area will probably have significant effects on wind loading and center of gravity. Its size and location should be finalized early in design. Installation of the accommodation requirements wholly or partly within the deck structure should be considered.

12.4.12 Helicopter Facilities

Facility design for helicopter operation should review the requirements of 46 *CFR* Parts 108.231 to 108.241 and Parts 108.486 to 108.489, for USCG considerations. In addition, the following are of use for design guidelines.

a) API 2L—API 2L at last review, was unacceptable for sizing floating structure helidecks. Helidecks for floating platforms should be in accordance with IMO MODU code. ICAO (International Civil Aviation Organization) also has an acceptable code.

b) FAA Advisory Circular 150/5390-1B—This booklet sets forth requirements for marking towers, poles, and similar obstructions. Platforms with derricks, antennas, etc., are governed by the rules set forth in this booklet. Refueling requirements for helicopters should be considered when required. Special attention to fire fighting and area classification requirements of regulatory agencies is advised.

12.4.13 Cranes

The methods for establishing rated loads for cranes can be found in API 2C. 46 *CFR* Parts 107.258 to 107.260 provides additional requirements for crane certification, inspection and testing. In addition the effect of TLP motions on all crane operations should be considered.

12.5 Hull System Considerations

12.5.1 Bilge

With the exception of ballast compartments, all compartments, passageways, and machinery spaces in the hull should be serviced by a bilge liquid removal system. Provisions for removal of bilge liquid should be made for installation, free-floating, and fabrication phases. Watertight hull compartments and hazardous and nonhazardous spaces should be provided with separate drainage or pumping arrangements.

All valves in machinery spaces controlling the bilge suctions from the various columns or hull compartments should be remotely actuated type; where fitted at the open ends of pipe, the valves should be of the non-return type.

Bilge pumps should be of the self or automatic priming type and capable of continuous operation in the absence of liquid flow. Bilge pumping capacity should be sized in accordance with applicable regulations. For machinery spaces containing equipment essential to safety, independently powered pumps should be considered with one pump supplied from an emergency source. Any hull compartment containing equipment essential for the operation and safety of the platform should be capable of being pumped out when submerged. Provisions should be made to dewater flooded machinery spaces with consideration given to the inclined angle possible during installation. If bilge piping is tied into the topside treatment facility, back flow of liquids or gas into the bilge system should be prevented. Void compartments drained by portable means should incorporate appropriate measures, such as lock-closed bilge valves and blinded ends, to ensure watertight integrity while bilging operations are not being conducted.

Bilges from areas normally containing hydrocarbons should be routed to a separation vessel prior to discharge overboard.

12.5.2 Ballast

The ballast system design serves numerous functions, including:

a) adjustment of platform center of gravity during fabrication, towing, installation, and operation;

b) TLP draft changes during fabrication, hull/deck mating, floating-out, tow, and installation;

c) tendon tensioning or tension adjustment;

d) hull compartment dewatering for inspection, or maintenance, after installation;

e) damage stability, correction of center of gravity.

Sizing of the ballast system should be done based on operation, initial launch, installation, integration, damage, and wet tow requirements. Damage requirements are also a sizing case. The TLP shall be able to make ballast compensation sufficient to meet the “compensated” load case criteria as defined in Section 5 (see Table 1) within a reasonable period of time that is determined by the designer and operator. If the TLP does not need any ballast change to meet any of this time based criteria, there is no implied pump rate capacity.

Redundancy and reliability of utilities, control and monitoring instruments and equipment during all phases of TLP operation should be given design emphasis and priority. A single point failure on any piece of equipment, or flooding of any single watertight compartment, should not disable the damage control capability of the ballast system. Where it is apparent that the free-floating inclined damaged condition trim (pre-tendon hookup) impairs the operability of the ballast system, additional means are to be provided for this phase of the operation.

Ballast pump and controls should be designed for numerous differential head conditions without damage due to excessive velocity or cavitation. Dewatering of ballast compartments may require a separate stripping system to lower the water below the level set by main ballast pump net positive suction head (NPSH) requirements. The stripping system may also serve as a partial rate backup to the ballast system. Provisions should be made to dewater flooded machinery spaces with consideration given to the inclined angle possible during installation. Integrating seawater supply and ballasting functions into a common system should be considered, but the reliability of the ballast system for in-place operations should not be impaired.

Control systems should be provided to prevent accidental opening of flooding valves for all modes of operation. Blinding off of systems not in use should be considered. The ballast system design should prevent uncontrolled flow of fluids passing into one compartment from another whether from the sea, water ballast or consumable storage. Ballast tank valves should be designed to be normally closed except when ballasting. It is recommended that ballast valves be set up to fail closed.

If the ballast system is intended to serve as a backup to or as an emergency bilge pump, using a cross connect, then check valves or other means of preventing backflow shall be provided.

Remote controlled ballast tank valves should fail closed and should be provided with open and closed position indication at the ballast control station. Position indication power should be independent of control power. Local position indication and control should be available at the valve.

The potential for hazardous contamination of the ballast system and tanks should be considered in the design and appropriate access should be provided for maintenance. Selection of tank vents and overflow locations should consider damage stability effects and installation design cases. Tank vents and overflows should be located so that they will not cause progressive flooding unless such flooding has been taken into account in the damage stability review. Arrangement and design of the vent systems should prevent liquid accumulation in the vent pipes.

12.5.3 Hull Systems Utility

Hull system utilities are those required for life support and functional operation of the platform excluding drilling and production. The TLP presents no significant unique utility requirements from those found on fixed structure platforms. However, as in process design, weight reduction and lowering of CG should be stressed. The considerations of 12.4.5 should be investigated for application to utilities.

12.5.4 Electrical

API 14F provides recommended practices for electrical design which should be consulted. IEEE 45 provides guidance for floating hull electrical design. The designer is advised to investigate all applicable regulations during initial design because they will influence design of the hull electrical system. 46 *CFR*, Subchapter J, establishes requirements for safe electrical installations and repair aboard vessels and mobile offshore drilling units in U.S. waters. Because of the similarities between the TLP and a MODU, the designer should anticipate that MODU rules may be applied to electrical installations.

When designing cable systems in the hull of a TLP, the designer should take into consideration the combustion byproducts of cable when choosing cable and cable materials. Flame retardant, fire resistant, smokeless, and zero halogen qualities are all characteristics of some cable that may be useful to the designer in making the hull safer during fires. Stainless steel cable ties should be used, and cable tray hangers should be the trapeze type to prevent cables hindering personnel escape during a fire.

Cable penetrations in hull bulkheads need to be rated for the same pressure rating as the bulkhead. Corrugated cables passing through a multicable transit may impede water tightness of the transit unless transits are designed for this use. Care should be taken with the use of multicable transits. If elastomer type cable transits are used a double row in a single penetration sleeve will allow pressure testing during construction and, if desired, for periodic inspections (see 12.9.2).

Electrical systems shall avoid cable splices that will be under water, such as for sump pile pumps. Specialty cables for home runs to junction boxes in the deck should be considered.

Tendon monitoring systems should be considered an essential system, and as such should be powered by an uninterrupted power supply (UPS). Other systems will also be considered essential systems as determined by regulatory bodies.

When designing any wireless systems that need to reach locations in the hull (i.e. handheld radios), consideration shall be given to the potential for blockage from steel bulkheads/grating.

Noise within the hull is amplified due to the hull structure and shape. This fact needs to be taken into consideration when placing equipment in the hull.

When designing the hull lighting system, special attention shall be paid to structural elements. The areas around these items are often forgotten during design and the resulting low lighting levels can cause a safety/tripping hazard.

Electrical equipment should be located to avoid the potential for submersion or splashing, or should be rated for submersible service. Require submersible equipment in areas that may be submersed at some point.

Regulatory requirements between hull and deck may differ between regulatory bodies (i.e. maximum allowable current carrying capacity allowed for cables based on temperature for MODUs or TLPs in U.S. waters).

Electrical system design shall take into account hurricane abandonment power needs. Use of a separate generator should be considered in case of damage to main, auxiliary, or emergency generators. If a battery backup system is provided a low-voltage battery disconnect should be considered for the condition where all generator fuel is exhausted and all useable battery power has been drained. This would protect the batteries from total discharge and the probable need for full replacement.

12.5.5 Hull Ventilation/Dehumidification

If applicable, 46 *CFR* Parts 108.181 to 108.187, and ABS 6 shall be adhered to. SNAME 4-16 may provide design guidance.

The following are design considerations.

a) Ventilation requirements for hull inspection and its impact on multiple compartment flooding.

c) Increased pressure drop due to long duct runs for fresh source air and discharge.

d) The need for powered air circulation to column/pontoon areas.

e) Ventilation rates (air changes per hour) should consider at a minimum the usage of the space and its area classification.

f) Care should be taken when locating intakes and exhausts to minimize recirculation of exhausted air.

g) Ventilation inlets should be located in nonhazardous areas.

h) In the case of nonhazardous ventilation duct passing through a hazardous area an overpressure in the nonhazardous duct should be maintained in order to avoid contamination.

i) In the case of hull spaces dependent upon ventilation to maintain area classification care should be taken to avoid a condition where loss of ventilation results in a loss of area classification and the necessity to shut down the facility. Ventilation fan redundancy or other means should be considered to avoid this possibility.

j) Black start procedures for classified areas should be developed early in the design, which consider the potential for explosive gas mixtures in hazardous area compartments following an extended shutdown of facilities.

k) The inside of the duct and related in-line components should be considered to have the same area classification as the space it is ventilating.

l) It is recommended that gas and smoke detectors in ducts be placed in a position which eases periodic inspection of these items. Remote tubing to detectors is one method of accomplishing this.

m) Ventilation lines passing through watertight bulkheads for a normally ventilated space shall include an actuated, fail closed, watertight valve attached to a bulkhead penetration capable of resisting the expected differential head pressure in a damage condition.

n) Noise attenuation studies should be conducted to limit or mitigate the noise level of ventilation fans. Consideration should be given to noise hindering personnel communication either directly or via communication devices. In high noise level environments, general alarm sounding devices may need to be supplemented by visual devices such as flashing lights.

o) Appropriate measures should be taken to protect personnel from asphyxiation hazards when routing nitrogen or other inert gases into the hull.

p) Desiccant-type dehumidification equipment may require a UL certification for USCG if the platform is located within U.S. jurisdiction.

12.5.6 Hull Machinery Area

In the arrangement of machinery, provisions for the safety of personnel responsible for the repair and maintenance of the equipment should be considered. Provisions should be made to ensure that all equipment installed and operated inside the hull can be readily serviced or replaced. The equipment should be placed and protected to minimize the probability of mechanical injury or damage by leaks or falling objects. Clear working space should be provided around the equipment to enable personnel full access for inspection or repair of the equipment as required as well as its handling and operation. Electrical equipment liable to arc should be ventilated or placed in ventilated spaces in which dangerous gases and oil vapors cannot accumulate. Additionally, the layout of machinery should incorporate the following provisions:

a) complete access to the areas as required for manual fire fighting where necessary,

b) personnel safe escape routes in an emergency,

c) facilities for the remote shutdown of any equipment during an undesirable event,

d) equipment handling facilities.

Due consideration should be given to understand the full extent of primary steel intruding into the areas reserved for equipment, piping, cable tray, access/egress.

Structural tripping brackets, high-fatigue zones, critical weld inspection zones, etc. should be taken into account and clashes/interferences avoided.

12.5.7 Hull Area Classification

When establishing classification of hazardous areas for hull system equipment, the following will influence design, selection, and arrangement of equipment:

— API 500;

— API 505;

— 46 *CFR* Part 111.105 (Subchapter J);

— *National Electrical Code*, Article 500.

12.5.8 Hull Compartment Penetration, Access and Inspection

Penetration plans and locations shall be addressed and fixed early in the design process since structural analyses and facilities routing plans cannot proceed without mutually agreed penetration locations.

When locating watertight hatches, and doors, care should be taken that a hatch is not placed so that an operator would have to push upwards while standing on a ladder. During compartment Inspections, hatches should be dogged open to ensure quick exits from the space.

The designer should consider the following.

a) Provision should be made in piping design for the effects of expansion and contraction due to thermal and structural effects.

b) Access/egress should be provided from all hull access and inspection spaces. Personnel access cannot be impeded by equipment.

c) Ventilation and access requirements during inspection of hull compartments might create potential for multiple compartment flooding.

d) Ventilation shall be provided to remove potential accumulation of hazardous vapors prior to entry. A means for verification of safe atmosphere prior to entry such as sampling connections should be provided on all hull compartments. Provisions for portable detection devices should be planned for hull inspection. Remote air sampling should be planned for closed compartments requiring inspection access.

e) Bulkhead configurations, tank layouts and tank access openings should be designed to facilitate safe tank inspection activities. The preferred layout of tanks, where feasible, is such that tank entry occurs from a normally accessed adjacent compartment, such as a machinery space. Tank entry from an adjacent tank or void compartment is discouraged.

f) Where nonvolatile fluids are stored in an integral hull storage tank, the preferred tank access method is side entry near the bottom of the tank. A method to safely open/remove the tank manways should be provided, such as the provision of a davit or an overhead padeye/lifting aid. Where top-entry manways are provided, permanently installed access ladders terminating at the tank floor should be considered.

g) Consideration should be given to providing a separate utility access opening into the tank to route temporary cable, hoses and other equipment required to support tank inspection/maintenance activities. Cable, hoses, and equipment (such as temporary ventilation fans) should not block the manway that serves as the primary means of egress from the tank. The provision of scaffold clips on vertical bulkheads should be considered to allow easy installation of scaffolding to support inspection/maintenance activities. Tank egress design should take into consideration the need to remove injured personnel from the tank.

12.6 Personnel Safety Considerations

12.6.1 General

Regulatory agencies have established certain requirements for personnel safety which will affect the design. The designer is advised to consult the regulations identified in this section during initial project planning.

12.6.2 Means of Escape

The space limitations imposed will require early planning for means of escape for personnel. Each space that is:

— an accommodation space over 28 m^2 (300 ft^2),

— continuously manned, or

— used on a regular working basis.

The above spaces will need two means of escape. Escape means should be planned to allow personnel to move from the uppermost level of the TLP to successively lower levels to lifeboats and, if possible, the water level. Whenever possible, two separate isolated escape routes from any working or accommodation area should be provided. Fire and gas systems provided in a column structure should consider the effect on a person trying to exit from below this space. Use of CO_2 or other asphyxiating gases may then be more of a hazard then a benefit.

Use of composite materials cable tray, grating, or pipe within an enclosed hull compartment shall take into account the smoke and flame characteristics of the fiberglass. If located within U.S. waters, USCG 16000.7A provides guidance in this area.

When planning/arranging escape routes, the following should be considered since they can influence the design:

- Outer Continental Shelf activities, 33 *CFR* Part 142;
- requirements for MODUs, 46 *CFR* Parts 108.151 to 108.167;
- IMO safety of life at sea (SOLAS).

12.6.3 Life Saving

The following regulatory requirements may influence the design criteria for life saving:

- Outer Continental Shelf activities, 33 *CFR* Part 144;
- requirements for MODUs, 46 *CFR* Parts 108.501 to 108.527.

These regulations stipulate requirements for lifeboats, life rafts, ring buoys, preservers, communications, distress signals, and methods of embarkation

12.6.4 Alarms

A general alarm system is required. The system should be capable of being activated by manually operated alarm boxes and by an automatic fire detection system.

The alarm system should be continuously powered with an automatic change over to standby power in case of loss of normal power supply. The alarm system should be designed to handle simultaneous alarms with the acceptance of any alarm not inhibiting another alarm.

The alarm system is required to be audible in all parts of the platform. In high ambient noise level working areas, a visible means of alarm should be provided.

The following regulatory requirements may influence the design criteria for alarms:

- electrical engineering regulations 46 *CFR* Part 113.25,
- outer continental shelf activities 33 *CFR* Part 146.

These regulations stipulate specific requirements for alarm systems.

12.7 Fire Protection Considerations

12.7.1 General

API 2G (historical), API 14C, API 14G provide guidelines on design of fire protection systems and should be consulted.

Regulatory agencies have established certain requirements for fire protection which will affect the design.

The designer is advised to consult the regulations specified herein plus those of the country the platform will be located in, during initial design.

Due consideration should be given to 46 *CFR* Part 108 requirements which provide guidelines for MODUs for platforms in U.S. waters. Further guidance can be found in:

- USCG NVIC 6-72, including Change 1;
- USCG NVIC 9-97.

12.7.2 Structural Fire Protection

NVIC 9-97 provides regulatory guidelines for structural fire protection for floating platforms in U.S. waters.

The merits of an active or passive system for protection of the structural steel should be determined. Considerations are:

a) active systems can increase water system capacity requirements and demand provisions for drainage for fire water runoff,

b) passive system materials such as intumescent coating provide protection but may not represent a minimum weight solution,

c) requirements for structural inspection may be more onerous with a passive system coating,

d) testing requirements for active system.

The potential for ruptured utility and instrument air lines to feed a fire in the hull should be considered in the analysis of the fire protection strategy.

12.7.3 Detection Systems

Gas and fire detection systems utilized on fixed structures are applicable to TLPs. ABS *Rules for Building and Classing Offshore Installations* provides guidelines. In U.S. waters, 33 *CFR* Part 144 provides guidelines along with 46 *CFR* Parts 108.404 to 108.413.

ESD philosophy should consider whether:

— receipt of a fire or gas signal inside the hull justifies a platform shutdown, and

— shutting down ventilation inside the moonpool is in fact, the best resp;nse to detection of gas inside the moonpool.

12.7.4 Fire Extinguishing

46 *CFR* Part 108 provides regulatory agency established requirements in U.S. waters. The NVIC 6-72 and NVIC 6-72, Change 1, provide accurate interpretation of the regulatory rules. The following are design considerations.

a) Use of sea chest vs outside casings for firewater lift pump. (External pump casings reduce watertight integrity issues).

b) Location alternatives for diesel powered fire pumps versus:

   — use of electric power pumps with separate power source, or

   — diesel hydraulic units.

c) Use of lightweight piping for firewater where permitted by regulations can be considered, but use of composite piping materials inside a hull structure introduces additional design issues such as fatigue, watertight integrity, and smoke and flame ratings.

d) Hull system protection using deluge should consider the possible impact on bilge pump sizing.

12.8 Interacting (Interfacing) Checklists

12.8.1 General

An optimized design will require close coordination between the facilities designer and other design disciplines. See Annex E for drilling and production interacting checklist that can assist in identifying coordination points. A good working design is often seriously weakened by a lack of definition between the various design disciplines on how the drilling rigs interface with the TLP. Drilling rig interface points with TLPs are identified in 12.8.2 through 12.8.11.

12.8.2 Structure Layout Interface Checklist

Structure layout interface considerations include:

a) position and strength of beams and trusses on platform deck(s);

b) allowable loadings for deck areas between major support members;

c) deck layout plans for open areas;

d) design loads due to wind on drilling packages;

e) dynamic loads from drilling packages resulting from horizontal accelerations of platform;

f) loading conditions from drilling packages due to construction, tow out and temporary mooring phases;

g) CG and weight impact due to rig layouts, drilling live loads, and rig packaging/module design;

h) rig skid beam spacing, position, and strength;

i) jacking systems that can be accommodated;

j) elevation of well heads;

k) strength and layout of local beams around wellhead area;

l) strength points available for pulling heavy loads; e.g. hanging bop units;

m) position of “rat” and “mouse holes” (beam web penetrations placed for internal tank draining);

n) access into/out of the hull for equipment when the drill rig is in place;

o) increased accommodation needs;

p) use of brine tanks in the hull.

12.8.3 Utilities Interface Checklist

Utilities interface considerations include the following.

a) Sharing with production systems.

b) Lightweight machinery valving and piping.

c) Area classification requirements resulting from drilling rig modules.

d) Liquid storage in hull vs decks—consideration should be give between weight and CG-positive impacts and negative fire and gas and hazardous area effects.

e) Piping for fuel, water, etc., and transfer to and along the platform:

   1) location distribution, size and number;

   2) access points.

f) Electrical power and communication/instrumentation:

   1) quantity, distribution, and location of cables;

   2) remote BOP control points (including pre-run hydraulic lines);

   3) drilling instrumentation.

12.8.4 Rig Services Interface Checklist

Rig services interface considerations include the following:

a) drilling drains, sumps, and solids handling to avoid coating or plugging lines, sumps, or other discharge points:

   1) down comers for overboard disposal of cuttings from shale shakers, desilters, desanders, and sand traps;

   2) drilling mud from active and reserve mud pits;

   3) cement and cooling water;

b) impact of solid discharges on underwater equipment structures or intakes;

c) supply barge handling and consumable loading/unloading;

d) handling and operations of drilling risers, blowout preventers and deep well tools;

e) penetrations through the hull to be used for acoustical positioning equipment (serious consideration should be given to locating this type of system outside the hull);

f) ROV interfaces, ROVs shall be able to plug all penetrations;

   NOTE ROVs are limited in the amount of direct overhead work they can do and penetration design shall keep this in mind;

g) maintenance and operations of equipment used by the drilling team but located in the hull in areas that affect watertight integrity shall be agreed by both teams;

h) if used, the weight of brine and the possibility and impacts of tank overflowing shall be considered both by the structural group and the marine systems group.

12.8.5 Safety Interface Checklist

Safety interface considerations include the following:

a) two escape routes from working area: from rig modules onto platform then to lifeboats;

b) coordinated communications.

12.8.6 Regulations Interface Checklist

Regulations should be reviewed for impact on design resulting from drilling rig.

12.8.7 Production Systems Interface Checklist

Production equipment and piping can be placed in a variety of positions. Early coordination between platform designer and facility designer will result in a more workable optimum design. The following is provided to assist the facility designer in identifying unique interaction between facilities and hull systems which may not exist on a fixed platform.

12.8.8 Structural and Layouts of Production Systems Checklist

Considerations for structural and layouts of production systems include the following:

a) deck height limitations;

b) weight and CG limitations;

c) plate girder bulkhead design and routing of services;

d) height restrictions on mezzanine levels;

e) hazardous area impacts due to equipment location selections (bulkheads, firewalls);

f) dynamic loads from and on production equipment resulting from horizontal accelerations of platform;

g) loading conditions from and on production systems due to construction, tow out, and temporary mooring phases of project;

h) integrated or palletized (skid) construction;

i) watertight bulkhead penetrations;

j) deck PSF loading required for maintenance and equipment access/egress;

k) bulk storage in hull/columns;

l) ballast tank and compartment arrangements and effect on ventilation and access for inspection;

m) fire and gas impacts due to production system arrangements in the hull;

n) crane location and operation

o) supply boat mooring vs dynamic positions.

12.8.9 Process/Utilities Design Checklist

Process and utilities design considerations include the following:

a) limitation on gravity systems caused by inadequate deck height;

b) equipment height limitations;

c) maximum use of lightweight equipment;

d) shared utilities with drilling and hull systems;

e) loads generated by horizontal, vertical, and rotational movements of TLP during fabrication, tow out, mooring, and operations;

f) damping liquid movement and stabilize process levels;

g) drain system influence on buoyancy and CG;

h) TLP hydrodynamics impact from facilities installations;

i) riser connections and support;

j) drain/bilge system interfaces;

k) regulatory requirement impact on design;

l) cool flowing wellhead temperatures and possible hydrate formation due to extreme water depth.

12.8.10 Hull Systems Checklist

The following are provided to assist the facility designer in identifying unique systems and/or considerations which may not exist or are different on a fixed platform:

a) bilge and ballast system requirements;

b) vents, sounds, and overflow locations;

c) potential for multicompartment flooding, especially during inspection;

d) tension measurement device;

e) shared utilities with production and drilling;

f) underwater inspection requirements;

g) ventilation/dehumidification

h) access for inspection of compartments and tanks;

i) handling of solids discharges and oily water from bilges.

12.8.11 Hull Systems and Topsides Facility Interface Checklist

Interface of the hull and hull systems with the topside facility should be considered in the predesign stage of the facility. Areas to consider include the following.

a) Extreme wave forces on externally mounted items in the wave zone.

b) Facility fluid loading, storage and transfer within the hull.

c) Supply of seawater to the facility.

d) Connections of piping and structures to the hull such as:

   1) process and utility piping;
   2) structural connection alignment (x, y, z tolerances) between hull and deck;
   3) external production and export riser pipe routing;
   4) riser porches;
   5) pipeline valves mounted on the hull: placement, access, support;
   6) external casings, skim piles.

e) Other considerations include:
   1) injured personnel removal with space for stretchers, etc.;
   2) hull statically and dynamically induced forces in internal and external piping;
   3) access/egress—internal and external stairs, ladders, walkways;
   4) elevators;
   5) equipment removal;
   6) platform crane access to upper decks;
   7) marine information systems such as:
      — ADCP (acoustical Doppler current profiler for VIV monitoring),
      — tendon instrumentation systems, and
      — draft sensors;
   8) electrical/instrumentation cable issues such as:
      — routing of cable into hull,
      — internal and external cable transits, and
      — AC and DC power needs;
   9) moonpool ventilation;
   10) moonpool oily water removal;
   11) moonpool gas detection systems;
   12) hull column compression during deck integration.

12.9 Interface Planning

12.9.1 General

Planning for interface points coordinates recording in interface documents. Interface agreements (such as for scopes of work and material provisions) should be negotiated between involved parties.

12.9.2 Internal Hull Interface

Internal hull interface considerations include:

a) access/egress,

b) injured personnel removal,

c) equipment maintenance/removal,

d) working space,

e) local lifting devices,

f) sealed compartment inspection.

12.9.3 Watertight Integrity

Required operator action to ensure watertight integrity ideally should be kept to a minimum and should be a goal for TLP designers, as multiple compartment flooding would reduce tendon tension beyond acceptable levels. Consideration should be given to the 12.9.3.2 through 12.9.3.13 during design.

If sea chests are used, platform inspection requirements should be stringent and an exterior means of closure should be provided, in addition to the interior means of closure. The exterior means of closure should be able to be installed and operated by a diver or ROV. Locating the sea chest within a ballast tank or unmanned compartment may mitigate the risk of progressive flooding. Another option would be the use of external casing pumps to provide ballast water. If a sea chest is located in a normally accessed space (such as a pump room), additional water level monitoring devices, or increased watertight subdivisions can be used. Provision for in-situ isolation of sea chest (if used) and intake system or any discharge below the water-line level should be provided.

Watertight electrical cable penetrations should be carefully chosen for the application. For cases where high hydrostatic head is expected, use of pressure testable back-to-back cable transits and/or resin should be considered. Single cable transits are typically available for a higher hydrostatic head rating than a multiple cable transit, which may offset the increased number of penetrations in terms of safety. Care should be taken to verify proper installation of both single and multiple cable transits in the yard to prevent problems offshore.

As HVAC penetrations shall be rated to the rating of the bulkhead they are passing through, designers should consider the use of a flanged piping penetration piece with a valve in order to maintain watertight integrity at lower cost.

Automated (hydraulically operated) watertight doors mitigate the risk of progressive flooding more effectively than manually dogged doors. However, the designer should consider the increased potential for personnel injury and the increased maintenance and quantity of watertight penetrations. Furthermore, system effects caused by using centrally located HPUs should be considered in the hydraulic system design.

Utility bulkhead penetrations should be considered to accommodate cables and hoses during inspections/operations, especially in areas where a tank is only accessed through another tank.

Preferably exterior watertight hatches should be located above the design storm wave height.

Lockout/tag out capability for valves should be provided. Interlocks, car seals or other devices should be employed to prevent inadvertent water transfer.

All watertight tanks should be provided with leak detection and level measurement capability.

Possible impacts to watertight integrity caused by the potential for leakage of a pressurized piping system (i.e. firewater).

Materials for watertight penetrations should be chosen to minimize corrosion, and the piping arrangement should lend itself to in-service inspection and replacement. Material characteristics should be considered when specifying antifouling systems to eliminate the possibility of increased brittleness and stress fractures. For example, use of chlorine to prevent marine growth in a sea chest can lead to brittleness in the sea-chest materials and the design should be reviewed with this in mind. Use of an anode-based antifouling system may be a more suitable alternative.

Materials should be chosen to maintain the field life. Strong consideration should be given to the use of corrosion-resistant materials for seawater piping systems. If carbon steel is used for seawater service, the designer shall provide a sufficient corrosion allowance and an accessible means of cleanout. Ballast tank vents should be designed with this in mind, as blockage of vents by rust would impair the platform’s ballast transfer ability.

Galvanic corrosion should be considered where dissimilar materials exist. Particular emphasis should be given to bulkhead penetrations. Means of isolation should be provided.

12.9.4 Semi-enclosed Moonpools in Monocolumn Structures

In cases where a TLPs moonpool can be considered a semi-enclosed space as defined by API 500, additional systems should be provided by the hull designer. These include but are not limited to the following:

a) oil removal,

b) ventilation,

c) gas detection,

d) firefighting,

e) access,

f) injured personnel rescue.

Oil removal is necessary in a dry tree TLP moonpool as a semi-enclosed space lends itself to the buildup of vapors from spilled hydrocarbons. Provision of skimmers or sorbent systems or other such commonly used pollution control systems shall be made so that the risers are not fouled by the system and so that TLP setdown does not affect system performance. Skimmer provision should be designed to eliminate entanglement in the risers.

Semi-enclosed moonpools should be provided with redundant sources of ventilation air. Ventilation equipment provided for this purpose should be specified as explosion proof. Consideration of whether shutdown of this equipment upon receipt of a gas signal actually increases platform safety should be included, as gas in this area will not disperse without ventilation. TLPs in existence have used both exhaust and dilution type ventilation, but choice of type may affect air changes per hour required

A minimum of two gas detectors should be provided at opposite sides and at varying elevations within the moonpool.

Firefighting capability (such as a hose reel with AFFF foam capability) should be located on the top of the hull close to the moonpool. Regulatory requirements for AFFF in moonpool should be considered.

Handrails should be provided around semi-enclosed moonpools. Means of access/egress should be provided into the moonpool. Consideration of removal of injured personnel should be a design case when designing access to this area.

12.9.5 Hull Marine Systems Operator Training

Increased awareness by operators of TLP hull marine systems functionality should be provided by the platform designers through training as a part of platform acceptance in order to increase platform safety. A marine operations manual is required to be onboard U.S. platforms by USCG. A similar document is recommended for all TLPs. However, many operators are unaware of its existence or its purpose without training. Operators other than ballast control operators should be conversant with the basics of the marine systems design and where to find emergency response procedures for the TLP hull. This will benefit the platform in terms of emergency response and in avoidance of incidents during maintenance activities.

Operators should all be aware of hurricane abandonment procedures for the TLP hull as well as for the process facility.

Operators should be aware of fire and gas shutdowns, alarms, and firefighting equipment within the hull even if they do not normally enter the space.

12.10 Volatile Fluid Storage [Flash Point < 60 °C (140 °F)]

The benefits of storing volatile fluids in the hull should be weighed against the design penalties, including area classification implications and the need for additional vents, fire protection, increased ventilation and gas detection.

Appropriate measures should be employed to provide overpressure protection of volatile fluid tanks with consideration given to the potential for higher static pressure head in the tank in the event of an overflow due to remote venting of volatile fluids. Where volatile tanks are vented to a vent or flare tower and it is impractical to design the tank structurally for the full head of the tower, then appropriate protection should be provided to prevent an overflow condition.

Inert gas (IG) blanketing of hull volatile fluid tanks should be considered in lieu of natural gas blanketing. However, if used, then IG or nitrogen system is needed for purging and gas freeing.

Provisions for degassing and ventilation of volatile fluid tanks for personnel entry should be considered early in the design. Purging/degassing of the tank prior to ventilation hookup and personnel entry should be employed without the need to open any manways or connections into adjacent enclosed compartments.

Installation of a crude oil wash (COW) system shall be considered when storing crude oil in hull tanks. COW systems may be a regulatory (OPA 90) requirement.

For TLPs in U.S. waters with storage of hydrocarbon fluids in the hull, refer to OPA 90 requirements. The applicability of OPA 90 to hydrocarbon-containing production chemicals should be determined early in the design.

OPA 90 will generally disallow storing of hydrocarbons in collision damage areas. The risk and consequences of a boat collision should be considered in the selection of tank locations for volatile fluids not governed by OPA 90 (such as methanol).

The number of nozzles, manways, and openings should be minimized on volatile fluid tanks located in the hull. Where feasible, top-mounted nozzles, manways, and openings should be employed to reduce the potential for liquid leakage into adjacent compartments due to static head.

The potential for leakage from volatile fluid tanks into adjacent compartments and methods to detect and remove flammable gas should be considered in the tank layout. The impact on area classification and the potential for contamination should be accounted for when considering integral hull volatile fluid tanks located next to ballast tanks.

Firesafe valves tested in accordance with API 607 should be used in piping systems within the hull where the fluid flashpoint is less than 60 °C (140 °F).

12.11 Hull Piping

Where drain valves are installed in volatile fluid piping systems, consider employing spring-closed “dead-man” valve handles to minimize the risk of leakage due to operator error.

The potential for water hammer should be considered when designing piping systems, particularly hull systems containing long vertical runs of pipe in the columns.

In addition to stresses induced by such factors as pressure, weight, and thermal expansion, the design of hull piping systems should consider external factors that may cause relative motion between pipe and structural steel. These include compression, bending, and expansion of the structure in response to environmental conditions, as well as column compression that results from loading topsides modules onto the hull structure.

12.12 Marine Monitoring Systems For TLPs

The monitoring system includes components which are critical to the installation and long-term operation of the TLP. The TLP monitoring system generally has two main functions: measurement of parameters critical to the calculation of the platform weight and center of gravity, and measurements used to evaluate the platform’s performance.

Items typically monitored are:

- tendon tension/load;
- draft;
- ballast and void tank liquid levels;
- local environmental data such as wind speed, air temperature, etc.;
- current profile;
- an inclinometer (may be provided as a platform installation aid);
- riser load;
- platform position (GPS);
- platform accelerations;

Tendon tension is monitored for the following reasons.

a) To monitor platform weight during the platform’s service life. Tendon tension is commonly measured through the use of load cells on tendon porches or through the use of an in-line strain measurement system.

b) To monitor the load history of the tendon system to estimate fatigue damage accumulated.

c) To provide performance data during severe weather conditions to validate the design and improved design prediction tools. In-service performance can often be used to extend the platform capacity and service life.

Draft is measured through the use of either pressure sensors, a bubbler system, or air gap sensors. A draft measurement is used to provide platform displacement to part of the weight calculation.

Ballast and void tank levels are measured to determine whether platform watertight integrity is being maintained, and to determine whether ballast tanks contain the amount of ballast determined necessary by the platform designers for each weight condition.

Local environmental data can be incorporated into the monitoring system, to provide information such as wind speed, barometric pressure, temperature and humidity. This data can be used to aid in crane operations, to judge safe landing conditions for helicopters, and and as part of platform performance verification

Current monitoring is mandated by an MMS NTL, and is used in performance evaluation and subsea operation support.

The monitoring systems should be provided with an UPS so that the system continues to take data when the platform is evacuated. This is especially important for monitoring extreme condition performance and fatigue accumulation during hurricane condition. This system should be specified to meet applicable regulations while also providing sufficient battery life so that critical data in peak storm conditions is collected. A minimum capability of five to seven days is recommended. Recent developments in use of small stand-alone generators supplemented with a 24-hour battery system can reduce the cost of extensive battery systems. The area classification requirements of large battery system spaces should also be considered.

12.12.1 Regulations

Regulatory organizations have established rules that might influence the design. Rules developed for mobile offshore drilling units, offshore installations, marine, and electrical engineering are applicable in part. A list of these regulations is included in Annex F.

12.12.2 Classification Societies

A classification society should be consulted if the TLP is to be certified or classed as an offshore installation. Applicable portions of appropriate classification society rules should be investigated if the TLP is to be classed. Care should be taken in managing the interfaces if the hull is classed and the facilities are not (or vice versa).

13 Corrosion

13.1 General

Steel materials shall be protected from the effects of corrosion by the use of a corrosion protection system that is in accordance with DNV-RP-B401 or NACE SP0176. The corrosion protection system generally includes coatings, CP, corrosion allowances, and corrosion monitoring. Internal spaces can also be protected by controlling the environment. Care should be taken that the CP for the various subsystems (hull, tendons, foundations, risers, pipelines) are designed to work together in harmony. Overprotection by cathodic protection which may cause hydrogen embrittlement and coating damage should be avoided.

13.2 Antifouling

In areas where organisms are active, marine fouling is significant, and the use of antifouling coatings may be considered to reduce the effects of marine growth. It is noted that antifouling coatings are being developed with ever-increasing life spans, but are rarely effective for more than seven years with current technology.

13.3 Splash Zone

Special consideration should be given to the splash zone. Options include using extra wall thickness as a corrosion allowance and special coatings. As an example, some TLPs have used 9 mm (0.35 in.) extra plate on the legs and 13 mm (0.50 in.) extra plate on water piercing diagonals, combined with coatings, with good success. Other TLPs have relied on reinforced coatings without specific wall thickness allocated to wastage.

Coating failures in the splash zone are primarily related to damage due to local impact. Special glass-flake reinforced epoxy coatings have been used with good success on TLP splash zones. Thermally sprayed aluminum has also been used successfully.

The coatings in the splash zone are difficult to repair or replace. Cathodic protection is effective through at least the middle of the splash zone, so anything below that level should not need to be re-coated if the coating fails. However, replacing the coatings near the waterline does present difficulties in staging and environmental protection. Organic coatings such as epoxies/urethanes are currently rated at 15 years to 17 years without impact damage. Glass flake reinforced coatings may last longer from a mechanical damage perspective. Thermally sprayed aluminum can be used for up to 30-year life.

13.4 Corrosion Protection of Internal Surfaces

Internal surfaces exposed to a corrosive environment shall be protected from corrosion. Corrosion protection can be achieved by the use one or more of the following corrosion protection technologies: coatings, dehumidification, or cathodic protection (when seawater exposed). A corrosion engineering analysis should be conducted to determine the most cost effective corrosion protection scheme.

13.5 Corrosion Protecton of Hull External Submerged Surfaces

The below water portions of the hull are typically protected with cathodic protection systems, in some cases supplemented by coatings. Use of coatings with cathodic protection offers large weight savings when using sacrificial anodes. Cathodic protection can be provided by sacrificial anodes, by an active impressed current system, or by a combination of the two. Issues of concern for typical TLP hulls include shielding and shadows preventing adequate coverage, and adverse interaction and anode wastage caused by adjacent components (tendons, risers, pipelines), and overprotection leading to hydrogen embrittlement.

Protection of the internals of flooded caissons, enclosed and/or complicated tendon and riser porches, and connections of risers and pipelines requires special design consideration.

13.6 Tendons

Tendon protection can be accomplished by several methods. All TLPs to date have used coated tendons [fusion bonded epoxy (FBE), polyethylene (PE), or thermally sprayed aluminum (TSA), or combinations thereof], combined with some form of sacrificial anode based cathodic protection. The cathodic protection systems have included bracelet anodes on each tendon element, and cathodic protection projected from the top (anodes on hull) and bottom (anodes on foundation). In all cases, the tendon CP design should account for interaction with the cathodic protection of the hull, foundations, risers, and pipelines. Impressed current systems should not be used for tendons.

The key to using sacrificial anodes to protect tendons from their ends is the potential attenuation along the tendon. Potential attenuation is reduced by good coatings and a sufficient conductor area (wall thickness to diameter ratio). Since coatings are usually in excellent condition at launch, this is not a problem for tendons in the 5000+ ft range. As coatings deteriorate over time, the tendons are normally protected from both ends by platform anodes and pile anodes. Coating deterioration rates should be based on actual experience, rather that rates provided by coatings vendors.

The tendon system corrosion protection should also include consideration for the top and bottom connectors, and the tendon tension monitoring system. These often include shielded spaces and crevices combined with high-stress components.

13.7 Foundations

The foundations should be included in the overall corrosion protection design. The lower regions of the pile are embedded in the soil with limited oxygen. The upper sections of the pile may have sufficient thickness to provide a reasonable corrosion allowance, but the pile does provide a large current drain on any CP system which is grounded to the piles. This is well recognized by NACE. Coating the upper pile and connector receptacle can reduce this current load. Pile geotechnical performance is generally based on rough raw steel surfaces, and coatings may reduce skin friction, leading to lower pile performance. Any coatings on the pile below the mudline should meet the requirements of 10.5.5. The connector/receptacle on the pile is part of the tendon system, and should be protected. Impressed current systems should not be used for foundations.

13.8 Cathodic Protection (CP) Interaction

There is debate among corrosion protection system designers as to whether adjacent components should be isolated or grounded to each other. Isolation when there is a structural connection is tenuous. One of the advantages of isolation is that one system cannot draw current from and deplete the anodes on the other system. One disadvantage of isolation is that is that near the connection, the near field flowing currents on one system can locally damage the other unless both are locally protected quite thoroughly in this location. The general recommendation herein is to ground all connected systems, and to ensure that all are sufficiently protected to ensure that any one will not cannibalize the capacity of the others. In-service, this should be checked through scheduled potential voltage monitoring as described in 13.9 and Section 15.

13.9 Monitoring

The cathodic protection system should be checked upon installations, and again on a regular basis through visual examination and through potential voltage monitoring. Monitoring/surveying the CP system and inspecting the platform for corrosion is addressed in Section 15.

14 Fabrication, Installation and Inspection

14.1 Introduction

14.1.1 Scope

This section deals with the fabrication, assembly, installation and fabrication inspection of a TLP. Specific additional criteria for the fabrication of structural components, tendons and foundations are found in Section 8, Section 9 and Section 10, respectively. Installation and marine operations are addressed for load-out, launching, transportation, stability, positioning and inspection as they apply to the platform, foundations and well templates. Tendon installation issues such as running, connecting, pretensioning are also discussed.

General guidance on documentation requirements for long-term operation is given. Typical documents include the marine operations manual, the in-service inspection plan, and the construction portfolio.

14.1.2 Practices and Procedures

Fabrication, assembly, and installation procedures for the platform, tendons and foundations should be developed during the design process so as to meet work requirements. A design basis document should be developed by the contractor and approved by the client prior to the commencement of detailed engineering. Close coordination between the designer, fabricator, installer, and operator is essential in developing these procedures. The following serve as guidelines for acceptable practices.

a) Fabrication should be in accordance with applicable sections of recognized standards such as the AISC 360-05 and API 2A-WSD, 21st Edition (2002). Hull and deck fabrication may follow class society rules. Riser and tendon fabrication may follow the ASME *BPVC*.

b) Welding should be performed in accordance with API 2A-WSD, Section 10 and AWS D1.1 (2000).

c) All work should be carefully executed with proper quality and testing procedures to assure that the work product meets design specifications and drawings. All faults and/or deficiencies should be corrected before the material is painted, coated, or otherwise made inaccessible.

d) Prior to commencement of work, specification for the fabrication and quality control procedures covering critical aspects pertinent to the product's quality should be developed and agreed upon by the designer, operator, fabricator, and applicable regulatory agencies. Further, a program for nondestructive testing (NDT) should be developed and agreed upon. This program should contain information and documents for planning, controlling, reporting, standards, etc.

e) Personnel safety during all phases of fabrication and installation shall be maintained.

f) Consideration should be given to providing temporary access, lighting, ventilation, fire fighting, etc., during all phases of fabrication, assembly, and installation.

14.2 Structural Fabrication

14.2.1 General

This section addresses fabrication of the hull and deck structures, foundations, and well templates. Specific guidance is provided in Section 8. API 2A-WSD, Section 4 and Section 11 should be consulted for guidance on splices, welded tubular connections, and plate girder fabrication.

14.2.2 Welded Stiffened Plates and Shells

Fabrication of large diameter shells stiffened by either ring frames or a combination of ring frames and longitudinal stiffeners requires consideration of local fabrication tolerances, weld details, connection details and fabrication sequence.

If localized heating is proposed for straightening or repair of out of tolerance, the designer should assess its effects on the material properties. Assembly of substructures can result in built in stresses. A construction sequence should be developed and agreed by all parties for all structures to minimize this condition.

14.2.2.1 Fabrication Sequence

A fabrication sequence should be established so as to minimize the extent of residual stresses. Some recommended guidelines for establishing this sequence are:

a) welds should progress in a direction from higher to lower restraint,

b) joints with expected significant shrinkage should be welded before those of lesser-expected shrinkage,

c) joints should be welded with as little restraint as possible,

d) splices in component parts of built in members should be made before welding to other component parts.

The overall fabrication sequence should be such that defects and deficiencies can be found and corrected prior to completion of the affected part being made inaccessible.

14.2.2.2 Weld Details

In fabricating cylindrical, and noncylindrical sections including flat plate structures, the following recommendations should be considered in addition to those discussed in 14.4.

a) Weld Proximity—All parallel welds (butt, tee, or fillet) should be separated considering the thickness of the material and the heat-affected zone (HAZ). However, in no case should this toe-to-toe separation be less than four times the plate thickness ($4t$). The most common case is the seam weld in a plate or cylinder parallel to a stiffener.

Longitudinal butt welds should be offset a sufficient distance to avoid having all welds intersecting at the same corner.

b) Weld Intersections—Where the intersection and overlap of butt welds by butt, tee, or fillet welds is unavoidable, the intersected (first) weld should be ground flush for a distance of 50 mm (2 in.) where possible on either side of the abutting plate. Additional NDT may be required.

c) Weld Continuity—Intermittent welds are a stress concentration source that could lead to fatigue cracks if oriented in the direction of varying tensile stresses. At points of intersecting stiffeners, stiffeners with larger varying stress range should be welded continuously with interruptions in welding on the secondary stiffeners. Cutouts (mouse holes) or clearances at these intersections should be of adequate size to provide access for complete end welds, if permitted by the designer. The radius of these cutouts or clearances should be at least 50 mm (2 in.). Intermittent welds should not be used where corrosion is likely.

d) Seal Welds—Fillet welds in tank spaces should be detailed so as to limit the possibility of fluids encroaching behind the welds. This can be accomplished by the use of seal welds.

14.2.2.3 Fabrication Details

When detailing the final construction drawings, consideration should be given to the following.

a) Drainage—Adequate drainage should be provided for the webs of deep non watertight ring frames.

b) Cutouts—The cutouts where stiffeners pass through deep nonwatertight ring frames should be designed to provide support for the stiffener, retain adequate ring frame shear area, and limit the extent of stress concentration.

c) Plate Orientation—The direction of rolling of plates should, where practical, line up with the direction of the primary load path to minimize the fatigue effects in critical areas, such as pontoon or brace connections to columns.

d) Tapers—When joining items of different thicknesses and widths, tapers of 2.5:1 to 4:1 are recommended depending on service requirements.

14.2.3 Tolerances

Deviations should not exceed the design assumptions regarding buckling strength (i.e. out-of-planeness for unstiffened plating, out-of-straightness for plate stiffeners, out-of-roundness for circular members). Special consideration should be given to alignment between welded structural members. Allowable misalignment depends on stress level and type of loading, as well as type and importance of the joint. Therefore, unless specifically incorporated in the design approach, each member should be fabricated and positioned accurately to tolerances to the standards shown in Table 13.

Table 13—Reference Standards for Design Tolerances

Structural Member	Reference Standard
Tubular	API 2B
Welded plates	AWS D1.1
Beam-columns	AWS D1.1
Trusses	AWS D1.1
Girders	AWS D1.1
Stiffened plates	API 2V
Cylindrical shells	API 2U
Deck and cap beams, piles, grating, handrails and fences	API 2A-WSD, Section 11

14.3 Welding

14.3.1 Specifications

Welding should be performed in accordance with AWS D1.1 (2000) and other AWS documents as follows.

a) Sections 1 through 6 are applicable and constitute a body of rules for the construction of any welded structure governed by AWS D1.1. Part C of Section 6 should not apply to tubular nodes. API 2X provides guidance of ultrasonic techniques, procedures, reports and qualifications of technicians for tubular nodes.

b) Section 8 applies for general structural welding of plates and structural plates, e.g. portions of deck sections.

c) Section 10 may apply to various TLP components.

d) AWS D1.1 alone may not be adequate for high-strength steels.

e) Supplementary requirements should be specified for the effects of dynamic loading on the structural welding requirements for the fatigue sensitive portions of the TLP hull and deck.

14.3.2 Welding Procedures

Written welding procedures should be required for all work, including repairs, even where prequalified. The essential variables specified in AWS D1.1, Section 5 and Appendix E should be shown in the welding procedure and adhered to in production welding.

14.3.3 Welders

Welders should be qualified for the type of work assigned and be issued certificates of qualification stating such limitations as required by AWS D1.1, Section 5 and Appendix E.

14.3.4 Qualification

14.3.4.1 General

Welding procedures, welders, and welding operators should be qualified in accordance with AWS D1.1 as further qualified herein. A competent testing laboratory should be used to perform qualification tests. New qualifications may be waived if prior qualifications and experience are deemed acceptable.

14.3.4.2 Impact Requirements

Impact requirements should be included in the fabrication or purchase specification. When the purchase specification does not specify impact requirements for Group II, Class A and B, Group III and Group IV, the as-deposited weld metal and HAZ in the procedure qualifications should meet the minimum toughness requirements specified in 8.8.2. Additional guidance for the selection of toughness requirements is given in 8.8.4.

Charpy V-notch tests should be performed in accordance with ASTM A370. The longitudinal axis of the specimen should be at a minimum depth of $T/2$ for T = 19 mm ($^3/_4$ in.) or less and $T/4$ for T > 19 mm ($^3/_4$ in.), from a weld surface.

14.3.4.3 Hardness

Hardness requirements should be by agreement of the manufacturer and the purchaser.

14.3.4.4 Gas Metal Arc Welding

The short arc process should not be used without prior approval of the purchaser.

14.3.4.5 Large Diameter Pipe

The procedure for submerged arc metal welding of girth joints on large diameter pipe should be qualified on the smallest diameter for which the procedure will be used during production.

14.3.5 Welding Inspection

As a minimum, a visual inspection of welded joints should conform to the appropriate requirements of API 2A-WSD and AWS D1.1.

Supplementary requirements should be specified for the effects of dynamic loading on the structural welding requirements for the fatigue sensitive portions of the TLP hull and deck.

14.3.6 Unspecified Welds

Complete penetration groove welds should be used to join intersecting and abutting parts, unless otherwise specified. This includes hidden intersections, as may occur in overlapped braces and pass-through stiffeners.

14.3.7 Groove Welds Made from One Side

At intersecting tubular members, were access to the root side of the welds is prevented, complete penetration groove welds conforming to AWS D1.1, Figure 10.13.1A may be used. When tubular members are large enough to allow welder access to the inside of the member, consideration may be given to cutout windows to allow access for welding the backside of the joint. The cutout should be replaced and rewelded using a properly fit backing bar with all splices in the backing bar full penetration welded.

14.3.8 Seal Welds

Unless otherwise specified, all faying surfaces should be sealed against corrosion by continuous fillet welds. Seal welds need not exceed 3 mm ($^1/_8$ in.) regardless of base metal thickness, provided low hydrogen welding is used.

14.3.9 Post Weld Heat Treatment (PWHT)

Stress relief by PWHT of cylindrical members fabricated form carbon steel is generally not required where the weld joint thickness is 50 mm (2 in.) or less. Welding procedure qualification tests should be included when

PWHT is used in production. A detailed PWHT procedure should be written for each heat treatment. In specifying PWHT other factors such as high yield joint restraint should be considered in addition to thickness.

14.3.10 Weld Toughness

Where minimum toughness requirements are specified they should be applicable to the entire weldment (base material, weld deposit and heat affected zone) as specified in 8.8.

14.4 Platform Assembly

14.4.1 General

Assembly of subcomponents depends on structural design and proposed fabrication technique. Several different methods for fabrication and assembly may be considered. Some methods include the following.

a) Hull assembled on land and launched into water. Deck assembled at a different site, and loaded onto a barge. Both hull and deck transported to a preselected integration site. Deck added by hull/deck mating operation or by individual module lifting operations.

b) Hull assembled in dry dock and floated out; deck added as in item a).

c) Hull and deck assembled on land and launched into water. Deck modules may or may not be added at a later floating stage.

d) Hull and deck assembled in dry dock and floated out.

e) Hull fabricated in sections and joined in a free-floating condition or on barges. Deck added as in item a) above.

f) Hull assembled onshore; loaded onto a transport vessel or barge; then launched or floated off of the transport vessel or barge at the integration site. Deck added as in item a).

In the selection of a fabricating and assembly method, some factors to be considered include:

— platform size, weight and draft;

— number of pontoons and columns;

— type of deck construction, e.g. open truss or plated;

— size and type of deck modules;

— fabricators’ facilities (inclusive of size and dry docks, overhead cranes, skid ways, etc.);

— depth of water at launch site and connecting waterways or channels to open sea or mating site.

Additional temporary buoyancy may be considered to reduce draft during fabrication and assembly operations.

14.4.2 Erection Sequence

The fabricator should develop a detailed erection sequence showing a step-by-step plan for assembling subcomponents to make up the hull and deck. Careful planning is required to ensure that subcomponents fit-up within specified tolerances and that overall global dimensions are met.

14.4.3 Dimensional Control

Careful attention to dimensional control is required to ensure that proper fit of fabricated modules and structures is achieved during the assembly, mating and installation phases, so that time delay is minimized and that fabricated structures meet design requirements.

The global as-built geometry of the structure should not deviate from the design in a way that may cause significant change in load path.

Dimensional control operations should be planned to suit the design, fabrication, and erection plans, and provide early warning for necessary corrective and/or reanalysis requirements.

Corrective and/or reanalysis results should be determined based on the survey results and the calculated dimensions of the modules and structures for the actual support and loading condition during the particular phase of constructions.

14.4.4 Weight Control

The actual weights of the fabricated modules and structures often vary from the calculated weight. An effective weight control program should ensure that the final as-built weight meets the design requirements.

Selected subcomponents should be weighed to verify the calculated weights and centers of gravity. A deadweight survey and inline test should be completed to verify the lightship weight and vertical center of gravity of the completed hull and deck.

14.4.5 Heavy Lifts

Lifting Forces should be computed as per API 2A-WSD, Section 2.

14.4.6 Hull and Deck Mating Operations

14.4.6.1 General

Hull and deck mating operations refer primarily to the setting or assembly of the deck onto the floating hull from a buoyant transport vessel. Mating operations include the approach, alignment, contact and load transfer of the deck onto the hull, as well as the separation of components from the transport vessel. The designer should prepare a detailed plan for these operations. Complete procedures for the intended method should be included.

14.4.6.2 Site Selections

If the fabrication sequence of the platform involves separate fabrication of the hull and deck, the mating site selection should provide, as a minimum, the following:

- adequate water depth to allow for the mating considering ballasting operations and changes in hull draft and transportation vessels;
- sufficient shelter from prevailing environmental conditions to assure that hull/deck motions are acceptable, and that the structures are not overstressed during critical interfacing operations.

14.4.6.3 Mating Hardware

Hardware involved in the mating operation should be specifically designed for the selected procedure and may include guidance cones, pins, or slots, rubber shock pads or absorbers, hydraulic jacks and rapid load separation equipment (e.g. pull-out blocks, hinged drop arms, rapid acting ballast systems, etc.).

14.4.6.4 Load Analysis

Detailed deflection and load analysis should be performed to determine applied forces on structural connections and mating hardware due to environmental loads, changes in ballasting arrangements or load transfer during mating operations. Sufficient clearance between the transport vessel and deck after load transfer may be achieved through deballasting of the hull and/or ballasting of the barge. It may also be achieved through mechanical means (e.g. pull-out blocks or hinged drop arms). In this manner, dynamic impact loads between the hull and deck may be lessened.

14.4.6.5 Equipment Testing

All mating equipment (such as ballasting arrangements, temporary generators, jacks and control systems, etc.) should be thoroughly tested before float out or commencement of operations.

14.4.6.6 Stability

Stability calculations should be performed for both the platform hull and transport vessel to ensure adequate stability during all phases of the ballasting and load transfer operations.

14.5 Transportation

14.5.1 General

Transportation operations should be planned concurrently with the structural design in order that loading conditions during loadout, tow, and launch are clearly defined. Applicable regulations and/or codes such as those of the United States Coast Guard (USCG) and the International Maritime Organization (IMO) should be considered. Model testing may be used to confirm analysis results.

All marine operations shall, as far as practicable, be based upon well-proven principles, techniques, systems and equipment, and shall be undertaken by qualified, competent personnel possessing relevant experience.

14.5.2 Platform

14.5.2.1 Launch

Calculations should be made to confirm that the platform can be safely skidded into the water or onto a barge, or if built in a dry dock, that it can transfer from the on-bottom condition to the floating mode without instability or overstressing.

14.5.2.2 Ballast Systems

The systems for ballasting and deballasting should be designed with sufficient numbers of valves and pumps to provide a fail-safe operation during loadout or launch, tow, integration and installation.

14.5.2.3 Stability

Seakeeping characteristics along with heeling and righting moment curves of the platform should be produced for the various free floating and towing conditions anticipated. The mathematical analyses may be correlated with scale model test results. Design calculations should show that adequate buoyancy and stability exists if damage occurs during transit.

14.5.2.4 Forces

The platform should be designed to resist all hydrostatic, environmental, and towing forces imposed on it during transit. Towing attachments to the platform should be stronger than the breaking strength of the largest towing wire and should be accessible during transit. Fatigue of the overall towing arrangement and at towing attachments should also be considered.

Refer to API 2A-WSD, Section 5 for fatigue calculation methods.

14.5.2.5 Towing Vessels

The proper number of seagoing and/or harbor tugs, with sufficient size and power, should be provided to safely operate in any sea environment that may develop for each particular transit route, transportation time and time of year.

14.5.3 Template Structures

14.5.3.1 General

Template structures (e.g. for foundations or wells) may be transported and handled by a variety of methods. Possible operations can include loadout or launching at the fabrication site, transportation by self-floating or as deck cargo, and either lift-off or launching at the installation site.

Refer to API 2A-WSD, Section 12.2, for additional guidance on transportation to an installation site.

14.5.3.2 Launch

A method of launch may be considered that utilizes the procedures and criteria established for the launching of jacket-type offshore platforms. Structural strength, launch trajectory, and structural equilibrium after launch should be assessed. A hypothetical damage condition should be considered when making these calculations. Prior to launching, procedures should include a check to ensure that all watertight closures and valves have been secured.

14.5.3.3 Barge Transport

Template structures transported as deck cargo are subject to loads generated by the vessel's dynamic motions. As required, motion analyses should be undertaken to determine the dynamic load components that should be incorporated in the structural and tie down analyses.

14.5.3.4 Free-floating Transport

Template structures transported by self-flotation will be subject to drag forces, still water bending, wave induced bending and hydrostatic forces. Environmental loads should be predicted for worst-case tow criteria and analyzed in accordance with procedures in 10.5. Points of attachment for towing hawsers should be designed to limit stress concentrations and crack initiation at these locations. Stability calculations, including a one-compartment damage condition, should be performed.

14.5.3.5 Offshore Lifts

Template structures lifted from transport barges should be designed following the guidance of API 2A-WSD. Prior to lifting, procedures should include a check to ensure that all watertight closures and valves have been secured.

14.5.4 Tendons

The transportation and handling of tendons between the fabrication site and the platform requires careful evaluation to ensure that the tendons, including the connectors, coatings, anodes and other appurtenances, are not damaged. Procedures should be evaluated following the guidance of API 2A-WSD. Consideration should also be given to the need for protection of tendons and tendon components during storage and handling following fabrication and prior to transportation. Protection means may include, but are not limited to, temporary coatings and coverings.

14.6 Installation Operations

14.6.1 General

All installation operations shall, as far as practicable, be based upon well-proven principles, techniques, systems, and equipment and shall be undertaken by qualified, competent personnel possessing relevant experience.

TLP installation operations consist of several major activities:

a) pre-installation activities, including deployment of the temporary mooring system;

b) installation of the foundation system;

c) makeup or tow and upending of the tendons;

d) hookup and tensioning of the tendons to desired level of pretension;

e) posttendon installation activities, including lift and set of structural deck components (e.g. equipment modules, flare booms, etc.), inspection of tendons and site cleanup;

f) installation of risers.

The sequence and specific tasks that will occur during each of these activities may vary depending on a number of factors, including the following:

— geometry of the overall system design and individual components;

— soil, environmental and geographic parameters;

— equipment capacity and availability;

— long-term field development plans and other economic considerations.

14.6.2 Site Survey

Prior to the initiation of installation operations, a survey of the proposed site should be carried out. This should include a bottom survey to ensure that no recent changes to the installation site such as debris and cuttings have occurred that would prevent installation of the seafloor structures. After installation of foundations and any other on-bottom structures, an accurate depth survey should be made to determine the as-installed position and depth of each component.

14.6.3 Environmental Envelopes

Based on the environmental conditions anticipated at the proposed installation site, calculations and/or wave tank testing should be performed to predict motion responses of the platform. In particular, the acceptable range of motions (from combined wind, wave, current and swell) that the platform can experience while being installed should be determined. These responses may be critical when the platform is transferring from a “free floatin”' to a “tension-moored” condition.

In addition, the designer should compute the acceptable range of motions of suspended or pre-installed tendons due to VIV. VIV may occur as a result of the relative motion of the tendon through the water column, due to a combination of extreme currents and motion of the platform, including the tow of suspended tendons.

14.6.4 Installation Plan

Installation procedures should be developed to ensure that the installation is accomplished in a satisfactory manner. In addition to defining the sequence and interface for completing the tasks of each major phase of the installation, it should define conditions for weather, equipment status and logistic support under which installation operations should be initiated, suspended, terminated or reversed for each major phase of the procedure. Weather window requirements should be established for critical activities identifying when they may commence.

14.6.5 Contingency Plan

Comprehensive contingency plans covering all phases of the installation should be included in the installation plan and procedures. Consideration should be given to the reversibility of each operation if a malfunction occurs or if acceptable weather conditions degrade.

14.6.6 Mooring and Stationkeeping

During installation, a temporary mooring system or other means of stationkeeping may be required. This system should be capable of maintaining the platform in position during the entire installation period including anticipated storm conditions. Calculations and/or wave tank testing may be conducted to ensure that this mooring system will handle the forces that result from platform motions.

14.6.7 Survey and Positioning Systems

Survey and positioning encompasses the means to align and maintain accurate location, azimuth, and levelness of the seafloor components and the platform. The accuracy required to position and align components is limited by installation equipment, but shall be within design tolerances.

Positioning may be relative to a seafloor grid (e.g. in the case of combined foundations and well templates) or relative to independently installed seafloor foundations (e.g. foundation piles relative to a well template). Although the means to monitor positioning tolerances are readily available with conventional electronic underwater acoustic devices, the means to achieve the necessary tolerances requires careful evaluation.

Possible positioning means available include:

- maneuvering installation vessel or platform on conventional catenary mooring system;
- maneuvering installation vessel(s) with dynamic positioning system;
- maneuvering lowered seafloor structure with localized thrusters;
- use of a bottom-founded positioning structure lowered separately to the templates, this would act as a guide around the well template and it may or may not be removed;
- use of positioning piles (e.g. pin piles).

Consideration should be given to special alignment appurtenances and monitoring systems (e.g. acoustic positioning equipment, GPS, CCTV, ROVs, etc.) in performing these tasks.

14.6.8 Seafloor Structures

14.6.8.1 General

The following may influence the means adopted for installing seafloor structures.

a) Seafloor Conditions—Water depth, soil properties, bathymetry, geohazards.

b) Type of Foundation—Multi-template, combined base template, piled structure, direct pile foundation, shallow foundation, or hybrid structure.

c) Type of Installation Vessel—Moored or dynamically positioned, semisubmersible, ship-shaped or flat-bottom barge, self-installed TLP or other.

d) Environmental Conditions—Mild or hostile area, length of installation periods.

e) Installation Equipment—Underwater hammer, drilling and grouting tools.

Proposed installation procedures should be considered early in the design process as they may impact final designs.

14.6.8.2 Handling and Lowering

When an installation method and equipment are selected, calculations should be performed to quantify dynamic loads and stresses during the lowering and placement of structures on the seabed. Factors that may impact surface handling and lowering include:

a) additional buoyancy required for transfer from floating condition to lowering condition;

b) amount of lowering capacity available on installation equipment;

c) stability of structure during surface transfer operation;

NOTE Structures stable in a floating mode on the surface may become unstable when negatively buoyant.

d) type of lowering equipment of installation vessel (e.g. whether lowering from a crane, a special winch module, or drill string);

e) rotational control and stability of the structure may create problems during lowering;

f) dynamic loads due to two body interaction; this may be minimized through use of motion compensators or elastic synthetic lowering lines;

g) control of position of direct pile foundations within target radius as they are lowered and penetrate under own weight.

14.6.8.3 Leveling

The means for obtaining leveling tolerances of seafloor templates depends on the nature of soil conditions, the size of bearing mats, the mechanism to operate bearing mats and other factors. Leveling methods may include hydraulic jacks, rack and pinion mechanisms, pile elevators, ballasting and grouting. Generally the leveling adjustments with multi templates should be small. Leveling adjustments of large combined or hybrid structures are likely to be difficult to achieve due to their overall mass.

14.6.8.4 Pile Installation

Piles may be installed using underwater driving techniques, by drilling and grouting, or by suction. With underwater driving, calculations should be performed to establish penetration rates and blow counts based on soil data, pile size and hammer energy. If considerable deviations are noted from the design criteria, this could mean incorrect soil data or inadequate transfer of energy of the hammer to the pile. In either case, the root case of the deviation needs to be resolved to ensure appropriate foundation design.

Drilled and grouted piles depend on the ability to drill the pilot hole while minimizing the possibility of cave-in and maximizing the efficiency of the grouting operation. Grouting techniques, although well established for deepwater oil well drilling operations, are still somewhat of an unknown technology with large diameter tension piles. Effective means to monitor the integrity of the grout in-place are available through specialized monitoring tools lowered from the surface vessel or deployed underwater by ROVs.

A comprehensive soils survey, engineering analysis and test program is recommended for both pile design and installation techniques.

14.6.8.5 Template-to-pile Connection

Present technology for the interface of piles to seafloor foundations includes grouting and mechanical connections. Grouting may be performed through drill strings or hoses. The grout may be monitored with special instrumentation (e.g. nuclear densimeters) either mounted on the template or deployed with ROVs. Mechanical connections include means of deforming the shape of the pile inside the template’s sleeve so that a connection is made between the two. It is necessary to ensure that the pile has deformed to the design specifications.

14.6.8.6 Shallow Foundations

Shallow foundations may be fabricated from concrete or steel and may include deadweight, hybrid pile/deadweight structures, or deadweight suction structures.

It is anticipated that these structures may include additional buoyancy for lowering operations. After installation, the foundations should be inspected and monitored to ensure that installation has been achieved in accordance with plans.

14.6.9 Platform

The platform may be installed over previously installed seafloor foundations, well templates, and/or tendons. Careful consideration should be paid to the ballasting system, temporary mooring, and/or positioning systems, etc., when positioning the platform over the location.

14.6.10 Tendons

Developing a concept and a procedure for installation of a tendon is intimately linked with the tendon design process. See Section 9. It is recommended that the designer and installer work closely together in developing an installation plan.

In view of the variety of configurations and design features that may be involved in a specific tendon design, it is not reasonable to attempt to outline detailed installation procedures. Regardless of the specifics of the design of an individual tendon or tendon system, the installation operations will involve the sequential completion of tasks discussed below.

14.6.10.1 Preparing to Install Tendons

The following is a partial list of tasks the designer and installer should consider in developing procedures to be followed in preparation for tendon installation:

a) inventory, inspect, and document the conditions of all tendon components, including components below water on the hull and foundations to confirm that they are ready for installation;

b) functionally test all equipment and system to be used during installation;

c) develop contingency plans and alternate procedures to be followed in the event damage to tendon components or installation equipment malfunction or failure.

14.6.10.2 Tendon Installation

Tendon installation operations generally include handling and running operations similar to riser running operations. There are a number of options for equipment utilization, sequencing and procedures that may be employed depending on the specifics of the individual tendon and overall mooring system design.

The following is a partial list of the tasks that should be considered in developing procedures to be followed during tendon installation, including landing and connection operations.

a) Define conditions for weather (including the effect of current speed on VIVs), equipment status and logistic support under which installation will be initiated, suspended, terminated or reversed.

b) Develop contingency plans and alternate procedures to be followed in the event of damage to tendon components, installation equipment malfunction or failure, unexpected deterioration of weather and interruption of logistic support.

c) Develop inspection procedures to be conducted during or shortly after completion of installation operations, including inspection for marine growth of components pre-installed under water.

d) Develop a comprehensive plan that includes appropriate inspection and recordkeeping procedures to ensure that individual tendons are deployed in a manner consistent with their design and service requirements.

e) Develop procedures to safeguard and inspect pre-installed tendons until the platform arrives and is ready for installation.

f) Develop a comprehensive tendon tensioning criteria that define when the tendons have been appropriately connected to either the foundation (for tendons installed from the platform) or to the platform (for pre-installed, buoyant tendons).

In many designs it may be prudent to conduct deployment operations with surface equipment offset from the locations of previously installed seafloor equipment to minimize the damage potential from dropped objects. Regardless of the specifics of the installation procedure, the need and potential benefits of comprehensive operator training and equipment familiarization including installation system trials cannot be overemphasized.

14.6.11 Risers

General recommendations on the running of risers can be found in API 16Q.

Previously installed multiple production risers may introduce clearance and contact problems during running of riser joints. The stab-in of riser joints into a seafloor template from a TLP offers somewhat different problems than a drilling vessel since the stationkeeping components do not readily provide lateral platform positioning adjustments as in the case of drilling vessels. The use of a temporary catenary mooring system, thrusters, tugs or other positioning mechanisms may be considered for the stab-in operations.

14.6.12 Special Operations

14.6.12.1 Environmental Monitoring

If installation is to be performed during a time of year and/or in an area where weather windows are relatively short or unpredictable, consideration should be given to special weather monitoring means to insure that operations may be completed within the constraints of the design environmental envelopes.

14.6.12.2 Standby Equipment

Adequate numbers of tugs, anchor handling vessels, etc. should be on location at all times during the installation should it become necessary to secure operations and/or abandon location.

14.7 Inspection and Testing

14.7.1 General

Quality control, inspection and testing should be performed to ensure adherence to the drawings, specifications, and procedures that contain the detailed instructions necessary to obtain the desired quality and service in the finished product. Quality control, inspection, and testing should be performed during all phases of construction, including the fabrication, loadout, seafastening, transportation and installation phases to ensure that specific requirements are being met. The most effective quality control and inspection system is one that prevents the introduction of defective materials or workmanship into a component rather than finding these problems after they occur.

Inspection and testing throughout the life of the TLP is necessary to ensure its continued satisfactory performance. Being a buoyant structure, the platform is weight sensitive. Accordingly, inspection during fabrication is necessary to maintain weight control in addition to the usual concerns of fabrication quality and dimensional tolerances. Tendon systems are sensitive to fatigue and fabrication inspection is essential to detect flaws that could reduce fatigue life. Once installed, the platform will likely remain on site throughout the life of the field. The monitoring of the platform’s performance and continued inspection of structural components to detect deterioration or damage should be performed to avoid removal of the structure for major repairs.

Unless otherwise specified, quality control, inspection and testing should follow the guidelines provided in API 2A-WSD, Section 13.

14.7.2 Fabrication

Inspection procedures should ensure that fabrication, including repair during fabrication, is undertaken in compliance with design drawings, specifications, and procedures.

Designers should specify inspection requirements that are consistent with service requirements, welding requirements and material selection. As a minimum, inspection requirements of welded joints should conform to the appropriate requirements of API 2A-WSD, Section 14, and AWS D1.1. Supplementary requirements for inspection as outlined in these codes and otherwise shall be specified for the effects of dynamic loading on the structural requirements.

14.7.2.1 General

Inspection and testing undertaken during fabrication of components should cover at least the following:

a) material quality;

b) material traceability;

c) welder performance qualifications;

d) weld procedure qualifications;

e) thickness tolerances;

f) fit-up and edge preparation;

g) weld inspection, visual and NDT;

h) weld size;

i) dimensional and alignment checks;

j) coating and anode application;

k) support for handling, shipment and storage;

l) repairs;

m) documentation of all inspection and testing.

The plans and specification for a component should clearly indicate which materials and items are to be inspected and by what method. To the fullest extent practical, inspection should be performed as the fabrication progresses.

The techniques for this inspection and testing are specifically defined in other sections, and in recognized codes currently being utilized in marine fabrication facilities.

14.7.2.2 Tendon System

The tendon manufacturer should use a system to maintain the traceability of each tendon assembly and its components, both metallic and nonmetallic. Prior to manufacture, the manufacturer should determine the level of traceability required jointly with the owner, regulatory authority, and designer. The manufacturer should then maintain the necessary detailed records consistent with the level of traceability agreed by the parties.

The manufacturer, designer, and/or owner may wish to demonstrate the acceptability of the product for its intended application. Such testing methods should be realistic and consistent with the factors of safety designed into the component. The testing of components should avoid damage to the component prior to initiation into service.

14.7.3 Assembly

The assembly of the structural components of the platform should maintain the quality control and alignment control established during the component fabrication as per 14.2. Particular care should be taken when mating cylindrical sections of the major columns.

When two-phase construction is undertaken, a procedural plan should be prepared that clearly outlines all steps of the mating. The plan should include information such as environmental constraints; alignment checks; weld details and procedures; inspection points and criteria; platform monitoring equipment; etc. The designer should analyze this operation as a load condition. The analysis should include allowable limits of misalignment, platform bending due to load and environmental conditions, and possible misapplication of load. It should be recognized that for mating the platform may be submerged beyond its design operating draft, and thus, special damage control precautions may be necessary. Instrumentation may be considered to measure the motions of the deck and hull components, and the alignments and stresses of the mating surfaces throughout the mating process.

Module lift procedures should be developed following current offshore practice with the additional consideration of the platform as a buoyant structure. This will require that the relative motions of the platform and lift vessel be included as an aspect of the lift analysis.

14.7.4 Preparations for Tow

A deadweight survey and inclining experiment should be carried out to determine the platform's lightship weight and center of gravity. The condition of the platform at the time of inclining should be clearly documented so that an accurate assessment of the effects of added loads can be made.

A final testing program should be undertaken prior to the transportation of the platform. This program should verify the operation of the ballast system, fire fighting system, normal and emergency utility systems, communication systems, alarms (as practical), life saving appliances, etc. In addition, watertight closures and automatic closing doors should be tested. Functional testing of tendon running tools and trials of tendon running operations is also recommended.

The buoyancy compartments and the flooding control system of the subsea structures should be tested prior to tow out.

14.7.5 Installation

Upon arrival at the installation site, the platform, foundations and tendons should be inspected for damage during transportation. Measuring and positioning devices should be tested for accuracy and all necessary installation equipment should be available and in good working order prior to any deployment. Installed components should be completed within tolerance and as-built positions should be measured and recorded in the platforms operating manual.

If grouted connectors are to be used for foundations and well templates, grout samples should be taken for strength tests, grout volume should be monitored during installation and compared with calculated volumes, and instrumentation such as nuclear densimeters deployed to monitor grout quality. For mechanical connectors, remote inspection techniques should be used to ensure that the connection is satisfactory.

The platform installation requires running and stabbing the tendons within the anticipated weather window. During this procedure, inspections should monitor:

a) tendon damage during handling, including coating scars and damage to cathodic protection system;

b) tendon element makeup sequence (identification);

c) tendon motions during deployment (monitored by divers, ROVs, acoustical devices, etc.);

d) connector makeup;

e) tensioning.

14.7.6 In-service

Maintaining the platform on station requires a continuing in-service inspection program. The design of the platform, seafloor structures, tendons, and risers should take inspection into account.

All platform compartments should be accessible, vented, and have either temporary or permanent means of lighting, staging, and cleaning provided to allow complete internal inspection. Sea chests should be provided with means of closing off so that they may be dewatered while at sea.

Seafloor structures should be designed such that underwater inspections of critical members utilizing ROVs or similar devices can be undertaken.

Tendon and riser system components should be inspected to detect deterioration and allow corrective action to be taken in a timely manner. Inspection intervals and methods should take into account design methods and assumptions, particularly those that concern fatigue life and corrosion. Innovative inspection methods may be considered by the designer and operator to meet unique requirements. The operator may elect to pull tendons and risers, or inspect them in place. Although slightly less thorough, a complete in-place examination may provide better information than a complete examination of a few pulled tendons and risers.

General inspection of all components is recommended to check for corrosion and damage. Detailed inspection for cracking or other deterioration of metallic components is recommended. Areas of geometric discontinuity that cause stress concentrations should be examined with particular care. The condition of anodes, coatings and other components of the corrosion protection system should be carefully inspected. Components having elastomeric or other nonmetallic parts should be inspected for failure or deterioration.

A complete examination can be performed on a tendon or riser pulled from the water after marine fouling has been removed. This examination typically would include a thorough visual inspection, appropriate nondestructive testing and measurements of material loss due to corrosion or erosion. The entire tendon or riser should be inspected with attention to areas of stress concentration and accelerated corrosion. Protective coatings may be removed if required to conduct a thorough examination. A sufficient number of tendons should remain in place to withstand environmental conditions likely to occur during the inspection period. Selection of tendons or risers to be inspected should take into account load history and any indication of damage. Thorough examination of one or more may be used as an indication condition of all tendons and risers having an equal operational life.

In-place or in situ examination of tendons and risers requires advanced techniques having a high probability of detecting cracks and other deterioration. Such inspections may be substituted for pulling tendons.

Any inspection program, whether involving pulled tendons or in situ checks, should include an in-place visual examination to check the condition of corrosion prevention components.

Immediately prior to initial installation of tendons, a thorough examination of each tendon component should be made and the exact location of any flaws or damage noted and appropriate corrective action taken. As soon as practical after installation, an in-place visual inspection of the tendons should be performed to check for damage that might have occurred during installation. Tendon loading history and information on the size and location of cracks and flaws may be used to modify the inspection frequency over the life of the structure.

In addition to the regularly scheduled inspections discussed above, inspections should be considered under the following circumstances:

a) tendons should be inspected after a failure or damage to a tendon if a similar problem could have occurred on other tendons;

b) tendons should be inspected when they are pulled for any reason, including relocation of the TLP;

c) a tendon should be inspected when the maximum allowable stress has been exceeded.

After inspection, coatings should be repaired or reapplied in accordance with the manufacturer's recommendations.

An inspected tendon should be reinstalled in accordance with design and fabrication specifications or stored in a protected location if future use is planned.

The owner should maintain detailed records of the inspection history of each component including the exact location and size of cracks, flaws, and damage.

15 Surveys and Maintenance

15.1 General

During the life of the platform, in-place surveys that monitor the adequacy of the corrosion protection systems and determine the condition of the structure should be performed in order to safeguard human life and property, protect the environment, and prevent the loss of natural resources. These surveys should be coordinated with a maintenance program that monitors changing conditions and corrects deficiencies.

A properly conducted risk-based inspection plan may be accepted for surveys and maintenance in lieu of the prescriptive survey requirements of 15.5 and 15.6. This plan is to be in accordance with an internationally recognized standard or if the TLP is to be certified or classed a classification society should be consulted.

15.2 Personnel

15.2.1 Planning

Surveys and maintenance should be planned by qualified personnel possessing survey experience and technical expertise commensurate with the level of survey and maintenance to be performed.

15.2.2 Survey

Surveys should be performed by competent personnel, in accordance with a survey and inspection planning document, and may also include the observations of platform operation and maintenance personnel familiar with its condition. The personnel conducting surveys of above water areas should know how and where to look for damage and situations which could lead to damage.

Visual inspection of the underwater portion of a platform should be conducted by divers and/or ROV under the supervision of personnel experienced in the underwater visual inspection methods employed. Personnel trained and experienced in application of the method being used should perform nondestructive examination of the platform. Cathodic potential surveys should be supervised by personnel knowledgeable in this area.

15.2.3 Maintenance

Maintenance should be performed by competent personnel, in accordance with the maintenance planning document. A competent person shall have suitable experience in undertaking the specific tasks required of him. In addition, he shall be adequately trained and, whenever reasonably practicable, certified by an applicable recognized Society, Institute, or equivalent.

Maintenance should be coordinated with the inspection program, and should be based on the results of the surveys and inspections.

15.3 Survey and Maintenance Planning and Recordkeeping

The requirements as noted are a generic list of items that should be considered for all TLP’s; however, the most significant parts of these requirements are the survey planning and inspection document and the maintenance planning document. Development of these documents is critical to the success of an effective survey and maintenance scheme. The survey and maintenance documents shall be developed for each individual platform and take into consideration the location, design basis, and other unique feature of each individual platform. The list of critical joints for nondestructive testing, coating inspection and maintenance methodology, etc. shall be developed based on design, thus only a general requirement has been considered in this publication.

15.3.1 Survey and Inspection and Maintenance Planning Documents

Plans detailing the scope and methods of surveys, inspections, and maintenance to be carried out are to be prepared prior to installation and commissioning the platform. It is preferable that the design team for the project prepares these documents, although experience in developing similar documents is critical. The survey document is to identify the areas to be inspected and the scope of work necessary to carry out these inspections and surveys, as required to insure that the platform is fit for service through its design life. Ideally, the document should set out base data points that have been established during construction. These base data should include actual plate thicknesses, details on welds, information on coatings, and other relevant vessel specific data that will assist the survey and maintenance crews. It is likely that underwater ROV attachment points will be established on the unit. The placement of these needs to be tied to the inspection of critical components/areas. Specific points should be marked throughout the unit that can be monitored for coating and/or material loss. The locations of these points need to be set out in the survey and maintenance planning documents, along with coating and plate thicknesses at these points. The recommendations contained in 14.7.6 are to be considered when preparing the survey and inspection planning document. Any novel features incorporated in the design are to be given special attention according to procedures developed in the survey plan and inspection document.

15.3.2 Survey Reports File

All survey reports and records of all abnormalities found are to be compiled into a survey report file that is to be kept by the operator for reference during any survey. The records to be kept include but are not limited to the following:

a) survey and inspection plan as required by 15.3.1;

b) the records of all abnormalities found that are to include all videos and photographic records;

c) the records of all repairs performed on any abnormalities found and any further repetitive abnormalities found subsequent to the repairs;

d) records of all corrosion protection system maintenance, including records of all cathodic potential readings taken, records of depletion of all sacrificial anodes, impressed current maintenance records, such as voltage and current demands of the system, coating breaks, and the monitoring records of the steel material wastage in way of the coating breaks;

e) all records of any finding or abnormalities by the crew personnel on onboard, including any leakage in bulkheads and piping;

f) reports of thickness measurements of the platform;

g) reports of all NDT performed.

15.3.3 Maintenance File

Maintenance needs to be tied to the survey and inspection program, and clear records kept of the results of the survey, and any associated maintenance undertaken. The two records need to be cross referenced so that there is a correlation between the survey, the need for the maintenance, and the work undertaken. Notwithstanding the above, some maintenance records need to be kept that are independent of the survey records. These include, but are not limited to the following.

a) Complete records of all materials brought onboard, or removed from the installation so that there are clear records of all changes in weight and center of gravity. There is a strong tendency for offshore installations to get heavier over time, and it is important that any changes are properly reported, particularly on a vessel on which the draft cannot be used as a weight indicator.

b) The tendon tension monitoring equipment needs to be maintained in good working order, and every effort should be taken to maintain calibration.

c) Salt water systems in the hull need to be carefully monitored and maintained on a regular basis, including pipe thickness gauging. As with the weight and tendon tensioning monitoring, it is necessary to have a clear understanding of the condition on the facility since salt water leaks cannot be detected through changes in draft.

15.4 Survey Frequency

15.4.1 Annual Survey

Annual surveys should be carried out within a three-month period before or after each annual anniversary date of the crediting of the previous special periodical survey or the original commissioning date.

15.4.2 Intermediate Survey

Intermediate surveys are to be carried out either at the second or third annual survey or between these surveys.

15.4.3 Special Periodical Survey

A special periodical survey is to be completed within five years after the date of build or after the completion date of the previous special periodical survey

15.4.4 Continuous Survey

In lieu of special periodical surveys a system of continuous surveys may be undertaken whereby the special periodical survey requirements are carried out in regular rotation to complete all the requirements of the particular special periodical survey within a five-year period. Each item surveyed will become due again for survey within approximately five years from the date of survey. Twenty percent of the survey items are generally to be completed each year.

15.4.5 Surveys After Storm or Other Significant Environmental

A survey should be carried out after direct exposure to a significant environmental event (e.g. hurricane or typhoon, earthquake, eddy current, etc.). Surveys should also be conducted after severe accidental loading or damage (e.g. boat collision, dropped objects, fire, etc.). These surveys shall be comprehensive enough to fully discover any possible damage resulting from the above noted occurrences. In the event of fire damage, particular care needs to be taken to ensure no loss of strength or other properties of special steels.

15.5 Survey Requirements

15.5.1 Annual Surveys

Each annual survey is to include a through visual examination of all above water structure. Splash zones shall be examined for possible damage or deterioration from corrosion. Additionally, where it appears that significant deterioration or damage has occurred to an installation since the last survey, a general examination including any necessary NDT or thickness measurement, by diver, underwater camera, submersible, or other suitable means, of the underwater structure and the corrosion control system shall be carried out. Where thickness measurement and visual examination show evidence of significant structural deterioration the structural integrity of the platform for continued use shall be justified by engineering analyses. For spaces that will require internal examination the requirements of 15.6 shall apply.

Any modifications or repairs made as a result of findings at a previous survey should be re-examined at each annual survey to the extent considered necessary by the attending surveyor.

During any annual survey, assessment of the degree of marine growth shall be carried out. The operator should determine the marine growth thickness and access the effect on the structure. If the operator decides to leave the marine growth greater than that allowed in the original design, the operator is to justify, by engineering analysis, that the higher hydrodynamic loading due to the additional marine growth will not affect the integrity of the structure.

15.5.2 Intermediate Surveys

The requirements of the annual survey are to be met during the intermediate survey. Additionally, underwater inspection, as noted below, of the platform is to be carried out. Internal examination of representative salt-water ballast tanks is to be done at this time. Should the internal examination reveal excessive corrosion or damage, the internal examination should extend to all ballast tanks. For spaces that require internal examination the requirements of 15.6 shall apply.

15.5.2.1 Underwater Inspection

The underwater parts of the platform are to be examined at intermediate surveys and at special periodical surveys. The underwater inspection is to be carried out in accordance with procedures that are to be contained in the survey and inspection planning document; minimum requirements are noted in 15.5.2.2 through 15.5.2.6.

15.5.2.2 Underwater Inspection Procedures

Underwater inspection procedures shall consist of the following:

a) procedure for divers, or ROV operators, to identify the exact location at which they are conducting their inspection;

b) procedure for cleaning the marine growth for inspection purposes that is to include the extent and location of the underwater cleaning;

c) procedure for measurement of amount of marine growth;

d) procedure and extent for taking thickness measurements of the structure and NDT of critical joints;

e) procedure and extent for measuring cathodic potential readings in way of structures;

f) qualifications of all divers conducting the inspection, NDT, and thickness readings;

g) the type of underwater video and photography, including means of communication, monitoring, and recording;

h) for underwater inspections associated with a special periodical survey, means shall be provided to permit the opening up of all sea valves and overboard discharges for internal examination.

15.5.2.3 Scope of Underwater Inspection

The following are to be examined at each underwater inspection: external surfaces of the upper hull or platform, pontoons or lower hulls, underwater areas of columns, bracing, and their connections, as applicable, are to be selectively cleaned and examined. These areas include joints of critical structural members, areas susceptible to damage from supply vessels, dropped equipment, corrosion and erosion from loss of coating and areas of progressed and accumulated wear-and-tear.

a) Non-destructive testing may be required of areas found to be suspect. Joints of structural members of different configurations are to be selected, cleaned, and nondestructively tested. The selection of these joints are to be such that all joints underwater are to be inspected every five years.

b) Sea chests and strainer are to be cleaned and examined.

The type, location, and extend of corrosion control (coatings, CP systems, etc.) as well as effectiveness, and repairs or renewals to same should be reported in each survey. Particular attention is to be given to corrosion control systems in ballast tanks, free-flooding areas, and other locations subject to seawater from both sides.

15.5.2.4 Internal Inspection

In conjunction with underwater inspection the following ballast spaces are to be internally examined, and the effectiveness of coating or corrosion control arrangements are to be verified either visually, by indicator strips, or by thickness gauging (as per the requirements in the survey planning and inspection document), placed in satisfactory condition, as found necessary, and reported upon:

— representative ballast tanks in lower hulls or free-flooding compartments as accessible;

— at least two ballast tanks in columns or upper hull, if applicable.

15.5.2.5 Corrosion Protection System

In addition to the above requirements, the following are to be performed during all underwater inspections.

a) Cathodic potential readings are to be taken from representative positions on the entire underwater body and evaluated to confirm that the cathodic protection system is operating within design limits.

b) Sacrificial anodes are to be examined for depletion and replaced when no longer effective.

c) Impressed current system anodes and cathodes are to be checked for damage, fouling by marine growth, and carbonate deposits. The current and voltage demands of the system are also to be checked to ensure the system is functioning properly.

d) Additional examinations are to be performed on the wind and water areas of the structures where coating breaks are evident. Thickness measurements in these areas may be required if found necessary by the attending surveyor.

15.5.2.6 Tendons and Seafloor Structures

Tendons and seafloor structures are to be examined by remote operated vehicle at each underwater inspection. These examinations are to be carried out in accordance with the survey and inspection planning document noted in 15.3.1 and should also take into consideration the comments noted in 14.7.6. As a minimum, the tendons are to be visually examined for their entire length from the lowest exposed point at the seabed to the connection point at the TLP.

15.5.3 Special Periodical Survey

The special periodical survey is to include the requirements of the annual and intermediate surveys, (including underwater inspection). Internal examination of any tanks or other compartments are to be carried out in accordance with 15.6.

15.5.3.1 Parts to be Examined

The following are to be performed as applicable, the parts examined, placed in satisfactory condition, and reported upon.

a) The hull or platform structure, including tanks, watertight bulkheads and decks, cofferdams, void spaces, sponsons, deck, helicopter pad, machinery spaces, and all other internal spaces are to be examined externally and internally for damage, fractures, or excessive wastage.

b) All tanks, compartments, and free-flooding spaces throughout the platform are to be examined externally and internally. Internal examination of the lower hull is to be specially considered. Watertight integrity of tanks, bulkheads, hull bulkhead deck and other compartments are to be verified by visual inspection. Suspect areas may be required to be tested for tightness, nondestructively tested, or thickness gauged. Tanks and other normally closed compartments are to be ventilated, gas-freed, and cleaned as necessary to expose damage and allow for a meaningful examination for excessive wastage. Internal examination and testing of compartments filled with foam or corrosion inhibitors and tanks used only for lube oil, light fuel oil, diesel oil, or other noncorrosive products is not considered necessary, provided that, upon general external examination, the surveyor considers their condition to be satisfactory. External thickness gauging may be required to confirm corrosion control.

c) Secondary structures, such as pipe racks, process support structures, deck houses, superstructures, helicopter landing areas, and their respective attachments to the deck or hull.

d) Foundations and supporting headers, brackets and stiffeners for process related apparatus, where attached to the hull, deck, superstructure, or deckhouse.

15.5.3.2 Procedures for Special Periodical Survey

At each special periodical survey, thickness gaugings are to be performed where wastage is evident or suspected. Representative areas to be gauged are to be detailed in the survey and inspection planning document and should include areas such as the splash zones on hulls, columns and ballast tanks, free-flooded spaces, bottom of hulls, tendons and seafloor structures as accessible.

Where inspection of underwater joints is required, sufficient cleaning is to be performed in way, and water clarity to be adequate, to permit meaningful visual, video, camera, or NDT examination as required by the survey and inspection planning document. Every effort should be made to avoid cleaning damage to special coatings.

15.6 Examination of Joints and Connections

Connections that may require examination include:

a) connections of columns and diagonal to upper hull or platform and lower hull or pontoons;

b) joints of supporting structure, including diagonals, braces, and horizontals, together with gussets and brackets;

c) internal continuation or back-up structure for the above.

NDE may be required at suspect areas.

15.7 Requirements for Internal Examination

The following apply to all internal examinations of any spaces adjacent to shell plating, such as tanks, voids, or machinery spaces, and are applicable to annual, intermediate, or special periodical survey.

a) Precautions are to be taken to ensure safety during inspection. Tanks are to be made safe for entry and work.

b) In preparation of survey and to allow for meaningful examination, all spaces are to be cleaned including removal from surfaces of all loose accumulated corrosion scale. Spaces are to be sufficiently clean and illumination is to be provided to reveal corrosion, deformation, fractures, damages or to other structural deterioration.

c) Where soft coating are used, safe access is to be provided for the surveyor to verify the effectiveness of the coating and to perform an assessment of the conditions of internal structures that may include spot removal of the coating.

d) Based on conditions found, thickness gauging and means of access to upper parts of the tank or space may be required.

16 Assessment of Existing TLP's Designed for Hurricanes

16.1 Scope

This section addresses the initiators and methods for assessment of existing TLP's in a hurricane environment such as the Gulf of Mexico. These assessments do not apply to new-built systems, but provide guidelines for assessment of existing TLP systems when some material aspect of, or basis for, the platform changes.

The provisions of 16.1 to 16.8 apply to the assessment of existing TLP's located in the Gulf of Mexico and designed for hurricane conditions.

These provisions are minimum assessment requirements intended to reduce hurricane-related risks to existing TLP's.

TLP's should be assessed individually as well as on an area-wide basis including other offshore infrastructure (platforms, subsea, pipelines), in order to determine the consequences of a major structural failure on the owner and on other parties that could be affected either directly by a TLP's failure or indirectly by disruption of the TLP's operability (e.g., in the case of a hub TLP). For any TLP which represents a major investment, which contains oil production and handling, or which is normally manned, consideration should be given to exceeding the minimum acceptance criteria defined herein.

Because of their complex design, dynamic behavior, and strong coupling with other critical systems (e.g. risers), it is not sufficient to characterize TLP's by any single strength measure, such as the reserve strength ratio (RSR). A three-step approach is therefore used that includes a design level check, a survival check, and a robustness check. The three steps are described in the following sections.

16.2 Assessment Initiators

An existing TLP shall be assessed at the onset of one or more of the following conditions, which could result in significant changes in the performance of the structure:

a) planning for the addition of topsides facilities not included in the original design (e.g. topsides equipment packages, drilling rigs, supplementary process components);

b) planning for the addition of wells, risers, boat landings, auxiliary floatation and other components that could increase hydrodynamic loading;

c) damage to the hull or tendon system that is likely to reduce strength or resistance to hurricane conditions;

d) substantial variations in site-specific (or regional) hurricane parameters with respect to the metocean parameters used in the original design. 1

16.3 Assessment Conditions

TLP's that are assessed because of damage or a variation in site-specific hurricane conditions, as defined in 16.2, shall use the assessment process described in 16.4.

TLP's assessed because of any other assessment initiators shall use the same design process as described in prior sections of this document, including all normal factors of safety. The TLP configuration shall be updated as necessary to reflect the proposed changes to the configuration or other factors that initiated the assessment.

In the case of variations in site-specific hurricane conditions, the metocean parameters for use in the assessment shall be as specified in API 2INT-MET or derived from a site-specific study as defined in API 2INT-MET. Site-specific conditions are typically used to design TLP's. If the site-specific conditions used to design the TLP are of equal or greater severity than the revised environmental conditions defined in API 2INT-MET or derived with the methods described in API 2INT-MET, and the TLP has not been modified from the design configuration, then the TLP is deemed to have passed the assessment.

16.4 Assessment Process

16.4.1 General

Existing TLP's shall be assessed using 100-year hurricane conditions using one of the following approaches.

1) By reference to the original design cases for hurricane conditions accounting for the as-is configuration of the TLP.

2) By re-analysis of the as-is configuration of the TLP. A three-step assessment process is recommended as described below. Analysis methods should give accurate or conservative representations of the TLP's response as validated by model tests or field data. Loads due to loss of air gap shall be included.

3) By proven survival, in the TLP's as-is configuration, of an actual hurricane event that meets or exceeds the 100-year hurricane condition (see 16.5.2).

The results of the most recent inspection including hull, tendon system, and other components should be used where appropriate to update the corrosion allowances and other assumptions used for the original design of the facility.

16.4.2 Step 1 – Design Level Check

16.4.2.1 Current Condition Design Check

Using the environmental conditions employed in the original design, a design level check of the TLP should be performed taking into account all changes on the TLP since its original installation. This check is intended to evaluate the consequences of changes in configuration that could increase or decrease the loads on, or operating envelopes of, critical structural components.

The changes considered for this check should include not only additions or removal of payload, but also any damage or corrosion incurred by the risers, by the hull or by the tendon/mooring system. 2

16.4.2.2 Life Safety and Operational Checks

The life safety and operational checks should be performed to evaluate the TLP for conditions while manned and operating during the hurricane season.

Life safety is assessed by comparing the 100-year sudden hurricane condition (see API 2INT-MET) to the 100-year hurricane condition used for the original design of the facility. If the 100-yr sudden hurricane condition is more severe than the 100-yr hurricane condition used in the original design, repeat the design check in 16.4.2.1 with the 100-year sudden hurricane condition.

Operational and damaged conditions used for this check should be consistent with the original criteria except that updated hurricane conditions should be used.

Acceptance criteria are provided in 16.5.1.

16.4.3 Step 2 – Survival Check

Evaluate the TLP's ability to survive 100-year hurricane conditions using the hurricane analysis procedures in this document. The response of the TLP should not exceed the capacity of the critical components or cause disconnection of the tendon/mooring system.

Acceptance criteria are provided in 16.5.2.

16.4.4 Step 3 – Robustness Check

The robustness check for TLP's that passed the survival check in Step 2 should be performed using a return period equal to or higher than 200 years, preferably 1000 years, to determine the capacity of each critical component. The robustness check is similar to the Category S survival conditions procedures described in prior sections of this document including 5.2.4 and 9.2.6. Additional guidance can be found in these sections. TLP's that did not pass the survival check in Step 2, the highest acceptable return period should be determined for each critical component to identify components that control the TLP's capacity.

Acceptance criteria are provided in 16.5.3

16.5 Acceptance Criteria

16.5.1 Design Level Check Acceptance Criteria

The design level check should use the more severe of either the original design environmental criteria or the sudden hurricane conditions contained in API 2INT-MET, and Category B factors of safety. If a TLP does not meet or exceed the recommended criteria, modifications to the hurricane and damage control procedures should be evaluated to mitigate the additional risk while manned.

16.5.2 Survival Check Acceptance Criteria

Acceptance procedures and criteria for the survival check are based upon the type of initiator. If the initiator is a significant change in hurricane conditions, then this check is treated as a true survival case, and can be performed with survival case (Category S) factors of safety. Survival checks for all other initiators shall use extreme case (Category B) factors of safety.

Survival is defined as no failure of the floating structure, tendon system, risers, or pipelines that would lead to the catastrophic loss.

For survival acceptance, the TLP shall meet as a minimum the following criteria.

a) The floating stability of the TLP is maintained in accordance with the approved certification criteria.

b) The tendon system should not fail for the maximum tension case and should maintain a tensile load greater than zero for the minimum tension case in the intact condition. Minimum tension cases of zero or less can be allowed if it is part of the original design but should be demonstrated that unlatching would not occur. All tendon interface hardware should remain within geometric operating limits.

c) Stresses within the primary structural elements of the hull and deck, if required for hull integrity or stability, are generally below yield with Category S safety factors and the structural elements are fit for purpose to prevent loss of overall stability of the TLP. Stress redistribution to lower stress areas should be evaluated with regards to allowable strain limits and buckling.

d) Risers do not fail and all their interface hardware remains within geometric operating limits.

e) No catastrophic failure occurs at critical connections that secure major production and drilling modules to the structure.

TLP’s that do not pass the survival check should be evaluated parametrically, to determine the highest return period for which the TLP passes the survival check. This can assist in providing a clear understanding of the risks and identifying appropriate mitigating actions.

In addition, if a TLP does not pass the acceptance criteria, hydrocarbon inventories on the TLP and any incoming or outgoing flow should be significantly reduced to reduce environmental risks if the TLP does not survive in the extreme event. Also, mitigation efforts such as payload reduction or structural strengthening should be considered.

16.5.3 Robustness Check Acceptance Criteria

The structure component(s) that control the capacity of the TLP should be identified and the associated component and global structure failure mode defined. This can be used to understand the limitations of the TLP’s design for hurricane conditions. Consideration should be given to making mitigating modifications to the configuration of components that fail at unusually low return periods.

The robustness check should include, as a minimum, evaluation of the structural integrity of the deck and hull, the tendon system, foundations, and the production and export risers.

Key assessment aspects should be:

- movement of riser support systems should be within acceptable limits;
- capacity and ductility of key riser system components;
- tendon system safety factors, and the capacity of key tendon components as well as the capacity and ductility of their support structures;
- tendon unlatching;
- key structural components, such as: deck to hull connection, pontoon to column connections, riser porches, etc.;
- high-stress low-cycle fatigue of critical structural elements, or tendon components;
- global stability and downflood points (e.g. access hatches and other points) should be checked to prevent potential water ingress with regard to wave impact loads and full immersion to appropriate rule for the 100-year design wave crest conditions (see API 2INT-MET).

16.6 Configuration Changes

The TLP's configuration should not be modified such that the TLP no longer meets the design and survival level checks as described in Step 1 and Step 2 in 16.4.

Examples of configuration changes include additional equipment, topsides payload, additional risers, etc. Such changes are acceptable if it can be demonstrated that the global performance and the structural performance of the TLP has not changed with respect to the design checks. In some cases the TLP owner may be able to modify the current configuration to accept the changes without degrading the structural performance. Examples include removing unused equipment or modifications to ballast or payload.

16.7 Marine Operations Manual

The Marine Operations Manual (MOM) of the TLP should be updated to reflect any changes to the marine operations identified by the results of the structural assessment. Marine Operations staff on-board the TLP should be properly trained to assure that all procedures are followed for storm safe conditions and for hurricane evacuation.

16.8 General Recommendations for all Existing TLP's

16.8.1 Scope

The previous sections describe analytical assessments to be performed to determine that, following the onset of specific assessment initiators defined in 16.2, a TLP is still in a safe configuration. The assessment generally deals with global performance of the TLP; if the structure does not pass the assessment, then mitigation is recommended. Several types of mitigation are described in this section.

In addition, a continuous mitigation process should be considered regardless of the outcome of the analytical assessment, and even for TLP's where assessment is not required. A significant portion of post-hurricane downtime on TLP's and other offshore structures results from damage to structures and systems that do not affect the structure's global strength. Examples include damage to topsides safety equipment and systems, especially on lower decks, subject to wave loading, and toppled deck equipment due to a combination of inadequate securing, accelerations, and high winds. Such damage can result in safety issues when the TLP is re-boarded following a hurricane and may also result in significant repair, downtime, and economic consequences.

16.8.2 Mitigation

Mitigation can help extend the life of a TLP or improve its chances of survival in a design event if employed early. Mitigation typically involves reducing loads on the TLP such as removing unused risers, or increasing the structure's strength. Mitigation can also include active programs to minimize the consequence of damage or failure, such as plugging and abandoning unused wells or removing inactive process equipment. Mitigation opportunities should be evaluated on a cost-benefit basis for each structure on a case-by-case basis, although many of them can be implemented at low cost or as part of the normal planned structure maintenance.

Examples of load reduction are as follows.

- relocating or removing piping and other systems located below the lowest deck; 5
- relocating or removing equipment on the lowest decks subject to wave loading;
- removal of unused boat landings, walkways, stairs, barge bumpers, etc.;
- removal of unused wells and risers;
- removal of process equipment, tankage, or piping no longer employed in order to reduce surface areas exposed to wind and waves as well as dead load;
- raising the deck (s) to prevent wave loading on the deck;
- laying down or removing a drilling rig during hurricane season;
- operational plans to reduce hydrocarbon or other liquid inventories prior to an expected hurricane event.

Strengthening should be based upon a specific engineering assessment for the TLP. Examples of strengthening are as follows:

- improved tie-down of topsides structure and equipment (see API RP 2TD for guidance);
- strengthening members or adding auxiliary bracing members;
- strengthening of joints;
- examples of actions that can minimize the consequences of damage or failure are as follows;
- relocating or removing piping and other systems located below the lowest deck;
- relocating or removing equipment on the lowest decks subject to wave loading;
- "hardening" of piping, equipment and other systems located on the lowest decks from potential damage due to wave loading;
- plug and abandon unused wells;
- reduction of any hydrocarbons and/or chemicals on the facility;
- provision of alternate means of production if a TLP is damaged or destroyed, such as pre-planning for alternate sales lines, emergency jumper lines to alternative undamaged platforms, etc.

16.8.3 Hurricane Preparedness

Advanced planning can also assist in reducing hurricane risks as well as improving post-hurricane response. Owners should develop a written hurricane preparedness plan describing general activities for their inventory of offshore structures as well as the plans for each specific structure. Checklists and platform specific guides can assist during the evacuation process. TLP's with higher life safety exposure and/or economic risk may require additional consideration.

Examples of hurricane preparedness are as follows.

a) Evacuation planning for major hurricanes, including first evacuation for platforms that are at greater risk of failure and those that are furthest from shore. Initial evacuation of non-essential personnel should begin early.

b) Evacuation planning for sudden hurricanes, which occur at short notice, should be given special consideration, including evacuation to offshore structures that have been demonstrated to be able to safely survive sudden hurricane conditions.

c) Begin preparing operations for safe shut-in as early as possible including system pump down, securing equipment and control panels, reducing liquid inventories, etc.

d) Secure loose objects and equipment that can become airborne projectiles. Store movable equipment in safe and dry areas.

e) Develop advance plans for post-hurricane access to the TLP, in case normal access and safety systems such as boat landings, walkways, power, etc. are not be available or functional due to damage.

f) Establish guidelines for safe re-boarding of a damaged TLP, with minimum acceptance criteria for platform access and egress.

Annex A
(informative)

Commentary on Global Response Analysis and Design Checks

A.1 VIV of Hull, Tendons, and Risers

A.1.1 Introduction

VIV is an important response for the design of systems in areas with substantial currents. VIV is an interactive load/response in which vortex shedding of flow around bluff bodies, when occurring at resonant frequencies of the body, is capable of exciting resonant system response. It is a feedback and lock-in phenomenon, wherein the motion of the body increases and correlates the vortex shedding. Depending on the system, the response can be onerous in generating high loads and/or stress. Because of the continuous nature of the response, the number of cycles possible, and the duration of some current events, high fatigue damage due to VIV is often a concern. In addition to the dynamic response, when a system is experiencing a VIV response the steady drag coefficients are also generally increased, leading to increased mean loads due to currents.

VIV is especially a concern for long slender members of bluff cross section (e.g. risers and tendons). For these members, the VIV response is typically a transverse modal response. The issues in this type of response include bending stress fatigue, increased drag loads, and the end effects that transmit loads into either wellheads or foundation piles, and into the TLP hull.

The other area of significant VIV concern is the excitation of the hull in sway resonant motion. This has primarily been thought to be a concern for single column structures such as spars and single column TLPs, but recent tests have also shown VIV response of multicolumn structures. This has included square column as well as round column structures. Hull VIV for TLP's is not generally a strength issue, as it might be for a catenary moored structure, but does have implications for maximum offset and for riser response and fatigue.

VIV is currently a topic of much research. References for the basic phenomena of VIV may be found in review articles by Williamson and Govardhan (2004) [246]; Sarpkaya (1979) [216] and (2004) [217]; Griffin and Ramberg (1982) [149]; Bearman (1984) [98]; Parkinson (1989) [204]; in a book chapter by Anagnostopoulos (2002) [88]. Books on VIV include Blevins (1990) [100]; Naudascher and Rockwell (1994) [197]; and Sumer and Fredsøe (1997) [229]. Additional useful references include Barltrop (1991) [96]; Vandiver (1993) [238]; and Vandiver, Allen and Li (1996) [239].

A.1.2 Observations of VIV on TLPs

With the development of TLPs in the deepwater portions of the Gulf of Mexico, which are subject to the Loop Current and its eddies, there is now field experience with VIV effects on TLPs. observations include the following.

a) Hull VIV in existing systems has been observed to be small and not a major design issue. Motions and increased offsets should be included in the riser design, especially for SCRs.

b) The VIV of tendons has been observed to provide a significant excitation of the TLP structure, both at rigid body resonances (heave, pitch, roll), and at higher frequencies which may affect internal structural resonances. The observed motions have been sufficient to affect comfort of personnel, operation of production equipment, and provided concern for fatigue loading of TLP local and primary structure (Leverette, et al. (2003) [179]).

A.1.3 Analysis of VIV for TLPs

Most ongoing efforts in VIV response analysis are targeted at risers, where VIV is an established design constraint. Further details on VIV analysis for risers (and tendons) may be found in API 2RD.

The primary tools in riser/tendon VIV analysis are modal response methods based on empirical load/response techniques. Cylinder and riser model testing forms the basis for most of the industry capability in this area. In addition, progress has recently been made on computational fluid dynamics (CFD) modeling of the flow around cylinders and other structures. This is currently adding to the understanding gained from model testing, and is being used in a limited number of applications in strip theory models. Full 3D simulation of a substantial portion of a riser is currently at the outer limits of our computational capacity.

There are no proven analytical tools for the coupled analysis of tendon VIV exciting the structure. Leverette, et al. (2003) [179] describe one analysis which combines a traditional riser analysis with a time domain coupled numerical TLP model.

A.1.4 VIV Mitigation

The mitigation of VIV is typically done with either helical strakes or fairings. Strakes are devices that disrupt the coherence of the flow and reduce the VIV effects. Fairings are streamlining shrouds which make the bluff body into a shape where vortex shedding either does not occur, or does not communicate from one side of the body to the other, thereby disrupting coherence necessary for lock-in.

Figure A.1 shows a typical strake pattern. Parameters governing the effectiveness of the strakes to reduce VIV are strake height, usually specified as a fraction of the riser diameter, strake pitch, and number of strakes (typically three). Strakes typically increase drag while eliminating a significant portion of the VIV response.

Figure A.1—Helical Strakes

Figure A.2 shows a typical fairing. Parameters governing effectiveness of fairings are the length-to-diameter ratio and shape. Fairings may also reduce drag. Recent developments (Allen, 2003 [87]) include very short fairings which do not reduce drag, but which appear to be effective on VIV and are much easier to handle.

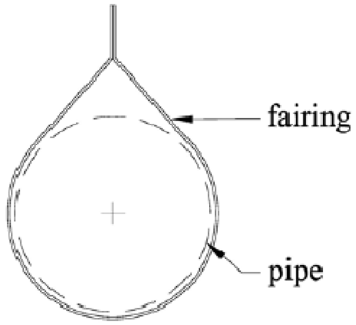


Figure A.2—Short Fairing

A.2 High-frequency TLP Responses

A.2.1 Introduction

The high-frequency responses of TLPs are significantly affected by nonlinear mechanisms, particularly in moderate to extreme seastates. The primary nonlinear mechanisms are as follows:

a) springing,

b) ringing,

c) vortex shedding excitation of lateral tendon vibrations, and

d) deck wave impacts.

Since all of these mechanisms may be contributing to the high-frequency responses, it is basically impossible to separate them from a time series simply by filtering techniques. However springing will always be present in the high-frequency response.

In low to moderate seastates, there is generally significant wave energy in the frequency range overlapping the natural heave/pitch/roll frequencies of a TLP; consequently both first-order (linear) and second-order diffraction forces should be considered to evaluate the total forcing at the resonant frequencies of the vertical modes. In extreme seastates, the wave energy in the frequency range overlapping the natural heave/pitch/roll frequencies of a TLP is relatively small and the total forcing at these frequencies is dominated by second-order springing and higher-order nonlinear effects.

From band-pass filtered time series of vibrations at, and close to, the natural period it is generally difficult to separate the contributions caused by the different sources: first-order waves, springing and (not severe) ringing, which makes utilization of these time series difficult in design. For certain structures and in certain extreme seastates, the ringing response events stand out so clearly from the background springing that it is useful and unambiguous, from a practical perspective, to identify and separate the two types of responses.

However, since ringing is normally caused by the same forcing mechanisms that contribute to springing (neglecting the special case of ringing caused by waves impacting the deck), it can be expected that there will be conditions where the delineation between the two types of responses will not be so clear, to the point of being impractical.

A.2.2 Springing

Springing forces at or near the resonant heave/pitch/roll natural periods of TLPs are an important contributor to tendon fatigue and shall be properly accounted for to assess fatigue damage accumulation. Springing forces are also important in the assessment of extreme tendon tensions in extreme design seastates (Mercier, et al. 1997 [190]).

The springing response is, in contrast to ringing, very dependent on the damping of the system. The springing response does commonly not appear in “bursts”, like the ringing response, but more in terms of continuous, modulated groups. The full calculation of second-order springing forces is quite involved, but the theory has been validated experimentally (Mercier and Niedzwecki, 1994 [189]). However the implementation of the theory for random seastates is not routinely done, primarily because it is not clear that application of the second-order diffraction theory for calculation of springing forces is sufficient in that third- and higher-order springing forces should also be included in the analysis (Newman, 1995 [200]). In some cases, ringing responses are known to be important but are not included in the theoretical modeling.

A.2.3 Ringing

Ringing responses of TLPs are (Natvig, 1994 [196]; Davies, et al. 1994 [123]):

a) transient free vibration responses at the high-frequency resonant periods associated with impulsive loading due to very steep and high individual waves;

b) a rare event, showing a burst-like occurrence only a few times an hour in relatively severe seastates, and consequently usually contributing to the extreme responses only, and not to fatigue;

c) sensitive to relatively small changes in the geometrical form of the individual wave, as well as small changes in the wave kinematics.

Two waves that, from a record, seem similar might lead to quite different ringing response: one might lead to severe ringing, the other might not initiate any noticeable ringing at all. All observations of ringing events indicate that most of the excitation takes place in the wave crest, above the mean free surface, but that the excitation in the wave trough has a significant effect on the level of severity of the ringing response. Furthermore, the forcing does not seem to be caused by viscous effects, but rather by "inertia" effects. This, in turn, indicates that proper use of potential theory might lead to a numerical model capable of computing the ringing forces. However, neither first-order nor second-order theory are expected to be capable of describing ringing, which also is in line with practical experience.

Ringing is a highly nonlinear phenomenon that is not well understood theoretically. Ringing has been recognized to be present for all TLPs designed to date, and it has contributed, to a varying extent, to the extreme tether tension in all cases.

A.2.4 Vortex Shedding Excitation of Lateral Tendon Vibrations

A third mechanism responsible for nonlinear excitation of high-frequency responses is due to lateral tendon vibrations caused with vortex shedding in strong currents (Leverette, et al. 2003 [179]). For example, vortex shedding from the tendons at a period near six seconds will transmit three-second period vibrations to the hull.

A.2.5 Deck Wave Impacts

TLP ringing is the result of one or several steep waves impacting the columns of the TLP. A related source of high-frequency excitation is wave impact loading on the side or underside of the deck. Due to the wave inundation effect, the forcing event is not necessarily as short as that associated with ringing, consequently the response following the main impulse may be more highly damped or confused. Nevertheless, depending on the extent of inundation, the wave impact forcing may be quite large (Schott, et al. 1995 [219]).

A.2.6 Numerical Modeling Techniques

From the transient nature of the ringing and wave impact responses it is clear that any numerical computations of this effect have to be executed in the time domain. The description of ringing excitation should be sought within the framework of the hydrodynamic theory of potential flow. It is equally clear that linear or second-order perturbation theory is not adequate for this kind of computation. Though much effort has been expended in developing and verifying analytical models of TLP ringing (Faltinsen, et al. 1995 [138]; Jefferys and Rainey, 1994 [163]; Davies, et al. 1994 [123]; Malenica and Molin, 1995 [185]; Krokstad, et al. 1996 [170]), no widely accepted modeling approach has emerged. It is likely that the only numerical modeling approach that will be successful in predicting ringing is solving the exact 3D free surface problem, a capability which does not yet exist.

Analytical or numerical models for springing, ringing and wave impacts have not yet been sufficiently validated with experimental or full-scale data to justify their use in detailed analysis and design verification. These models are suitable only for preliminary design. For these reasons, model tests are typically used to quantify the high-frequency responses of TLPs (Schott, et al. 1995 [219]). Nevertheless, a fundamental understanding of the underlying physics is needed to ensure that the model tests are set up properly.

A.2.7 Recommended Design Verification Procedure

A.2.7.1 General

Due to the lack of reliable analytic tools for modeling high-frequency responses and forces, one should either resort to model tests to provide the needed information or turn to past experience to establish conservative design allowances for these responses. The former is the preferred approach since it leads to a more reliable and optimized design. However, even with this approach a number of ill-defined issues should be considered related to what seastates to use as the basis for the design, how to set up and conduct the model tests, and most importantly, how to interpret the measurements and incorporate them in the design process.

The selection of environmental criteria for high-frequency responses should consider the spectral wave parameters and statistics of individual waves in the seastate. The selection of spectral wave criteria for high-frequency responses ideally should be response-based. However, since reliable tools for analytic modeling of high-frequency responses do not yet exist, it is necessary to resort to an investigation of the sensitivity of the response to variations in the spectral wave parameters near the 100-year seastate. To determine the appropriate design level response, the responses to the various seastates investigated should be weighted according to their relative probability of occurrence.

Carefully conceived and executed model tests using dynamically faithful scale models are the most reliable way to quantify the high-frequency responses and should be an integral part of the design process. The tests should be performed as early in the design process as possible, definitely before the final sizing is complete. Unless test data from previous tests can be extrapolated with confidence to provide the requisite design information, postponing the model tests until after the final sizing is complete to verify the final design may pose a substantial risk to the project schedule and should be avoided.

The interpretation of measured or simulated response time series is also a challenging part of the design process. The goal is to identify the extreme value distribution of the high-frequency response. This information is then used to calibrate design recipes, which are equations for combining the responses from the various frequency bands.

A.2.7.2 Interpretation of Model Test Results

The use of model tests for determination of high-frequency responses imposes a number of requirements on the interpretation of such tests. It is sometimes difficult to distinguish between springing responses, ringing responses, and those due to wave impact on the deck of the TLP. The high-frequency responses are most directly observed in tendon tension responses, and in heave/pitch/roll acceleration responses. In addition to examining the times series, visual examination of video records is critical for identifying events such as deck impacts and breaking waves (Schott, et al. 1995 [219]).

One means of separating responses in tension data is to extract the heave, pitch, and roll induced tension by modal decomposition (Jefferys and Rainey, 1994 [163]). This is typically done by summing and differencing the tension from the various tendons according to the contribution each motion mode gives to each tendon. This is useful in separating pitch/roll from heave effects, but has been of only limited use in separating ringing responses from other responses.

The primary tool used to distinguish the various response components is filtering of the response signal. Low pass, band pass, and high pass filters are used to separate the slow drift, wave frequency, and high-frequency (heave/pitch/roll frequency) responses. This is useful for understanding the various responses, but suffers from the following limitations:

— filters will always produce some distortion of the signal, and shall be designed carefully to avoid adding more uncertainty to the measurements;

— the various responses may have quite separate frequency bands, but often have some degree of overlap, so that frequency separation does not completely separate the responses;

— ringing and springing are separate processes, but occur at the same frequencies, so that no separation is possible.

Significant ringing of a structure is recognized both in a plot of the filtered time series and in a plot of the probability distribution of the responses in that (Davies, et al. 1994 [123]):

— the high-pass filtered time series shows an oscillatory signal with a large amplitude being built up over a couple of cycles (at the natural period), followed by a slow decay of the amplitude in time at a rate that depends significantly on the damping of the vibrational mode;

— the existence of a dual population of responses is clearly indicated in that the extreme events due to ringing show a completely different probability distribution than the main bulk of events at a lower response level.

Figure A.3 illustrates the time series characteristics of springing, ringing, and wave impact responses (Schott, et al. 1995 [219]).

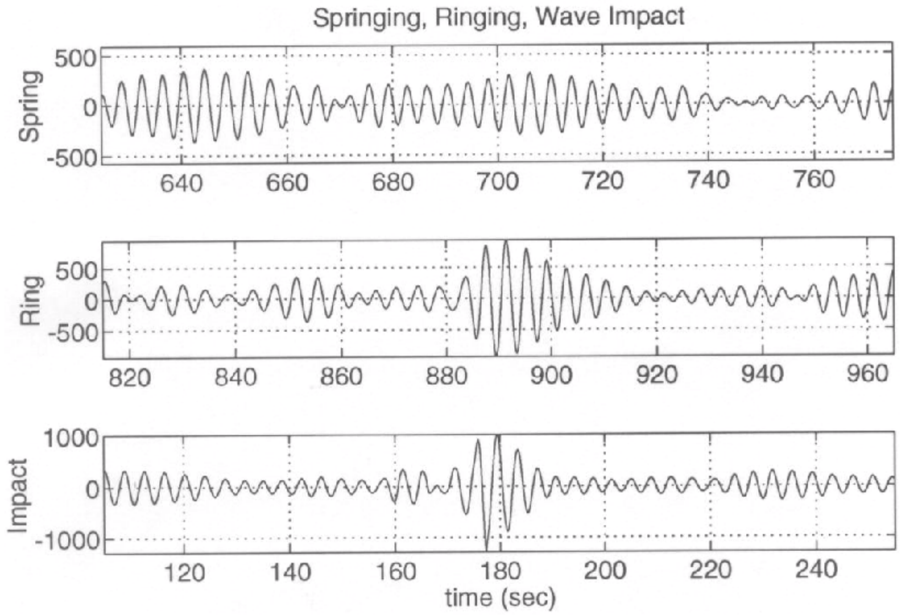


Figure A.3—Sample High-frequency TLP Tension Responses

A.2.7.2.1 Extreme Value Estimation

Extreme values interpreted from model test results are generally inferred from the statistics of peaks of the measured time series. The prediction of extremes of the complete response is complicated by the various components of response with differing statistical distributions. The makeup of the complete response varies with time during any single test run. The collection of complete wave responses during any single test falls into different populations, depending on which component is dominating each peak.

For linear wave responses, the response distribution is much the same as the distribution of wave height, and is well fit by a Gaussian distribution. For second-order forces (wave drift, second-order sum frequency springing forces), the response distribution is more skewed than Gaussian, and is often fit by a Gram-Charlier distribution or by Hermite polynomials used to map the process back to a Rayleigh distribution (Winterstein, et al. 1994 [248]). For weakly coupled, lightly damped linear system responses to second-order forces, the response distribution tends back to Gaussian based on the averaging properties of the system. However, for ringing dominated responses, the distribution is much more variable than commonly observed in offshore structure responses, and commonly used distributions are not at all appropriate. While linear Gaussian responses typically have a value of less than 4 standard deviations at the 1-in-1000 level, second-order responses typically have values between 4 and 6, and ringing responses have been observed with 1-in-1000 values of 6 to 20 standard deviations (Davies, et al. 1994 [123]).

The estimation of extreme values for nonlinear responses is often performed using generalized distributions such as Weibull, exponential, or Gumbel distributions. These functions are not related to the physics of the process, but are general purpose extreme value fitting functions which are used to fit data. Care should be taken to not apply the results to conditions other than those represented by the individual test, such as extrapolation to much longer return periods.

The fitting of extremal distributions to model test data with multiple populations should be performed to the segment of the data of interest. In the case of extreme value estimates, the fitting is generally done to the tail of the data. This is done by segmenting the data, or by masking the lower values, so that the fitting only sees a single population of points.

A.2.7.2.2 Event-based Statistics

Because ringing appears to be caused by an impulsive type of load, and there are multiple peaks in a given ringing event, an analysis of the peaks of a tension time series measurement will contain many events which are statistically correlated with other events. Since ringing responses are associated with specific waves, it has proven useful to extract snippets from the measured resample tension responses time series so that each snippet containing a ringing event is associated with a single unique on one sample per wave event. This is performed with a zero-crossing analysis conditioned on the zero-crossing analysis of the waves. In other words, a one-to-one correspondence between each candidate ringing event and an individual wave crest is established by cross-correlating tension and wave snippets extracted between zero- or mean-level threshold crossings. The resulting data set of snippets will have the same number of tension and wave events as there are waves, and is much easier to treat statistically (Davies, et al. 1994 [123]).

A.2.7.2.3 Statistical Stability, Confidence Bounds

The statistical stability and confidence bounds in fits to measured data are closely tied to the variability of the processes discussed above. In general, the fitting used in model test data analysis is based on fitting the tails of a process, and estimation of an expected largest value in approximately three to six hours of prototype response (0.0050 to 0.0005 exceedence levels). In a process which is well behaved, and which contains one statistical population, it is reasonable to estimate this from a single observation corresponding to the design storm duration. However, for processes which are much more variable, and for which only a few large events are observed in the typical three to six hour observation, much longer data sets are required for reasonable characterization of the process. The length of data sets required can be determined from the data itself. If the estimates of an expected design exposure maximum converge with additional observations, then sufficient data are present.

A.2.8 Design Recipes

In general spectral analysis, it is often assumed that the energy in one frequency band is statistically independent of the energy in other frequency bands, and that both are Gaussian in nature. In the case of narrow band spectra, the estimation of maxima is often done using the theoretical relationships first derived by Rice (1944 to 1945) [211]. Given a time record of response in which N extreme values between mean level threshhold crossings are observed, the most likely maximum value of all the extremes is given by:

$$\max = \sigma\sqrt{2\ln N} \tag{A.1}$$

where σ is the standard deviation of the response determined from the record. In cases where the spectrum is broad band (with spectral bandwidth ε), the most likely maximum value becomes:

$$\max = \sigma \sqrt{2 \ln \left\{ \frac{2\sqrt{1-\varepsilon^2}}{1+\sqrt{1-\varepsilon^2}} N \right\}} \tag{A.2}$$

However, if various frequency bands are not Gaussian, and are not statistically independent, the estimation of maxima is much more problematical. Empirical equations of the following forms have been used:

$$\max = \sqrt{c_1 \max_1^2 + c_2 \max_2^2} \tag{A.3}$$

$$\max = c_1 \max_1 + c_2 \max_2 \tag{A.4}$$

A.3 Long-term Analysis and Response-based Criteria

A.3.1 Introduction

One aspect of TLP global performance analysis which is unique compared to traditional design code calculations is the sensitivity to multiple environmental parameters. Although it is possible to generalize TLP sensitivities to the environment, some configurations are more sensitive to some combinations of parameters than are others.

The application of reliability methods inherently requires the use of probabilistic methods to evaluate a design. There are a number of implementations of reliability methods which involve performing probabilistic analysis to provide additional design checks. See Forristall, Larrabee and Mercier (1991) [141]; Spillane and Leverette (1991) [225]; Winterstein, et al. (1993) [247]; Leverette and Rashedi (1995) [178]; Wen and Banon (1995) [242]; and Tromans and Vanderschuren (1995) [234].

The TLP global responses are subject to many sources of variability and uncertainty, which should be accounted for by the designer. The major sources of variability and uncertainty in the global responses are:

a) Long-term environmental variability,

b) Short-term response variability,

c) inaccuracies in numerical and experimental methods,

d) platform condition uncertainties.

The main objective in establishing a TLP design is to provide a sufficiently “safe” design, without providing costly unnecessary strength or capability. As such, the design process should provide reasonable safety factors which are directly related to the uncertainties of the design response predictions.

The approach taken in this RP is to evaluate the TLP in conditions which produce the largest response that the platform is expected to experience, and then to provide additional safety factors on the response to provide the overall level of safety or reliability that is required for the application.

The procedures which follow are a means of selecting environmental design cases based on the response sensitivities of a particular TLP. By performing this selection probabilistically, the selected design cases are neither too conservative—in order to cover all possible configurations—nor are unconservative in missing more onerous and more probable seastate combinations.

The two parts of this analysis are a long-term probabilistic analysis of the structure to determine the long-term extreme responses, and a second step which defines environmental load cases which produce these extreme responses. The former may be performed with a relatively simple model which still contains the relative sensitivities of the specific TLP to the various environmental force combinations at site. The latter then produces conventional event-based criteria which are appropriate for the specific structure and location (e.g. a storm definition which produces 100-year return period responses).

It is noted that an alternate approach taken by some designers, which achieves a similar level of overall reliability, is to design to traditionally defined environments, and then perform a long-term analysis with more detailed models of the final structure. The result of this analysis is actual rather than notional extreme value responses for the structure. This analysis then confirms that the design conditions used in the design were conservative and sufficient to cover all likely combinations that would be controlling for the design (Baar, et al. 1997 [94]).

A.3.2 Long-term Response Analysis

A.3.2.1 Environmental Database

The input to the long-term response analysis is a database of environmental history, either measured or hindcast, for the site or region for the design. The database should be based on a reasonably complete representation of the area environment, accurate extreme event simulation, include direction, wind/ wave/current joint occurrence and directions, wave spectral information, storm surge effects. For the Gulf of Mexico, this is typically one of the hurricane hindcast data sets based on the 90 or so years of historical hurricane records. For the North Sea, this is typically based on measured and/or hindcast conditions for 30 years. The database should be sufficiently complete to allow 0.05 to 0.02 annual exceedence probability estimates to be made without extrapolation.

The data base should include a complete description of each environmental observation in order to identify appropriate joint statistical relationships. The following should be available for use in the analysis:

a) significant wave height;

b) modal peak period for wave spectrum (or other frequency dependent spectral description of wave energy);

c) spectral peak enhancement factor, gamma;

d) mean wind speed;

e) wave direction;

f) wind direction;

g) storm surge (water elevation);

h) mixed layer current speed;

i) current direction;

The database should comprise one to six hour samples of storm conditions. Multiple grid points/sites may be used to increase the data extent for hurricane data to improve the variability of the response estimates. The definition of wave spectral information is particularly important for TLPs. Care should be taken to ensure that peak periods and spectral models assigned to mixed sea and swell conditions do not incorrectly place all of the energy at sensitive peaks in the TLPs response functions.

A.3.2.2 Long-term Response Statistics

The database is processed sequentially using a simplified response model of the particular TLP to calculate approximate design load case responses for each environmental observation in the database. Various response models have been used for this type of analysis, including polynomial functional fit models and frequency domain, transfer function based load case models. The important aspect of the simplified model is that it be representative of the sensitivities of the full system to combinations of environmental parameters.

The input to the response model is seastate, wind, current, and water level values. Responses to wave H_S, T_P and direction, current speed and direction, and water level should be accounted for. Wind, wave, and current vectors may be taken in their true directions rather than assumed coincident during this evaluation. Wave spreading generally is not considered in extreme environments. Wave frequency effects (spectral peak frequency and width) should be considered. Setdown with offset should be included for tension, offset, and deck clearance calculations. Storm surge should be included in the database, while tide contributions should be handled parametrically by performing calculations at low- and high-tide conditions.

The output of the response model is expected maximum response and variability of response for each of the global performance responses. The TLP responses to all seastates in the environmental database then form a secondary database which is linked to the environmental database. This is evaluated in the following steps:

a) using a probability distribution model for extreme values (Weibull Type II or Type III) fit a cumulative probability distribution function to the response data (for each response);

b) using this fitted distribution, identify the 0.01 annual exceedence probability response.

NOTE This probability should be linked to the true probability distribution accounting for the observation period and sampling nature of the data set.

The simplified numerical model should be based on the expected value of the extreme response in each condition. As such, the analysis should not include factors and margins. The results are used in a relative sense, and are not used directly as design values. The 0.01 annual exceedence probability responses are notional, and typically will vary from the final design estimates.

A.3.3 Response-based Criteria

From the response data, subsets of storm condition may be identified which produce any given response. From these subsets of storm conditions, environmental combinations may be identified that provide a reasonable range of forcing functions for detailed analysis. These will typically include combinations that cover 0.01 annual exceedence probability levels of wind, wave, and/or current, and steep and/or long period wave conditions.

It is important that the combinations selected cover a range of environmental parameters so that small variations in sensitivity of the simple model relative to the final analysis model are accounted for. In practice, three sets of conditions for each response are considered reasonable, and may be selected so that each detailed simulation may be used for several responses.

These sets of conditions for each response then form the environmental design criteria to be used in predicting detailed responses used in the design equations in 7.8.

A.3.4 Special Considerations—Springing and Ringing

High-frequency (springing and ringing) TLP responses are not amenable to numerical simulations, and are generally best estimated with model tests. Some means should be included in the long-term analysis to account for high-frequency response contributions to peak loads in the tendon system. A commonly used method is parameterizing the high-frequency response as a function of wave height and steepness based on previous model test results, and including a high-frequency estimate for each seastate.

A.3.5 Special Considerations—Eddy Currents

The response based criteria method is especially useful in defining storm condition/eddy current combinations. Loop current eddies are statistically independent of hurricane events, but the combination can produce quite high offsets in a TLP. The response-based criteria methods establish a rational and defined return period event for the combination of eddy and hurricane. This joint event is typically the controlling event for maximum offset.

Annex B
(informative)

Commentary on Design of Tendon Porches

B.1 General

The previous edition (second) of this publication did not include guidance for tendon porches. The new text includes notes for tendon porch design to be performed for strength using maximum tendon loads from the global analyses. For fatigue, a factor of 10 is mentioned, based on an S-N approach. This is expanded in this commentary section.

The tendon porch and supporting structure are designed for static and dynamic tendon tensions. The tendon porch finite element model should be examined with the load matrix including operating-intact, extreme-intact and tendon-missing cases. Additional cases should be considered on an as needed basis. The horizontal load should be applied in the most onerous direction. Hydrostatic pressures should be included based on the operating draft or the extreme draft, including the effects of setdown, tide, and subsidence.

Detailed fatigue analysis should be performed with the local tendon porch and backup structure finite element model. The suggested procedure includes the application of six unit loads (axial, two shear, two bending, torque) to the tendon. Hotspot stress data can be extracted from the model for critical locations throughout. The detailed fatigue analysis should incorporate the unit stress response with low-frequency wave and high-frequency effects such as tendon ringing, spring, and VIVs from the tendon design group.

B.2 Fatigue Performance

Design of the overall tendon porch structure, and the interface of its component parts, should reflect consideration of the requirement for fatigue performance with respect to the type of weld details provided (i.e. by selecting weld details with known better fatigue performance in areas where appropriate) and by inclusion of access to completed welds for inspection of the welds after fabrication and prior to commissioning of the platform.

The tendon porch typically provides an interface contact surface with components of the tendon system with a relatively high degree of dimensional precision. Consideration should be made during fatigue analysis of the porch to consider the consequences of tendon porch deformation during fabrication that might lead to redistribution of the contact loads on this interface surface, and potential degradation in the fatigue performance of both the porch as well as interfacing components within the tendon system.

It is common that various appurtenances and/or machine features are added to the tendon porch area as temporary or permanent fixtures related to the tendon system. Examples of this are items related to securing cables running to tendon load monitoring equipment deployed on or near the porch; or drilled and tapped holes used for securing portions of the tendon system to the tendon porch. Early and continued dialog between the tendon porch designer and the tendon system designer shall ensure that these items/features are duly included in the fatigue analysis of the tendon porch.

It has been the practice on a number of TLPs to utilize cast sections for a significant portion of the tendon porch. Such items could also have as easily been provided as-built up fabrications or weldments. In such an event, the fatigue analysis of the tendon porch should also include hot spot stress areas in these cast or fabricated elements as well as the weld joints more typically considered as the fatigue damage dominant portions of the tendon porch.

The timing of the fatigue analysis of the tendon porch should reflect the expected fabrication schedule of the TLP hull. In cases where the tendon porch is (at least partially) integral with the fabrication of the surrounding area of the hull, this portion of the hull may be early in the fabrication sequence of the overall structure. This would require that fatigue analysis of the porch would have progressed to such an extent that the specified design and fabrication details were established to be of acceptable performance prior to fabrication occurring, to avoid costly and time intensive remedial actions at a later time. This need cannot be entirely avoided in the case where the tendon porch is fabricated totally as a separate unit, since internal details of the hull in the area of the attachment of the porch will require careful fatigue assessment.

In generating models of the tendon porch for fatigue analysis, it is critical that sufficient modeling of the hull structure itself is included so that realistic boundary conditions between the tendon porch and the hull are achieved. In nearly all cases, it is totally inappropriate to consider the interface with the hull as a rigid connection.

B.3 Design Loads

Practice for the design of the tendon porch has, in many designs, been to design the tendon porch to withstand the breaking strength of the tendon itself. While this approach may have lead to overly conservative tendon porch designs at some times, highly efficient porch designs would change relatively little if designed to the lower yield load of the tendon. The underlying basis for design of a tendon porch to be stronger than the tendon itself is the assumed catastrophic consequences to the TLP hull (flooding) if one or more porches were to fail. In the event that a design load for the porch is selected that eliminates the tendon as the weak link of the system, the designer shall ensure that the design is sufficiently robust that catastrophic failure of a tendon porch is highly unlikely.

In terms of actual project experience, the designer is reminded that the prediction of extreme tendon loads often evolves through the course of design, analysis, and model testing. The tendon system is specified to be robust, with survival checks in addition to extreme load checks. The tendon porch should have sufficient margin to not be an unnecessarily weak link in the overall system design. Using the strength of the tendon pipe for porch design is one way of achieving sufficient robustness.

Annex C
(informative)

Commentary on Tendon System Design

C.1 Single Event Fatigue

The intent of this section is to highlight the importance of the potential for significant fatigue damage due to high-stress/low-cycle fatigue in a single extreme event that is not catered for in the scatter diagram approach as discussed 9.2.5.4. It is not intended that this damage be added to the scatter diagram damage, which remains the primary means of assessing the anticipated fatigue life. Rather, it is intended as a check of the robustness of the design to insure that a sustained extreme event—beyond what contributed to the probabilities in the scatter diagram—does not significantly erode fatigue life.

In principal, the scatter diagram represents the complete probabilistic metocean environment, and hence, includes the extreme event in its tail, including ramp-up and ramp-down before and after the event. However, realistically, extreme events are such short duration compared to the rest of the time and data is generally limited, so the variability in extreme event duration is not well represented in the scatter diagram. This shortfall is of no consequence to typical structural components for which damage is generally proportional to seastate. However, certain mechanical components with geometric features that give rise to high-stress concentrations, and/or that rely on mechanical preload, may be particularly susceptible to low-cycle/high-stress fatigue due to local plastification or preload release. that will lead to higher stress ranges. The intent of the single event fatigue, check is to screen out components that may suffer catastrophic consequences under these circumstances.

A discussion of S-N curves for low-cycle fatigue is given in C.6.

The damage limit of 0.01 in a single event reflects 10 % of the allowable fatigue life based on a safety factor of 10. So if the platform does see such an event, as well as all of the damage predicted in the scatter diagram, the overall safety factor would only drop from 10 to 9.1, which is not a serious degradation of safety.

If the local environment includes distinctly different types of extreme events, e.g. hurricanes and loop currents in the Gulf of Mexico, all types of extreme events should be analyzed independently against these criteria. Again, the intent is not to sum the damage from these events with each other or the scatter diagram fatigue—rather it is a check of the robustness of the design against high-stress/low-cycle fatigue.

Durations should include the ramp up and ramp down time for the extreme event. For hurricanes, this may be as much as 36 to 48 hours. A good check on whether the duration is long enough is to test the change in damage accumulated by shortening or lengthening the duration. If the seastates at either end are still large enough to incur significant damage, then they should be included.

For loop current events, this may be as much as 100 days. The local conditions should be studied carefully to determine a reasonable test for robustness.

C.2 Robustness of Design

The objective of this section is to screen out components that may fail catastrophically just beyond the design conditions. This is not generally a problem for structural components when ductile materials are used since the ratio of allowable stresses to material limits is generally robust. It is more focused on mechanical components or system failure modes.

There is no specific guidance given around bottom connectors as the industry has yet to resolve the best way to address this vulnerability. However, this is a key area of concern and should be considered carefully. If solutions like latching bottom connectors are considered, care should be taken to avoid unintended consequences in other parts of the system–-e.g. up-lift on top connectors, local stresses, etc.

C.3 Hydrostatic Collapse Criteria

C.3.1 General

Prior editions of this publication provided reference only to the latest edition of API 2A-WSD for computation of hydrostatic collapse for tendon components. No guidance was provided for choosing between the WSD or LRFD formulation of the interaction equation. Subsequent work by Loh (API Report 90-56, Appendix B [181]) demonstrated that, based on a compilation of all available test data, the LRFD tension-collapse interaction equation is better suited for the design of welded tubulars subjected to combined loads.

In practice, the LRFD interaction equation has been the de facto standard for many years now, either in a WSD format using single safety factors, or using the LRFD partial safety factors. The WSD format takes advantage of the simpler, deterministic approach towards determining collapse capacity. The LRFD interaction equation describing the tendon capacity has been applied since ca. 1995 and, therefore, has been adopted for this publication. This does not imply that we are using LRFD methods, but are using the form of equation found in the LRFD documents.

C.3.2 Use of LRFD Partial Safety Factors

C.3.2.1 Although all agree that the LRFD equation is the appropriate interaction formulation, the industry is evenly divided between using it with WSD or LRFD formats, and therefore, the API 2T Task Group agreed to include both options to allow both approaches.

Points that were made during the committee discussion of this issue include the following.

a) The calibration of the LRFD load and resistance factors was conducted for jacket-type structures designed by Morison’s equation, so the application of LRFD factors for jacket structures to tendon design was questioned.

b) For the installation case of a pipe under no tension with only hydrostatic pressure, the API practice is to use a 2.0 safety factor to recognize that collapse is also a function of residual stresses and dimensional control during fabrication, not just in-service tension and hydrostatic pressure.

c) The quality control on tendon fabrication is higher than for jacket members.

d) For deepwater tendon systems, it is recognized that the LRFD partial safety factors approach is somewhat less conservative for tendons than WSD safety factor approach. However, the partial safety factor approach is consistent with the objective of the original LRFD effort, which was to maintain an overall industry level of safety/reliability by re-balancing the application of conservativism in a more rational way. The more uncertain load and resistance components received higher safety factors, while the more certain load and resistance components received lower factors. The assumption is that application of the LRFD format will result in lowering of reliability of the higher reliability of WSD structures, and raising of reliability of the lower reliability WSD structures.

C.3.2.2 The API 2T Task Group does recognize the need to rationalize the proposed safety factors with current practice, and to understand the implications. It was noted that the overall differences between WSD and LRFD approaches may be small.

The following points can be made in support of using the lower LRFD hydrostatic and pretension safety factors for the collapse-tension interaction check.

a) The pretension and hydrostatic pressure for TLP tendons is known very accurately compared to static loads on tubular structures. Pressure will not vary over the life of the structure. Operation requirements require the mean tension to be monitored and maintained to high levels of accuracy.

b) TLP tension response is more linear than jacket shear and overturning moment responses (relative to wave height and wind speed), which means the extreme values of the response do not deviate as much from the rms response (i.e. the peak factors are less).

c) Existing TLP tendon performance (tendon joints cumulative years of service) does not indicate any problem with current design practices for tension-collapse interaction by either design format.

d) Load prediction for TLPs is inherently less uncertain than that associated with Morison force prediction for jackets. Prototype measurements confirm this.

C.3.2.3 Observations from the one TLP failure were considered and discussed. The conclusion from this discussion is that the tendon pipes in current practice are robust, but that this TLP was a shallow water application, which may not necessarily shed light on the collapse interaction check for deeper waters. The lessons learned from this failure have been incorporated into 9.2.6 covering robustness checks.

C.3.3 Reduction of Collapse Safety Factor(s)

As TLP's have pushed into deeper water >1200 m (3940 ft), the criterion for Safety Category A has controlled over more severe design conditions due to the safety factor(s) on the hoop stress component of collapse. The API 2T Task Group has worked hard to address this issue, but no clear consensus has been reached that would allow further reduction in hoop stress safety factors. This subject needs to be a focus area for the next edition. Testing will likely be required to resolve this issue. The following paragraphs describe some of the information on this subject expressed to the committee.

There are a number of reasons for arguing that the hoop stress safety factors applied here are unnecessarily conservative for deepwater TLP tendon design. Virtually all of the test data available to establish collapse safety factors was gathered for jacket tubular design. For jackets in shallow water, the pressure is affected by wave height, wave kinematics, tide, and storm surge. In deepwater applications typical of TLPs, these factors are negligible in comparison to the hydrostatic pressure due to the water depth. Hence, the uncertainty inherent in shallow water design is not present in deepwater, and it may be argued that the safety factor on hoop stress can be reduced. This is reflected in some international codes.

There are also differences in the typical manufacturing processes for tendon pipe compared to jacket tubulars. In particular, tendon pipe made by the UOE process has dimensional tolerances that are generally more stringent than those resulting from rolled tubulars for jackets, which should improve the buckling performance of tendons. However, there is no collected fabrication tolerance data or performance test data on UOE pipe to make a rational reduction in the safety factor.

An alternate approach to justify the reduction of the original safety factor on collapse was also presented to the committee. It was based on a reliability analysis conducted for the LRFD hydrostatic collapse equation (Rinehart and Buitrago, 2006 [213]). This analysis calculated the Reliability index, β, as function of collapse safety factors, following an approach similar to that used to establish load and resistance factors for API 2A-LRFD. The analysis requires statistics (means and CoVs) for the collapse-failure prediction model and the random variables entering the model. Two sets of such statistics were used for the reliability analyses. The first set was obtained from the open literature, whereas the second set was taken as reported in PRAC 88-22 and PRAC 86-55 (Moses, 1989 [194] and Cox, 1989 [119]).

For the reliability analysis with the first set of statistics, the collapse model statistics were generated by directly comparing the original test data on tubulars subjected to hydrostatic collapse, as reported in PRAC 86-55, against the LRFD collapse equation, which formed the basis for the original API LRFD calibration.

In addition to the base-case analyses corresponding to each set of statistics, a number sensitivity cases were considered in which bias in material yield and uncertainty in the collapse model were varied.

The reliability analyses were carried out using the Monte Carlo approach with an explicit limit state function. As a check of the approach, the analysis cases studied in the original LRFD calibration of API 2A (PRAC 88-22) were first re-analyzed. The current analysis generally estimated somewhat lower values of β for a given safety factor. This difference can be attributed to the use of more accurate simulation and modeling. In this sense, the present analyses could be deemed more accurate and reasonably conservative with respect to the original LRFD calibration.

PRAC 88-22 points out that the β values associated with the safety factor of 2.0 are high (4.0 to 5.0) suggesting that such a safety factor may be excessive. Also, API 2A-LRFD commentary suggests a β of a least 3.0 be sought for hydrostatic collapse. This target is higher than the typical β range of 1.5 to 2.5 sought by API 2A. Thus, a β value close to 3.0 was deemed acceptable to arrive at the safety factor.

Overall, the analyses performed for RP 2T found β values equal to or greater than 3.0 for all benchmark analysis cases with a collapse safety factor of 1.67. Furthermore, the safety factor of 1.67 is consistent with the LRFD effective safety factor derived from the calibrated load and resistance factors for the Category A load case. A safety factor of 1.67 is recommended.

C.4 Girth Weld Analysis

C.4.1 Girth Weld Fatigue Damage Analysis

The S-N curves provided by BS 7608 are recommended. Other traditional curves (e.g. AWS, SWRI, etc.) may be used as long as they are justified by relevant data.

Historic practice has been to use a safety factor of 10 on life for critical welded components that are not inspectable. In the case of tendons, experience with operating TLPs has shown that actual implementation of in-situ inspection is a very challenging exercise and that opting for the noninspectable tendon design is a more cost-effective and reliable alternative. However, the cited factor of 10 on life only attempts to account for uncertainties in load, resistance, and damage accumulation, but not for the fact that tendons are serial components in nature and that the failure of a single weld is unacceptable not solely due to structural consequences, but also due to potential collateral damage of adjacent tendons and/or risers.

C.4.2 Girth Weld Fracture Mechanics Analysis

The apparent dichotomy in the selection of the life factors for FM and S-N analyses is related to the fact that S-N data/analysis includes both initiation and propagation, whereas, fracture mechanics only considers the propagation phase. Full-scale fatigue testing of production quality welds should be considered where uncertainty exists as to which S-N curve is appropriate. Likewise, fracture-mechanics tests in the applicable environment should be considered where there is uncertainty as to which da/dN crack growth curve should be used.

Although the leak-before-break design philosophy has been recognized in various engineering practices, recent tests on large girth welded pipe (Buitrago et al. 2003 [106]) has shown that the leakage of through-thickness cracks induced by cyclic loading is very limited, even under high pressure. It is not until the through-thickness crack becomes much longer than anticipated that measurable amounts of water flows through the crack. Therefore, true LBB may only be feasible when target fracture toughness values for the welds are established on the basis of fully re-characterized cracks after breaking through thickness and the leak rate is sufficiently large to be detected during operation at the time assumed in the design. Having said this, setting target fracture toughness values on the basis of through wall cracks in order to achieve through-wall flaw tolerance is a reasonable design practice.

Flow through cracks can be estimated analytically to check the feasibility of LBB. One such estimate is based on laminar flow between parallel plates (Clarke et al. [115]). Comparison of measured to predicted leak rates indicates that leak rates can be over estimated by factor of 5 to 10 for through-thickness cracks after re-characterization. This finding points toward exercising caution in assuming that LBB is viable.

C.4.3 Girth Weld Inspection

The inspection of tendon girth welds may preferably be carried out by ultrasonic means. Automatic or mechanized ultrasonic systems (AUT) can be used to reduce the effect of human factors in manual ultrasonic inspection. Multiple manual inspections, e.g. by different technicians, can also be used to reduce human factors. Characterization of AUT system reliability can be quantified in terms of the probability of detection (PoD) and false alarm (PFA); the former relates to the risk of missing an existing defect, whereas, the latter only impacts cost by potentially repairing defects that do not exist.

Reliability of the inspection process depends on a multitude of random variables associated not only with the hardware setup and signal-processing software, but also with the type of weld, access surface, and whether or not the weld has been ground. Also, operators, who interpret data become part of the process, and thus, affect the reliability too. Typically, a 90 % PoD with 95 % confidence may be used as an acceptable level.

The actual PoD qualification of a AUT system is costly and laborious, requiring physical and reliability models (Gray et al. [146]; Gray and Thompson [147]), inspections of actual welds under production conditions, and then detailed sectioning of the scanned welds. The sectioning not only corroborates the presence of the defects found, but also discovers any defects that were missed. Evaluation of accuracy in sizing entails the physical measurement of the defect found after sectioning the weld.

Due to the extensive testing requirements needed to confirm customized defect acceptance criteria and the practicalities of project schedules, standardized acceptance criteria may be incorporated into company specifications that should provide adequate performance for typical project needs.

C.5 Tendon Connector Stresses

C.5.1 Linearization of Stresses

The intent of linearization is to eliminate the effect of the peak stresses arising from elastic FEA at the location of the stress raiser and to account for the global section behavior. As shown in the following, linearization involves finding, for each stress component distribution across the thickness of the section, a linear distribution whose equivalent force and moment are the same as those of the actual distribution.

a) Stress distributions (actual or hoop stress).

— Actual: $\sigma = \sigma(r)$

— Linear: $\sigma_\ell = \dfrac{\sigma_1 - \sigma_0}{(r_o - r_i)}(r - r_i) + \sigma_0$

b) Conditions.

— Forces: $\int_{id}^{od} \sigma(r)\, r\, dr = \int_{id}^{od} \sigma_\ell(r)\, r\, dr$

— Moments: $\int_{\text{id}}^{\text{od}} \sigma(r)\, r^2\, dr = \int_{\text{id}}^{\text{od}} \sigma_\ell(r)\, r^2\, dr$

NOTE For hoop stress, divide integrands by *r*.

c) Linearized stresses.

— Average: $\sigma_{\text{av}} = 0.5(\sigma_0 + \sigma_1)$

— Differential: $\sigma_{\text{df}} = 0.5(\sigma_0 - \sigma_1)$

— Shear: $\tau_{\text{av}} = \frac{1}{t}\int_{\text{id}}^{\text{od}} \tau(r)\, dr$

— Radial: For radial stresses use the internal or external pressure value depending on whether the strength check is at the inner or outer surface.

The average and differential components of the normal axial stress distribution physically correspond to the membrane and bending components acting on that section in terms of membrane axial stresses (*P*/*A*) and bending stresses (M_c/I).

Linearization of the shear stress is not recommended. Instead, an average value across the section would suffice for the calculation of the effective von Mises stresses. Also, for the average plus differential checks at the ID or OD of a connector that contains internal or external pressure, use of the actual pressure values for the radial stress component at those locations is appropriate.

In cases where torsion is a significant external load, the average shear stresses $\tau_{r\theta}$ at the cross section of interest can be approximated by Tr/J, where T is the applied torque, r is the mean radius of the sections and J is the polar moment of the section.

When relevant, strength checks should be made on connector sections other than cross sections. For instance, in flanges, cylindrical sections parallel to the flange axis and containing the bolt circle should be made. For arbitrary sections, the stress components need to be rotated from the global coordinates to the local coordinates parallel and perpendicular to the section in question. The hoop component, however, remains the same for axi-symmetric models.

C.5.2 Connector Strength Criteria

C.5.2.1 General

Strength criteria are based on material yield strength only, as consistent with current practice in ASME *BPVC*, Section VIII, Division 2.

Safety factors are consistent with allowable stress criteria for riser systems as per API 2RD.

C.5.2.2 Primary Stresses

Primary stresses are normal and shear stress distributions across a connector section that result from the application of external action and are required to satisfy equilibrium. Primary stresses in this sense are not self-limiting and, if not controlled, will induce failure. Stresses arising from axial load and bending acting on the pipe are primary.

C.5.2.3 Secondary Stresses

Secondary stresses are normal and shear stress distributions across a connector section that are self-limiting and self-equilibrating. In connectors, stresses resulting from assembly may be secondary.

C.5.2.4 Pure Shear Stress

An average stress over a connector gross section that is parallel to the direction of the applied force. An example of this stress is the average stress across threads due to an axial load on the connector.

C.5.2.5 Bearing Stress

Average stress normal to contact surfaces between connector parts, such as those between engaged threads, at preload shoulders, or between washers, dogs, etc., and the connector body.

C.5.2.6 Stress Component Distributions

Finite element analysis is used to calculate the stress distributions induced within the connector to conduct strength checks. The analysis, however, should include the preload applied to the connector during the assembly or makeup operation. Preload has a profound effect how the load is transferred, and thus, on the internal stresses sought.

C.6 Connector Fatigue Initiation Life Method

C.6.1 General

The calculation of initiation lives at notches in the connector requires detailed FEA of the connector to generate local stresses at the notches and material data for both the monotonic (static) and the cyclic properties of the material in question. Chen, 1989 [114] contains one such set of data typical for connector material.

C.6.2 Calculations

C.6.2.1 Number of Reversals to Failure

The crack initiation life or number of cycles to failure, N_f, at a generic notch of a mechanical connector may be evaluated by solving for the number of reversals to failure, $2N_f$, in the following nonlinear equation:

$$\sigma_{re}\,\varepsilon_{re}\,E = \sigma_f'^{\,2}\left(2N_f\right)^{2b} + \sigma_f'\,\varepsilon_f'\,E\left(2N_f\right)^{b+c} \quad \rightarrow \text{Solve for } N_f \tag{C.1}$$

where

σ_{re} is the equivalent fully reversible elasto-plastic stress amplitude at the notch (unknown);

ε_{re} is the equivalent fully reversible elasto-plastic strain amplitude at the notch (unknown);

E is the modulus of elasticity (material constant);

σ_f' is the fatigue strength coefficient (material constant);

ε_f' is the fatigue ductility coefficient (material constant);

b is the fatigue strength exponent (material constant);

c is the fatigue ductility exponent (material constant).

C.6.2.2 Calculating ε_{re}

The coefficients and exponents defined above are generated experimentally for the material in question, and ε_{re} may be obtained using the cyclic stress-strain relation for the material:

$$\varepsilon_{re} = \frac{\sigma_{re}}{E} + \left(\frac{\sigma_{re}}{K'}\right)^{\frac{1}{n'}} \rightarrow \text{Solve for } \varepsilon_{re} \tag{C.2}$$

Here the cyclic strain-hardening coefficient (K') and the cyclic strain-hardening exponent (n') are known material constants determined experimentally. Calculating σ_{re}:

The equivalent fully reversible stress amplitude at the notch (σ_{re}) includes the effect of the mean stress at the notch:

$$\sigma_{re} = \left[\frac{\sigma_a}{1-\frac{\sigma_o}{\sigma_f'}}\sqrt{(\sigma_o+\sigma_a)\sigma_a}\right]^{0.5} \rightarrow \text{Solve for } \sigma_{re} \tag{C.3}$$

where

σ_a is the elasto-plastic stress amplitude at the notch, $\sigma_a = \frac{1}{2}\sigma_r$;

σ_r is the elasto-plastic stress range at the notch [Figure C.1 c)];

σ_o is the elasto-plastic mean stress at the notch [Figure C.1 c)].

C.6.2.3 Calculating σ_r and σ_o

Both σ_r and σ_o may be obtained by transforming the elastic notch response obtained from FEA. This transformation accounts for the local plasticity that takes place at the notch. The elastic notch response may be given in terms of the stresses directly calculated at the notch; the nominal pipe stresses and a geometric stress concentration factor (SCF), which relates the pipe stress (S) to the notch stress (σ) (preferred); or a combination of the two.

The elastic notch stresses may be transformed to elasto-plastic stresses by either of the following two methods:

C.6.3 Strain Energy Method

The energy method simply equates the elastic strain energy at the notch to the elasto-plastic energy given by the actual cyclic stress-strain behavior obtained experimentally for the material in question (see Figure C.3). This transformation is general and accurate.

Knowing the elastic notch stress range and peak stress [Figure C.1(b)], the following equations apply:

$$\frac{\sigma_r^{e\,2}}{2E} = \frac{\sigma_r^2}{2E} + \frac{\sigma_r}{n'+1}\left(\frac{\sigma_r}{K'}\right)^{\frac{1}{n'}} \rightarrow \text{Solve for } \sigma_r \tag{C.4}$$

$$\frac{\sigma_p^{e\,2}}{2E} = \frac{\sigma_p^2}{2E} + \frac{\sigma_p}{n'+1}\left(\frac{\sigma_p}{K'}\right)^{\frac{1}{n'}} \rightarrow \text{Solve for } \sigma_p \tag{C.5}$$

The variables in the equations are as follows:

σ_r^e is the elasto-stress range at the notch from FEA;

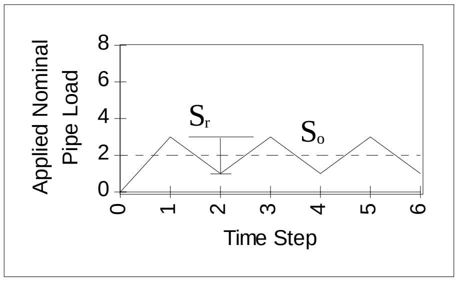
σ_r is the elasto-plastic stress range (transformed) at the notch;

σ_p^e is the elasto-peak stress at the notch from FEA;

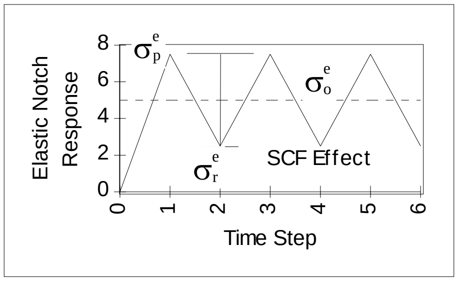
σ_p is the elasto-plastic peak stress (transformed) at the notch;

σ_o is the elasto-plastic mean stress at the notch.

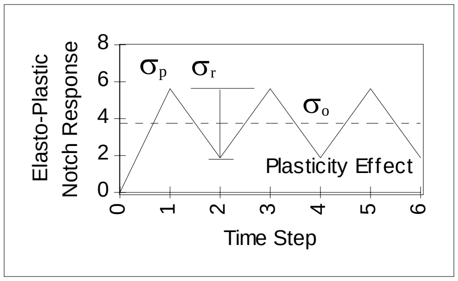
= $\sigma_o = \sigma_p - \frac{\sigma_r}{2}$



(a) Nominal Pipe Stress Variation



(b) Elastic Stresses at the Notch



(c) Transformed Notch Stresses

Figure C.1—Definition of Pipe and Notch Stresses

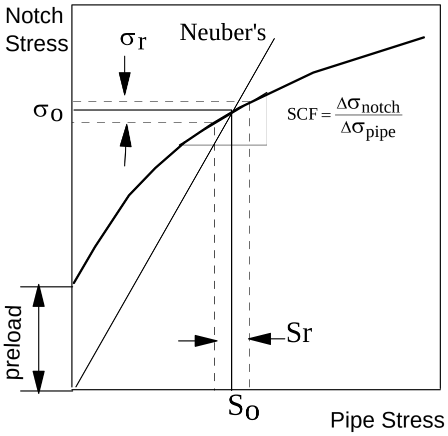


Figure C.2—Relation Between Notch and Pipe Stresses

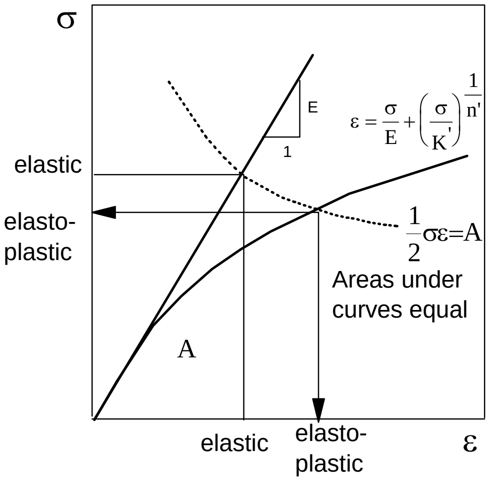


Figure C.3—Transformation of Elastic Stress via Strain Energy

C.6.4 Neuber's Method

Neuber's method represents an engineering approximation to the same transformation and is based on the Neuber's rule (the geometric mean of the strain and stress concentration factors remains constant with load) and Peterson's empirical fatigue strength reduction factor, K_f (Topper, 1969). Referring to Figure C.2, the notch stress is linearly related to the pipe stress via an SCF and there is no initial pre-stress at the notch.

Two approaches can be followed to obtain the notch peak stress and stress range to calculate the notch mean stress.

1) Knowing the nominal pipe stress range (S_r), the mean stress (S_o) and the elastic SCF (from FEA), the transformed elasto-plastic notch stress range (σ_r) and the peak notch stress (σ_p) can be obtained directly from the nominal pipe stresses (Figure C.5) according to the following two relations:

$$\sigma_r\left[\frac{\sigma_r}{E}+\left(\frac{\sigma_r}{K'}\right)^{\frac{1}{n'}}\right]=\frac{1}{E}\left(K_f S_r\right)^2 \rightarrow \text{Solve for } \sigma_r \qquad \text{(C.6)}$$

$$\sigma_p\left[\frac{\sigma_p}{E}+\left(\frac{\sigma_p}{K'}\right)^{\frac{1}{n'}}\right]=\frac{1}{E}K_f^2\left(S_0+\frac{S_r}{2}\right)^2 \rightarrow \text{Solve for } \sigma_p \qquad \text{(C.7)}$$

$$K_f = 1 + \frac{SCF - 1}{1 + \frac{A}{r}} \qquad \text{(C.8)}$$

$$SCF = \frac{\Delta\sigma}{\Delta S} \qquad \text{(C.9)}$$

$$A = 0.821\left(\frac{300}{\sigma_u}\right)^{1.8} \qquad \text{(C.10)}$$

The variables in the equations are as follows:

K_f is the fatigue strength reduction factor or effective fatigue SCF;

r is the notch radius (in mm);

σ_u is the ultimate stress of the material (in MPa);

σ_o is the elasto-plastic mean stress at the notch.

is the $\sigma_o = \sigma_p - \frac{\sigma_r}{2}$

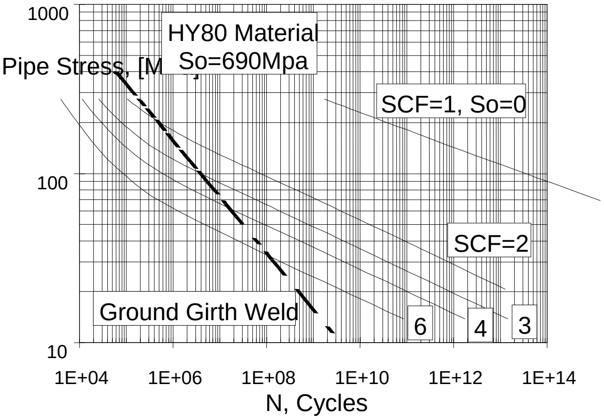


Figure C.4—Calculated S-N Curves using Initiation Life for Various SCFs and Constant Mean Stress

The accuracy of the transformation by the Neuber's method depends on the relative contribution of the connector preload to the notch stress and on the degree of nonlinearity between the notch stress and the pipe stress. If linearity between the notch and pipe stresses exists and there is no preload, the notch stresses can be calculated using the pipe stresses and an SCF, and the energy method can alternatively be used.

If the local notch stress is not linearly related to the pipe stress and the connector is preloaded (Figure C.4), then the SCF varies with the pipe stress and there is an initial stress at the notch that is related not to the pipe stress, but to dimensional interferences in the connector. In this case, the instantaneous SCF may be taken as the derivative of the notch stress with respect to the pipe stress to relate the pipe stress range to the notch stress range. However, the pipe mean stress can no longer be related to the notch stress via an SCF. To avoid this situation, the elastic mean stress directly calculated at the notch via FEA is used.

2) Knowing the elastic mean notch stress (σ_o), the pipe stress range (S_r) and the instantaneous SCF, the transformed notch stress range (σ_r) and the notch peak stress (σ_p) can also be obtained using Neuber's method by the following equations:

$$\sigma_r\left[\frac{\sigma_r}{E}+\left(\frac{\sigma_r}{K'}\right)^{\frac{1}{n'}}\right]=\frac{1}{E}\left(K_f\,S_r\right)^2 \rightarrow \text{Solve for } \sigma_r \tag{C.11}$$

$$\sigma_p\left[\frac{\sigma_p}{E}+\left(\frac{\sigma_p}{K'}\right)^{\frac{1}{n'}}\right]=\frac{1}{E}\left[\sigma_o^e+K_f\left(\frac{S_r}{2}\right)\right]^2 \rightarrow \text{Solve for } \sigma_p \tag{C.12}$$

Here the elasto-plastic mean stress (σ_o) at the notch is:

$$\sigma_o=\sigma_p-\frac{\sigma_r}{2} \tag{C.13}$$

Using σ_r and σ_o in the equation for the equivalent fully reversible σ_{re}, the corresponding strain ε_{re} can be calculated. With σ_{re} and ε_{re}, it is possible to solve for N_f in the first equation.

An example of S-N curves developed for an actual connector is presented in Figure C.5, compared to a girth weld estimated as the D-curve. In this example, the connector in question develops preload upon makeup, the notch stress is not linear with the pipe stress, and the notch mean stress is 690 MPa obtained from linear-elastic FEA (stresses greater than yield are allowed, since they are transformed, as shown in Figure C.3).

SCFs and Constant Mean Stress

Properties: n'= 0.147; K' = 1184 MPa; σ_f' = 1249 MPa

ε_f' = 1.456; b = -0.101; c = –0.693

C.7 Tendon Flex Element

Qualification and verification would also be required in the event that significant changes were made to the materials and/or manufacturing method of an existing, well proven, design.

For flex elements consisting of the “traditional” elastomer/steel sandwich configuration, qualification of manufacturability should include sacrificial testing of actual steel layers (commonly referred to as the flex element shim) or of material clearly representative of the shims (i.e. formed with the same or equivalent process, including forging reduction, heat treatment, etc. as appropriate) to verify achievement of acceptable mechanical properties, as well as rigorous dimensional testing of the actual sets of shims. Furthermore, testing should be performed of representative samples of the elastomeric layers recovered from full-scale prototype fully molded flex elements. These tests should verify total curing of the elastomer and that expected mechanical properties of the elastomer are achieved. In addition, tests should be performed of a prototype flex element to verify that the proper relative position (within design tolerances) of the shims is achieved, and that the elastomer pad thicknesses are within tolerance.

The flex element manufacturer should develop and implement a quality control process that verifies that subsequently produced flex elements will be manufactured from materials of equivalent performance as verified in the qualification tests, and that the dimensional features (pad thickness and shim relative position) are verified following fabrication of all flex elements. The flex element manufacturer should also have means to verify that the pad space (i.e. the volume between the shims) has been fully filled by elastomer, with absence of voids sufficient to cause degradation of elastomeric fatigue performance. The flex element manufacturer should also verify the elastomer cover over the shim edges is continuous so that the shims are protected from environmental exposure.

Selection of material for tendon flex element manufacture should include consideration of potential exposure to hydrocarbons prior to installation and during service. Provision should also be made for protection of the elastomeric material to both physical and environmental exposure both prior to installation and during service.

C.8 Tendon Flex Element Fatigue Design

The fatigue design of the flex may use an interactive fracture mechanics approach that accounts for material and geometric nonlinearities. The basis of the approach is the evaluation of the tearing energy available to propagate a unit area of tear surface assumed to be within a rubber layer (Gunderson, et al. 1992 [151] and 1997 [152]). Tests have demonstrated that properly bonded rubber layers do not fail at the rubber-steel interface, but within the rubber layer itself close to the steel-rubber interface.

A general discussion of the iterative steps follows.

An initial tear depth, c, may be assumed based on the ability of the inspection system to reliably find the tear. Consider that the reliability of the inspection system is typically unknown or is not readily calibrated.

The tear growth rate is based on the tearing energy (variation of stored energy per unit area), analogous to fracture energy in metals. The available tearing energy, T (kJ/m^2), may be obtained via FEA or closed-form solution for a given, load, lamina geometry, material moduli (E and G), and tear size present in the rubber lamina. The stored energy available for tearing that is associated with axial and bending loads applied may be calculated independently for each layer of the joint and then combined. It is assumed that both bending moment and axial force are in phase. The elastic moduli for a layer may be obtained from experimental data as function of the load. Varying layer thickness and moduli optimizes the fatigue performance of the joint.

The initial tear is propagated by the applied yearly histogram of stresses by integrating the tear-growth rate, dc/dN (mm/cycle), which is function of the applied tearing energy, $dc/dN = C\Delta T^{m}$. This growth law, which is analogous to that for steels, may be experimentally generated for the rubber in question and strongly depends on R, the ratio of the minimum to maximum tearing energy applied for the cycles. For design purposes, R may be conservatively taken as zero.

Because the shear modulus of rubber increases with time under anaerobic conditions, the shear modulus may need updating for subsequent year calculations. Nevertheless, due to the lack of oxygen and exposure to UV underwater, correction for modulus increase may be waived.

Repeat the calculations for subsequent years as the tear grows. No readily detectable initial al tear may propagate to be larger than 50% of the critical layer area over a period of time equal to the ten times the planned life of the facility.

Annex D
(informative)

Commentary on Foundation Design

D.1 Creep of Tension Piles

While little pile data exists, some long-duration pile test data indicate that at loads above about 30% of the ultimate axial failure load (see 10.6.2) pile displacement tends to increase with time and long after consolidation should have finished (Edil and Mochtar, 1988 [134]). Full-scale tests to induce creep rupture of piling have not been reported in the literature. Terzaghi and Peck, 1964 [231], also report in a discussion of remolded clays that, “As soon as the shearing stress in a clay becomes greater than about one-half the peak value, the clay is likely to creep at constant shearing stress.”

D.2 Fatigue Design of Driven Piles

For fatigue design of driven piles, combined installation and in-place cumulative damage calculations should be used. To evaluate fatigue damage, both applicable S-N curves and damage accumulation rules should be defined, once the loads have been defined.

D.3 Fatigue Loads

D.3.1 General

Dynamic loads due to hammer impact during pile installation will induce fatigue damage on both receptacle and pile girth welds. The evaluation of the cyclic loads involves the dynamic response of the pile-soil system due to the hammer impact. This requires a wave equation analysis per blow for a given hammer type and efficiency, pile penetration, and soil resistance. Various such analyses are to be conducted for judiciously selected pile penetrations. For each analysis, traces of stress versus time at the critical locations along the pile are to be developed, as well as the number of blows associated with the assumed penetration.

During the life of the structure the pile receptacle and girth welds are also subjected to cyclic loads due to the loads imposed by the tendon on the pile. The tendon loads are transferred to the pile via the tendon receptacle, and, thus the receptacle and pipe body sustain fatigue loads. A global pile response analysis accounting for the pile-soil interaction should be carried out for the tendon reactions due to the fatigue seastates acting on the system. The local stresses that accumulate fatigue damage in the pile should be obtained by calculating a SCF, relative to the nominal stresses generated by the global analysis, at the fatigue critical locations. These locations are typically at the engagement points between the pile and the receptacle and at the girth welds between the receptacle and the pile and between subsequent pile cans.

The evaluation of SCFs for girth welds needs to account for the local thickness misalignment at the weld. Equations for SCFs are given in Buitrago, et al. 1998 [108], DNV-RP-C203 [62], and Connelly and Zettlemoyer, 1993 [118].

NOTE The calculated SCF needs to be corrected by the ratio of the nominal thickness used in the pile response analysis to the lesser of the pile wall thicknesses joining at the weld. The SCF is to be applied to the nominal pile stress range obtained at the weld location due to in-place loads, from which damaged is to be calculated.

D.3.2 Fatigue Resistance

Applicable S-N curves depend on manufacturing processes and defect acceptance criteria. Typically, pile section are welded by a two-sided SAW process and left in the as-welded conditions. For this case, the D-curve, as defined in BSI BS 7608 [53], could be used. Use of a higher S-N curve for this application, without additional treatment of the weld, should be demonstrated by relevant data. Use of weld treatment methods, such as grinding may support the upgrading of the S-N curve, provided that the following occur:

1) the grinding process is properly implemented,

2) weld inspection methods and defect acceptance criteria are implemented, and

3) pertinent fatigue data area generated to qualify the weld to a performance level higher than that implied by the D curve.

D.3.3 Fatigue Damage

For either welds or receptacle, cumulative installation damage calculations should be carried out at various pile locations using local stress range, S_r, derived from the wave equation analysis at the selected pile penetrations. The location of the girth weld should be determined by the pile makeup schedule. The local response should include the corresponding SCF effect. The fatigue damage inflicted per blow is calculated by assuming that the Palgrem-Miner rule applies and the number of cycles of the stress history per blow is obtained using a variable amplitude (VA) counting method, such as the reservoir BSI BS 7608 or rainflow methods.

For in-service damage evaluation, the local stress range, S_r, obtained at the receptacle and girth welds locations, as described in D.3, should be used.

NOTE To obtain the local acting stress range, the nominal stress range should be multiplied by the SCF before entering the S-N curve.

It is suggested that Equation (D.1) be applied to calculate the total fatigue damage:

$$D = (F1 \times D1) + (F2 \times D2) \tag{D.1}$$

where

D is the total fatigue damage evaluated for the service (design) life of the structural component considered;

$F1$ is the factor of safety for Phase 1, i.e. installation (pile-driving) phase;

$D1$ is calculated fatigue damage for Phase 1, i.e. installation (pile-driving) phase;

$F2$ is the factor of safety for Phase 2, i.e. in-service phase; and

$D2$ is calculated fatigue damage ratio for Phase 2, i.e. in-service phase, during the service life (e.g. 20 years).

For $F2$, 10.0 is considered to be a normal factor of safety for critical and noninspectable structural components under in-service loading conditions. For $F1$, the factor may be less than 10, depending on the level of confidence in the following:

1) the quality of the site-specific soil data,

2) the quality control of the pile driving process, and

3) the procedure in estimating the pile driving stresses used in the analyses.

Further discussions on fatigue damage design for driven piles can be found in Hunt, et al. 1999 [157], and Buitrago and Wong, 2003 [109].

D.4 Discussion on Safety Factors to be Applied to the Axial Capacity of Piled Foundations

D.4.1 Background

Pile design is dependent on past successful practice, that is, empiricism. Lacking experience with TLP foundations, the design approach adopted utilizes the jacket-type platform pile design as the baseline for safety consideration. Factors, which could influence the safety of a TLP pile foundation, have been identified and compared to the design influence each factor has for a conventional jacket pile. Listed below are eight factors that were considered important for TLP pile design. A qualitative comparison or bias is discussed relating the TLP and jacket pile application. The last three factors were not included in the body of API 2T because their influence on design was deemed the same for the TLP and jacket foundations.

D.4.2 Factors Influencing TLP Piled Foundations

D.4.2.1 General

Factors considered as having possible influence on TLP piled foundations in comparison to compression piles in jacket-type structures are described in D.4.2.2 and D.4.2.8.

D.4.2.2 Soil-pile Behavior

D.4.2.2.1 Uncertainties in understanding soil-pile behavior under tensile loadings. Considerations include:

a) potential reduction of near-surface soil's effectiveness,

b) cyclic degradation,

c) axial flexibility of the pile-soil system,

d) effects of sustained tension,

e) suction.

D.4.2.2.2 Regarding D.4.2.2.1 a), relative to a jacket structure and driven piling, there appears to be no reason to apply any explicit penalty for this consideration.

D.4.2.2.3 Sections D.4.2.2.1 b), c), and d) relate to considerations that were felt to be difficult to quantify given the present state of knowledge. It was also felt that it would not be appropriate to suggest testing of calculation methodologies to help quantify these effects. Instead, these considerations should be explicitly mentioned as needing thorough investigation. Recommended safety factors should then be applied to the pile's ultimate axial capacity after it is suitably modified to account for these items.

D.4.2.2.4 Section D.4.2.2.1 b) considers the degradation of pile capacity due to the combination of sustained and cyclic loads. Several proprietary field studies are underway to quantify clay-pile behavior under sustained loading. These include a pile study by the Norwegian Geotechnical Institute at Haga and small diameter model pile segment tests by the Earth Technology Corporation at Shell's Beta pile test site, Conoco's Gulf of Mexico TLP pile test site, and Chevron's pile test site at Empire. In addition, J. L. Briaud at Texas A&M University is studying cyclic axial behavior under API's sponsorship. While none of the study results have been published, a generally conservative interpretation of some of these data indicate pile pullout does not begin until the sum of the sustained load plus the cyclic component reaches about 80 % of the static ultimate load.

D.4.2.2.5 Section D.4.2.2.1 c) relates to the development of progressive pile failure due to the axial flexibility of the pile-soil system under cyclic loading conditions. Two-way (i.e. tension-compression) load tests conducted in the above mentioned studies show an immediate degradation in pile capacity. Results from the full-scale Beta pile test (Doyle and Pelletier, 1985 [125]) showed temporary reductions of 61 % to 85 % of the precyclic pile capacity within 16 fully reversed load cycles. In addition, the weight of the soil plug was not evident during cyclic testing. However, other testing at Haga by NGI (Karlsrud, K., and Haugen, T., 1981 [165]) suggests that one-way cyclic loading of the pile relative to the soil causes significantly less degradation than two-way loading at discrete pile elevations. For long flexible piles, fully reversed cycling may occur even though the pile top is under a sustained bias loading. Thus, pile load capacity may be reduced due to cyclic loading for flexible piles.

D.4.2.2.6 Section D.4.2.2.1 d) considers the effect of sustained tension loading on soil behavior. Soils under sustained shear stress may deform in time. This effect should be considered in determining the long-term capacity of piles under sustained loading.

D.4.2.2.7 Section D.4.2.2.1 e) represents a consideration, which can be expected to aid the foundation's load carrying capacity. Since here again it is not possible to reliably quantify the effects of suction, it was decided to ignore this consideration.

D.4.2.3 Lack of Residual Strength of the Soil-pile System

A consideration included under this factor is the relative lack of residual strength for a pile loaded in tension compared to one loaded in compression. Schematically, the relative residual strength after pile overload in tension (T), and compression (C) may be viewed as shown in Figure D.1.

The potential for dramatic decreases in strength in the event of pile overload warrants an increased safety factor when compared to a compression pile. The assignment of specific numerical values to account for a tension pile's relative lack of residual strength is uncertain.

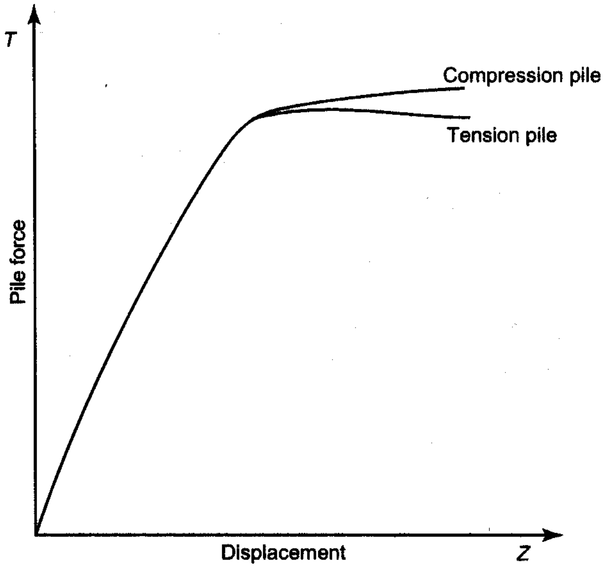


Figure D.1—Relative Residual Strength After Pile Overload

D.4.2.4 Load Redistribution Capacities of the Foundation

Redundancy in the form of clustered or grouped piles can mitigate concern over the lack of residual strength, since all piles would not reach their maximum capacity simultaneously. The bias factor should reward redundancy.

D.4.2.5 Relative Difficulty of Foundation Installation

The relative ability to install satisfactory driven piles is deemed comparable to the skirt piles of a jacket-type structure. For drilled and grouted piles and for connections between a pile and a foundation template, it is believed that these should be attainable in a manner comparable to a jacket platform. However, it is believed necessary to explicitly mention that special means should be provided to verify that grouted piles and pile to template connections are installed in a manner conforming to the design.

NOTE Provided explicit mention was made of the need to provide means to verify the adequacy of grout and pile to template connection installation.

D.4.2.6 Relative Integrity of Soil Samples Obtained from Deepwater

In this regard it is believed that adequate precautions are already mentioned in 10.2.2. It is also felt that the geotechnical consultant in conjunction with the operator’s staff, could properly interpret engineering soil properties resulting from deepwater soil samples.

D.4.2.7 Relative Character and Reliability of Load Determination

The determination of loading is assumed to be comparable to that obtained for a jacket structure.

D.4.2.8 Relative Lack of Ability to Inspect and Repair TLP Foundation Piles

The ability to inspect and repair TLP piles was deemed to be very similar to that of jacket-type structure.

D.4.3 Consequences of a Foundation Failure to the Integrity of the Overall Structural System

The consequence of a foundation failure for a TLP was deemed to be comparable to that of a jacket-type structure if a multi-pile bottom template is used to house the tendon receptacles. For the direct-connection method, pile failure is not comparable to that of a jacket-type structure. The number of piles per corner and the ultimate capacity of all the piles at the corner should be considered in evaluating the possible failure of a single pile when the B-factor is selected.

D.5 Discussion on Large Lateral Pile Deflections

Because it is a free-head pile, the direct-connect method may result in lateral deflections that exceed the criterion on which API 2A-WSD is based (see Matlock and Tucker, 1961 [186] and Matlock, 1970 [187]). The lateral deflections for the tests at Sabine, for example, did not exceed about 25 % of the pile diameter. Therefore, in lieu of other data, it may be assumed in clay soils that when lateral deflections (for the pile in the soil) exceed about 25 % of the pile diameter, the p_u (i.e. ultimate lateral resistance) given in API 2A-WSD should be reduced by the ratio of remolded to undisturbed strength and that the cyclic soft clay criteria governs the shape of the curve. This is based on published model test data and centrifuge tests by Doyle et al. (2005) [129] that indicate a reduced Pu is appropriate when lateral deflections exceed about 25 % of the pile diameter. In applying this recommendation, the criteria given in API 2A-WSD is followed until the pile deflection exceeds 25 % of the diameter. At that time the p-y curves are generated as normal until the value of p/p_u reaches the ratio of the remolded to undisturbed shear strength. At that time, all further values given in API 2A-WSD for p/p_u shall not exceed the ratio of remolded to undisturbed shear strength. The associated values of x/x_r shall remain the same.

Annex E
(informative)

Drilling and Production Interacting Checklists

A good working design is often seriously weakened by a lack of definition between the various design disciplines on how the drilling rigs interface with the TLP. Drilling rig interface points with TLPs are provided in Tables E.1 through E.3.

Table E.1—Structure Layout Interface Checklist

Item	Structure Layout Interface Point
1	Position and strength of beams and trusses on platform deck(s)
2	Allowable loadings for deck areas between major support members
3	Deck layout plans for open areas
4	Design loads due to wind on drilling packages
5	Dynamic loads from drilling packages resulting from horizontal accelerations of platform
6	Loading conditions from drilling packages due to construction, tow out and temporary mooring phases
7	CG and weight impact due to rig layouts, drilling live loads, and rig packaging/module design
8	Rig skid beam spacing, position, and strength
9	Jacking systems that can be accommodated
10	Elevation of well heads
11	Strength and layout of local beams around wellhead area
12	Strength points available for pulling heavy loads; eg, hanging BOP units
13	Position of “rat” and “mouse holes”
14	Access into/out of the hull for equipment when the drill rig is in place
15	Increased accommodation needs
16	Use of brine tanks in the hull

Table E.2—Utilities Interface Checklist

Item	Utilities Interface Systems and Equipment
1	Sharing with production systems
2	Lightweight machinery valving and piping
3	Area classification requirements resulting from drilling rig modules
4	Liquid storage in hull vs decks—consideration should be give between weight and CG positive impacts and negative fire and gas and hazardous area effects
5	Piping for fuel, water, etc., and transfer to and along the platform a) location distribution, size and number b) access points
6	Electrical power and communication/instrumentation a) quantity, distribution and location of cables b) remote bop control points (including prerun hydraulic lines) c) drilling instrumentation

Table E.3—Rig Services Interface Checklist

Item	Utilities Interface Systems and Equipment
1	Drilling drains, sumps, and solids handling to avoid coating or plugging lines, sumps, or other discharge points a) down comers for overboard disposal of cuttings from shale shakers, desilters, desanders, and sand traps b) drilling mud from active and reserve mud pits c) cement and cooling water
2	Impact of solid discharges on underwater equipment structures or intakes
3	Supply barge handling and consumable loading/unloading
4	Handling and operations of drilling risers, blowout preventers and deep well tools
5	Penetrations through the hull to be used for acoustical positioning equipment (serious consideration should be given to locating this type of system outside the hull)
6	ROV interfaces ROVs shall be able to plug all penetrations ROVs are limited in the amount of direct overhead work they can do and penetration design shall keep this in mind
7	Maintenance and operations of equipment used by the drilling team but located in the hull in areas that affect watertight integrity shall be agreed by both teams
8	If used, the weight of brine and the possibility and impacts of tank overflowing shall be considered both by the structural group and the marine systems group

Annex F
(informative)

Regulations Governing TLPs

F.1 USCG Regulations for TLPs Located in U.S. Waters

Applicable regulations for TLPs in U.S. waters include the following.

a) 33 *CFR* Parts 140 to 147 (Subchapter N), *Outer Continental Shelf Activities*. These regulations stipulate requirements for identification marks for platforms, means of escape, guard rails, fire extinguishers, life preservers, ring buoys, first aid kits, etc.

b) 46 *CFR* Parts 107 to 109 (Subchapter IA), *Mobile Offshore Drilling Units*. These regulations govern the inspection and certification design and equipment and operation.

c) 46 *CFR* Parts 50 to 64 (Subchapter F), *Marine Engineering*. These regulations prescribe the requirements for materials construction, installation, inspection and maintenance of boilers, unfired pressure vessels, piping and welding.

d) 46 *CFR* Parts 110 to 113 (Subchapter J), *Electrical Engineering*. These regulations prescribe in detail the electrical engineering requirements for vessels.

e) 33 *CFR* Part 67, *Aids to Navigation on Artificial Islands and Fixed Structures*. These regulations prescribe in detail the requirements for installation of lights and foghorns on offshore structures in various zones.

f) Oil and Pollution Act (OPA 90); governs storage of hydrocarbons at the waterline.

g) Minerals Management jurisdiction for TLPs located in U.S. waters—30 *CFR* Part 250—oil and gas and sulfur operations in the outer continental shelf and outer continental shelf orders for U.S. waters. These orders govern the marking, installation, operation, and removal of offshore structures and facilities.

F.2 International Regulations

Applicable international regulations include the following:

a) International Maritime Organization (IMO), *Code for the Construction and Equipment of Mobile Offshore Drilling Units* [Resolution A.414 (XI)].

b) International Regulations for Preventing Collisions at Sea, Rule 24a, *Towing and Pushing*.

c) *International Electrical Code* (*IEC*).

Bibliography

[1] API Recommended Practice 2A-WSD (21st Edition), *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms— Working Stress Design*

[2] API Recommended Practice 2A-LRFD, *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Load and Resistance Factor Design*

[3] API Specification 2C, *Offshore Cranes*

[4] API Specification 2B, *Fabricated Structural Steel Pipe*

[5] API Recommended Practice 2G (historical), *Recommended Practice for Production Facilities on Offshore Structures*

[6] API Bulletin 2INT-MET, *Interim Guidance on Hurricane Conditions in the Gulf of Mexico*

[7] API Recommended Practice 2RD, *Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs)*

[8] API Recommended Practice 2SK, *Design and Analysis of Stationkeeping Systems for Floating Structures*

[9] API Bulletin 2U, *Stability Design of Cylindrical Shells*

[10] API Bulletin 2V, *Design of Flat Plate Structures*

[11] API Recommended Practice 2X, *Ultrasonic and Magnetic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Technicians*

[12] API Recommended Practice 2Z, *Preproduction Qualification for Steel Plates for Offshore Structures*

[13] API Recommended Practice 14C, *Analysis, Design, Installation and Testing of Basic Surface Safety Systems on Offshore Production Platforms*

[14] API Recommended Practice 14E, *Recommended Practice for Offshore Production Platform Piping Systems*

[15] API Recommended Practice 14F, *Recommended Practice for Design and Installation of Electrical Systems for Offshore Production Platforms*

[16] API Recommended Practice 14G, *Recommended Practice for Fire Prevention and Control on Open Type Offshore Production Platforms*

[17] API Recommended Practice 17A, *Design and Operation of Subsea Production Systems—General Requirements and Recommendations*

[18] API Recommended Practice 17B, *Recommended Practice for Flexible Pipe*

[19] API Specification 17D, *Subsea Wellhead and Christmas Tree Equipment*

[20] API Specification 17E, *Specification for Subsea Umbilicals*

[21] API Recommended Practice 17G, *Recommended Practice for Completion/Workover Risers*

[22] API Specification 17J, *Specification for Unbonded Flexible Pipe*

[23] API Recommended Practice 16Q, *Design, Selection, Operation, and Maintenance of Marine Drilling Riser Systems*

[24] API Recommended Practice 505, *Classifications of Locations for Electrical Installations at Petroleum Facilities Classified as Class 1, Zone 0, Zone 1 and Zone 2*

[25] API Recommended Practice 520 (All Parts), *Sizing, Selection, and Installation of Pressure Relieving Systems in Refineries*

[26] API Recommended Practice 521, *Guide for Pressure Relief and Depressuring Systems*

[27] API 607, *Testing of Valves—Fire Type-testing Requirements*

[28] API Recommended Practice 1111, *Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipeline and Risers*

[29] ABS 2 (All Parts) [5], *Rules for Building and Classing Steel Vessels*

[30] ABS 6 (All Parts), *Rules for Building and Classing Mobile Offshore Drilling Units*

[31] ABS 29, *Rules for Building and Classing Offshore Installations*

[32] ABS 82*, Guide for Building and Classing Floating Production Installations*

[33] ABS 115, *Guide for the Fatigue Assessment of Offshore Structures*

[34] AISC 325-05 [6], *Manual of Steel Construction—Allowable Stress Design*

[35] AISC 360-05, *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings*

[36] ASME *Boiler and Pressure Vessel Code* (*BVPC*) [7], *Section VIII*: *Rules for Construction of Pressure Vessels, Division 2: Alternative Rules*

[37] ASME B31.1, *Power Piping*

[38] ASME B31.3, *Process Piping*

[39] ASME B31.4*, Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids*

[40] ASME B31.8, *Gas Transmission and Distribution Piping Systems*

[41] ASTM A6 [8], *Standard Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling*

[42] ASTM A139, *Standard Specification for Electric-Fusion (Arc)-Welded Steel Pipe (NPS 4 and Over)*

[43] ASTM A370, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*

---

[5] American Bureau of Shipping, ABS Plaza, 16855 Northchase Drive, Houston, Texas 77060, www.eagle.org.

[6] American Institute of Steel Construction, One East Wacker Drive, Suite 700, Chicago, Illinois 60601, www.aisc.org.

[7] ASME International, 3 Park Avenue, New York, New York 10016-5990, www.asme.org.

[8] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

[44] ASTM A381, *Standard Specification for Metal-Arc-Welded Steel Pipe for Use With High-Pressure Transmission Systems*

[45] ASTM A450, *Standard Specification for General Requirements for Carbon and Low Alloy Steel Tubes*

[46] ASTM A671, *Standard Specification for Electric-Fusion-Welded Steel Pipe for Atmospheric and Lower Temperatures*

[47] ASTM D412, *Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension*

[48] ASTM D429, *Standard Test Methods for Rubber Property—Adhesion to Rigid Substrates*

[49] ASTM D624, *Standard Test Method for Tear Strength of Conventional Vulcanized Rubber and Thermoplastic Elastomers*

[50] ASTM D2240, *Standard Test Method for Rubber Property—Durometer Hardness*

[51] AWS D1.1 [9], *Structural Welding Code*

[52] BSI BS 7910:1999 [10], *Guide on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures*.

[53] BSI BS 7608:1993, *Fatigue Design and Assessment of Steel Structures*

[54] DNV-OS-C103 [11], *Structural Design of Column-stabilised Units (LRFD method)*

[55] DNV-OS-C105, *Structural Design of TLP's (LRFD method)*

[56] DNV-OS-C201, *Structural Design of Offshore Units (WSD method)*

[57] DNV-OSS-101, *Rules for Classification of Offshore Drilling and Support Units*

[58] DNV-OSS-102, *Rules for Classification of Floating Production and Storage Units*

[59] DNV-RP-C103, *Column Stabilised Units*

[60] DNV-RP-C201, *Buckling Strength of Plated Structures*

[61] DNV-RP-C202, *Buckling Strength of Shells*

[62] DNV-RP-C203, *Fatigue Strength Analysis of Offshore Steel Structures*

[63] DNV-RP-C205, *Environmental Conditions and Environmental Load*

[64] FAA Advisory Circular 100/5390-1B [12], *Heliport Design Guide*

[65] IEEE Standard 45 [13], *Recommended Practice for Electric Installations on Shipboard*

---

[9] American Welding Society, 550 NW LeJeune Road, Miami, Florida 33126, www.aws.org.

[10] British Standards Institution, Chiswick High Road, London, W4 4AL, United Kingdom, www.bsi-global.com.

[11] Det Norske Veritas, Veritasveien 1, 1322, Hovik, Oslo, Norway, www.dnv.com.

[12] Federal Aviation Administration, 800 Independence Avenue, S.W., Washington, DC 20591, www.faa.gov.

[13] Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, New Jersey 08854, www.ieee.org.

[66] IMO MARPOL 73/78 [14], *International Convention for the Prevention of Pollution From Ships*, 1973 as Modified by the Protocol of 1978

[67] IMO SOLAS, *Safety of Life at Sea*

[68] ISO 19901-4 [15], *Petroleum and natural gas industries—Specific requirements for offshore structures*—Part 4: *Geotechnical and foundation design considerations*

[69] ISO 19901-5, Pe*troleum and natural gas industries—Specific requirements for offshore structures*—Part 5: *Weight control during engineering and construction*

[70] ISO 19902, *Petroleum and natural gas industries—Fixed steel offshore structures*

[71] ISO 19904-1, *Petroleum and natural gas industries—Floating offshore structures*–Part 1: *Monohulls, semisubmersibles and spars*

[72] NFPA, *Fire Protection Handbook* [16]

[73] NFPA 1, *Fire Code*

[74] NFPA 70, *National Electrical Code*

[75] SNAME T&R Bulletin 4-16 [17], *Recommended Practices for Merchant Ship Heating, Ventilation and Air Conditioning Design Calculations*

[76] SSC 266 [18], *Review of Ship Structural Details*

[77] SSC 272, *In-Service Performance of Structural Details*

[78] SSC 294, *Further Survey of In-Service Performance of Structural Details*

[79] USCG COMDTINST 16000.7A [19], *Marine Safety Manual, Volume II, Materiel Inspection*

[80] USCG NVIC 6-72, *Guide to Fixed Fire-Fighting Equipment Aboard Merchant Vessels*

[81] USCG NVIC 9-97, *Guide to Structural Fire Protection*

[82] *Manual of Safe Practices in Offshore Operations* [20]*,* International Association of Drilling Contractors, Offshore Operator's Committee, 1972

[83] OPA 90 [21]*, U.S. Oil Pollution Act of 1990*, 101 H.R.1465, Public Law 101-380

---

[14] International Maritime Organization, 4 Albert Embankment, London, United Kingdom, www.imo.org.

[15] International Organization for Standardization, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, www.iso.org.

[16] National Fire Protection Association, 1 Batterymarch Park, Quincy, Massachusetts 02169-7471, www.nfpa.org.

[17] The Society of Naval Architects and Marine Engineers, 601 Pavonia Avenue, Jersey City, New Jersey 07306, www.sname.org

[18] Ship Structure Committee, U.S. Coast Guard, 2100 Second Street, S.W., Washington, DC 20593, www.shipstructure.org.

[19] U.S. Coast Guard Marine Safety Center (part of DOT), 2100 Second Street, S.W., Washington, DC 20593, www.uscg.mil.

[20] International Association of Drilling Contractors, P.O. Box 4287, Houston, Texas 77210, www.iadc.org.

[21] U.S. Environmental Protection Agency, Ariel Rios Building, 1200 Pennsylvania Avenue, Washington, DC 20460, www.epa.gov.

[84] 33 *CFR*, *Navigation and Navigable Waters,* Part 142—*Workplace Safety and Health,* Part 144—*Lifesaving Appliances,* Part 146—*Operations*

[85] 46 *CFR* Part 108—*Shipping—Design and Equipment,* Part 111—*Shipping–Electric Systems—General Requirements, Part 113—Communication and Alarm Systems and Equipment*

[86] Allen D. W. and Henning, D. L., "Prototype VIV Tests for Production Risers," OTC 13114, 2001 Offshore Technology Conference, Houston, Texas

[87] Allen, D. W., "Performance Characteristics of Short Fairings," Offshore Technology Conference, OTC 15285, Houston, Texas, May, 2003.

[88] Anagnostopoulos, P. (Editor), *Flow-Induced Vibrations in Engineering Practice*, Ashurst, UK, WIT Press, 2002

[89] Andersen, K. H., Kleven, A. and Heien, D. (1988), "Cyclic Soil Data for Design of Gravity Structures," ASCE, *Journal of Geotechnical Engineering*, Vol. 114, GT5, pp. 517 to 539

[90] Andersen K. H. and Lauritzen, R. (1988), "*Bearing* Capacity for Foundations with Cyclic Loads," ASCE, *Journal of Geotechnical Engineering*, Vol. 114, No. GT5, pp. 540 to 555

[91] Andersen, K. H. (1991), *Foundation Design of Offshore Gravity Structures, Chapter 4, Cyclic Loading of Soils. From Theory to Design*, Edited by M. P. O'Reilly and S. F. Brown, Blackie and Son Ltd., Glasgow and London

[92] Andersen, K. H. and Jostad, H. P. (1999), "Foundation Design of Skirted Foundations and Anchors in Clay," 31st Annual Offshore Technology Conference, OTC 10824, Houston, Texas, May

[93] Andersen, K. H. and Jostad, H. P. (2002), "*Shear Strength Along Outside Wall of Suction Anchors in Clay after Installation*," Proceedings of 12th ISOPE Conference, Kyushi, Japan, May 26 to 31

[94] Baar, J. J. M., Howell, C. T., Mercier, R. S. and Rodenbusch, G., "Long-term Response of Tension leg Platform," Proceedings of Seventh International Offshore and Polar Engineering Conference (ISOPE), Honolulu, Hawaii, May, 1997

[95] Banon, H., Toro, R. G., Jefferys, E. R., and R. S. De, "Development of Reliability-Based Global Design Equations for TLPs," OMAE, Houston, Texas, February 1994

[96] Barltrop, N. D. P.; Adams, A.J., *Dynamics of Fixed Marine Structures*, Third Edition, Butterworth-Heinemann, Oxford, 1991

[97] Bearman, P. W., *Wind Loads on Structures in Turbulent Flow, The Modern Design of Wind-Sensitive Structures,* Construction Industry Research and Information Association, London, UK, pp. 42 to 48, 1971

[98] Bearman, P. W., "Vortex Shedding from Oscillating Bluff Bodies*," Annual Review of Fluid Mechanics*, Vol.16, pp. 195 to 222, 1984

[99] Bergdahl, L. and Johannson, M., "Time Simulations of the Motion of a Tension Leg Platform," Proceedings of Fifth International Conference on the Behavior of Offshore Structures (BOSS '88), Trondheim, Norway, June 1988

[100] Blevins, R. D., *Flow-Induced Vibrations*, Van Nostrand Reinhold, New York, 1990

[101] Borel, D., Puech, A., Dendani, H., and de Ruijter, M. (2002), “High Quality Sampling for Deepwater Engineering: the STACOR Experience,” Ultra Deep Engineering and Technology Conference (UDET 2002), Brest, France

[102] Bogard, J. D. And Matlock, H. (1990), “Application of Model Tests to Axial Pile Design,” Offshore Technology Conference, OTC Paper 6376, May

[103] Bogard, J. D., Matlock, H. and Chan, J. H.-C. (2000), “Comparison of Probe and Pile Tests in Normally Consolidated Clay,” ASCE Geotechnical Special Publication No. 100, Proceedings of GeoDenver 2000 Conference, Denver, Colorado, August

[104] Bogard, J. D., (2001) “Effective Stress and Axial Pile Capacity: Lessons from Empire, 33rd Annual Offshore Technology Conference,” OTC 13059, Houston, Texas, May

[105] Brebbia, C. A. and Walker, S. (1980), *Boundary Element Techniques in Engineering*, Newnes-Butterworths London

[106] Buitrago, J., Weir, M. S., and Kan, W., “Fatigue Design and Performance Verification of Deepwater Risers,” Proceedings of 22th International Conference on Offshore Mechanics and Arctic Engineering, June 2003

[107] Buitrago, J. and Sele Arne, “Strength and Fatigue Provisions for Mechanical Connector Design: New ISO Standard for Offshore Structures,” Proceedings of 17th International Conference on Offshore Mechanics and Arctic Engineering, July 1998

[108] Buitrago, J., and Zettlemoyer, N., *Fatigue Design of Critical Girth Welds for Deepwater Applications*, Proceedings of Offshore Mechanics and Arctic Engineering, Paper 98-2004, Lisbon, July 1998

[109] Buitrago, J. and Wong, P., “Fatigue Design of Driven Piles for Deepwater Applications,” Proceedings of 13th International Offshore and Polar Engineering Conference, Honolulu, Hawaii, May 2003

[110] Burns, G. E., “Calculating Viscous Drift of a Tension Leg Platform,” Proceedings of Second International Offshore Mechanics and Arctic Engineering Symposium, ASME, New York, 1983

[111] Chakrabarti, S. K. and Cotter, D. C., “First and Second Order Interaction of Waves with Large Offshore Structures,” Second International Symposium on Offshore Mechanics and Arctic Engineering, ASME, Houston, Texas, February 1983

[112] Chakrabarti, S. K. (1984), “Moored Floating Structures and Hydrodynamic Coefficients,” Ocean Structural Dynamics Symposium, Corvallis, Oregon

[113] Chakrabarti, S. K. (1987) *Hydrodynamics of Offshore Structures*, WIT Press, p. 440

[114] Chen, W-C, “Fatigue Life Predictions for a Threaded TLP Connector,” OTC 5938, May 1989

[115] Clarke, L. V., Brainbridge, H., Beck, S.B.M., and Yates, J. R., “Measurements of Fluid Flow Rates Through Cracks,” *International Journal of Pressure Vessels and Piping,* 1997

[116] Clough, R. and Penzien, *Dynamics of Structures*, McGraw Hill, Inc., New York, 1993

[117] Clukey, E. C., (2001), “Suction Caisson Design Issues, Geological, Geotechnical, and Geophysical Properties of Deepwater Sediments,” Proceedings of OTRC 2001 International Conference Honoring Prof. W. A. Dunlap, Conducted by the Offshore Technology Research Center, Edited by C. Aubeny and J.-L. Briaud, Houston, Texas, May

[118] Connelly, L. M. and Zettlemoyer, N., “Stress Concentrations at Girth Welds of Tubulars with Axial Wall Misalignment,” Proceedings of Fifth International Symposium of Tubular Structures, Nottingham, UK, August 1993

[119] Cox J. W., *Tubular Member Strength Equations for LRFD*, Final Report for API (American Petroleum Institute) PRAC Project 86-55, Dallas, Texas, October, 1989

[120] Cummings, W. E., *The Impulse Response Function and Ship Motions*, David Taylor Model Basin Report 1661, Washington, DC, 1962

[121] Daily, J. W. and Harleman, D. R. F. (1966), *Fluid Dynamics*, Addison-Wesley Publishing Co., Reading, Massachusetts

[122] Davies, K. B. and Mungall, J. C. H., “Methods for Coupled Analysis of TLPs,” Offshore Technology Conference, OTC 6567, Houston, Texas, May, 1991

[123] Davies, K. B., Leverette, S. J. and Spillane, M. W., “Ringing Response of TLP and GBS Platforms,” Proceedings of Seventh International Conference on the Behaviour of Offshore Structures (BOSS ’94), Cambridge, Massachusetts, 1994

[124] DeBoom, W. C., Pinkster, J. A., and Tan, S. G. (1983), “Motion and Tether Force Prediction for a Deepwater Tension Leg Platform,” OTC Paper 4437, OTC, Houston, Texas

[125] Doyle, E. H. and Pelletier, J. H. (1985), “Behavior of a Large Scale Pile in Silty Clay,” 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, California

[126] Doyle, E. H., (1998), “The Integration of Deepwater Geohazard Evaluations and Geotechnical Studies,” 30th Annual Offshore Technology Conference, OTC 8590, Houston, Texas, May

[127] Doyle, E. H., (1999), “Pile Installation Performance for Four TLPs in the Gulf of Mexico,” 31st Annual Offshore Technology Conference, OTC 10826, Houston, Texas, May

[128] Doyle, E. H. and Kaluza, M. J. (2001), “A Review on the Use of 3-D Exploration-Level Data for Geohazard Studies,” Proceedings of OTRC 2001 International Conference Honoring Prof. W. A. Dunlap, Conducted by the Offshore Technology Research Center, Edited by C. Aubeny and J.-L. Briaud, Houston, Texas, May

[129] Doyle, E. H., Dean, E. T. R., and Newlin. J. A. (2005), “Lateral Design of the Ursa Tension Leg Platform,” International Symposium on Frontiers in Offshore Geotechnics, September, Perth

[130] Dutt, R. N., Doyle, E. H. and Ladd, R. S., (1992), “Cyclic Behavior of a Deepwater Normally Consolidated Clay,” ASCE Civil Engineering In The Oceans V, Texas A&M University, November 2 to 4

[131] Dutt, R. N., Doyle, E. H., Collins, J. T., and Ganguly, P., (1995), “A Simple Model to Predict Soil Resistance to Driving for Long Piles in Deepwater Normally Consolidated Clays,” 27th Annual Offshore Technology Conference, OTC 7668, Houston, Texas, May

[132] Dutt, R. N., Rainey, W. S., Hamilton, T. K., Pelletier, J. H., and Doyle, E. H. (1997), “Recent Advances in Deepwater Gulf of Mexico Geotechnical Investigations,” 29th Annual Offshore Technology Conference, OTC 8303, Houston, Texas May

[133] Eatock-Taylor, R. and Rajagopalan, A. (1981), *Superharmonic Resonance Effects in Drag Dominated Structures, Integrity of Offshore Structures*, Faulker, Cowling and Frieze, Editor, Glasgow, p. 85, Applied Science Publishers, London.

[134] Edil, T. B. and Mochtar, I. B. (1988), “Creep Response of Model Piles in Clay,” *ASCE J. Geotechnical Engr.*, 114(11), pp. 1245 to 1260, November.

[135] Evangelinos, C. and Karniadakis G. E. (1999), “Dynamics and Flow Structures in the Turbulent Wake of Rigid and Flexible Cylinders Subject to Vortex-induced Vibrations,” *Journal of Fluid Mechanics*, Vol. 400, pp. 91 to 124

[136] Faltinsen, O. M., and Michelsen, F. (1974), “Motions of Large Structures in Waves and Zero Froude Number,” Proceedings of Government Symposium Dynamics of Marine Vehicles and Structures in Waves, London

[137] Faltinsen, O. M. and A. E. Loken (1979), “Slow Drift Oscillations of a Ship in Irregular Waves,” *Applied Ocean Research*, Vol. 1

[138] Faltinsen, O. M., Newman, J. N. and Vinje, T., “Nonlinear Wave Loads on a Slender Vertical Cylinder,” *Journal of Fluid Mechanics,* Vol. 289, pp. 178 to 198, 1995

[139] Feng, C.C. (1968) “The Measurement of Vortex Induced Effects in Flow Past Stationary and Oscillating Circular Cylinder and D-Section Cylinders,” M.A.Sc, Thesis, University of British Columbia

[140] Ferrant P. and Le Touze D. (2002), “Fully Nonlinear Spectral/BEM Solution for Irregular Wave Interactions with a 3-D Body,” Proceedings of 21st OMAE Conference, Oslo, Norway

[141] Forristall, G. Z., Larrabee, R. D., and Mercier, R. S., “Combined Oceanographic Criteria for Deep Water Structures in the Gulf of Mexico,” Offshore Technology Conference, OTC 6541, 1991

[142] Forristall, George .Z., “Wave Crest Heights and Deck Damage in Hurricanes Ivan, Katrina, and Rita,” Offshore Technology Conference, OTC 18620, 2007

[143] Frank, W. (1967), *Oscillation of Cylinders in or Below the Free Surface of Deep Fluids*, NSRDC Report 2375

[144] Funke, E. R. and Mansard, E. P. D., *On the Synthesis of Realistic Sea States in a Laboratory Flume*, Hydraulics Laboratory Technical Report LTR-HY-66, National Research Council of Canada, 1979

[145] Gilbert, R. B. and Murff, J. D. (2001), “Workshop Report Design Methodologies and Criteria for Suction Caissons for Deepwater Mooring Applications,” Offshore Technology Research Center, College Station, June

[146] Gray, J. N., Gray, T. A., Nakagawa, N. and Thompson, R. B., “Models for Predicting NDE Reliability,” *Metals Handboo*k, Ninth Edition, Vol. 7, *Nondestructive Evaluation and Quality Control*, ASM International, 1987

[147] Gray, T.A. and Thompson, R. B., *Nondestructive Evaluation—Application of Ultrasonic Inspection to Girth Welds in Steel Catenary Risers*, Report to Sponsors—ARDAMA Project, Iowa State University, Center for Nondestructive Evaluation, 1999

[148] Griffin, O. M. (1981), “OTEC Cold Water Pipe Design for Problems Caused by Vortex-Induced Oscillations,” *Ocean Engineering*, Vol. 8, No. 2, pp. 129 to 209

[149] Griffin, O. M. and Ramberg, S. E*., “*Some Recent Studies of Vortex Shedding with Application to Marine Tubulars and Risers,” Trans*.* ASME*, Journal of Energy Resources Technology*, Vol. 104, pp. 2 to 13, 1982

[150] Grue, J. and Huseby, M. (2002), “On the Occurrence of Strong Higher Harmonic Wave Forces and Induced Ringing Loads on Vertical Cylinders,” Proceedings of 21st OMAE Conference, Oslo, Norway

[151] Gunderson, R. H., Stevenson, A., and Harris, J. A., "Fatigue Life of TLP Flex Elements," OTC 6898, 1992

[152] Gunderson, R. H., Stevenson A., and Harris, J. A., "Ageing and Fatigue of Structural TLP Flex Elements," OTC 8517, 1997

[153] Hoerner, S. F. (1965), *Fluid Dynamic Drag*, Published by the Author

[154] Hover F. S., Smogeli O., Harper J. A., and Triantafyllou M. S. (2002), "Low Damping of Cylinders Vibrating in Still Water," Proceedings of OMAE, Paper No. OMAE2002-28161, Oslo, Norway

[155] Hover F. S., Techet A. H. and Triantafyllou M. S. (1998), "Forces on Oscillating Uniform and Tapered Cylinders in Crossflow," *Journal of Fluid Mechanics*, Vol. 363, pp. 97 to 114

[156] Hover F. S. and Triantafyllou M. S. (1998), "The Lock-in Phenomena for Cylinders with Nonlinear Compliance," Proceedings of ASME Fluids Engineering Division Summer Meeting, June 21 to 23, Washington, DC

[157] Hunt, R. J., Chan, J. H-C., and Doyle, E. H., "Driving Fatigue Damage Estimation for URSA TLP 96," The Ninth International and Polar Engineering Conference, Brest, France, May 1999

[158] Im, S., Powers, E. J. and Park, I.-S., "Advanced Volterra Models for Fluid-Structure Interactions," Proceedings of 1998 International OTRC Symposium on Ocean Wave Kinematics, Dynamics and Loads on Structures, Houston, Texas, April 30 to May 1, 1998

[159] Imas L., Triantafyllou M. S., Thompson H. M., Hsu T. M. and Young R. (2001), "Sensitivity of SCR Response and Fatigue Life to Variations in Hydrodynamic Loading at low Keulegan Carpenter Numbers," Proceedings of Offshore Technology Conference, Paper No. OTC 13109, Houston, Texas

[160] Ippen, A. T. (1966), Editor, *Estuary and Coastline Hydrodynamics*, McGraw-Hill, Inc., New York

[161] Jeanjean P., Andersen K., and Kalsnes, B., (1998), "Soil Parameters for Design of Suction Caissons for Gulf of Mexico Deepwater Clays," 30th Annual Offshore Technology Conference, OTC 8830, Houston, Texas, May

[162] Jefferys, E. R. and H. Banon, "Model Code for Design of Floating Platforms—Global Response Calibration," SUT Conference, London, November 1993

[163] Jefferys, E. R. and Rainey, W. S., "Slender Body Models of TLP and GBS Ringing," Proceedings of Seventh International Conference on the Behaviour of Offshore Structures (BOSS '94), Cambridge, Massachusetts, 1994

[164] Kareem, A., "Dynamic Effect of Wind on Offshore Structures," Offshore Technology Conference, OTC 3764, Houston, Texas, May, 1980

[165] Karlsrud, R. and Haugen, T., *Cyclic Loading of Piles and Pile Anchors, Field Model Tests at Haga*, Contract Research Report, Norwegian Geotechnical Institute (NGI), February 1981

[166] Kim, M. H., Mercier, R. S., Gu, G., Wu, C. and Botelho, D., "PC-based Wave Load Computation on Large-volume Multi-column Structures," Proceedings of Third International Offshore and Polar Engineering Conf. (ISOPE-93), Singapore, 1993

[167] Kim, M. H., Celebi, M. S., Kim, D. J. (1998), "Fully-nonlinear Interactions of Waves with a 3D Body in Uniform Currents," *Journal of Applied Ocean Research*, Vol. 20, pp. 309 to 321

[168] Kim, M. H., Tahar, A., Kim, Y. B. (2001), "Variability of TLP Motion Analysis against Various Design Methodologies/Parameters," Proceedings of 11th International Offshore and Polar Engineering Conference, Stavanger, Norway

[169] Korsmeyer, F. T., Lee, C.-H., Newman, J. N., and Sclavounos, P. D. (1988), "The Analysis of Wave Interactions with Tension Leg Platforms," OMAE Conference, Houston, Texas

[170] Krokstad, J. R., Stansberg, C. T., Nestegard, A. and Marthinsen, T., "A New Non-Slender Ringing Load Approach Verified against Experiments," Proceedings of Offshore Mechanics and Arctic Engnrg. Symp. (OMAE), 1996

[171] Lambrakos K., Triantafyllou M. S., and Moros T. (2002), "Hydrodyanamic Coefficients for Risers with Strakes," Proceedings of OMAE, Oslo, Norway

[172] Lee, C.-H. and Newman, J. N. (1992), "Sensitivity of Wave Loads to the Discretization of Bodies," Behavior of Offshore Structures Conference (BOSS '92), London

[173] Lee, C.-H. and Newman, J. N. (1994), "Second-order Wave Effects on Offshore Structures," Behavior of Offshore Structures Conference (BOSS '94), MIT

[174] Lee, C.-H., Newman, J. N., and Zhu, X. (1996), "An Extended Boundary-integral-equation Method for the Removal of Irregular-frequency Effects," *International Journal for Numerical Methods in Fluids*, Vol. 23, pp. 637 to 660

[175] Leverette, S., Rijken, Dooley, W., and Thompson, H. (2003), "Analysis of TLP VIV Responses to Eddy Currents," OTC15289

[176] Leverette, API TAC 93-20

[177] Leverette, S. J., Bradley, M. S. and Bliault, A., "An Integrated Approach to Setting Environmental Design Criteria for Floating Production Facilities," Behavior of Offshore Structures (BOSS) Conference, Cambridge, Massachusetts, August, 1982

[178] Leverette, S. J., and Rashedi, R., "Reliability-based Design Methodology for TLP Design," Proceedings of Fourth Offshore Symposium on Tension Leg Platform Technology, Society of Naval Architects and Marine Engineers, Houston, Texas, February 23 to 24, 1995

[179] Leverette, S. J., Rijken, O., Dooley, W. E. and Thompson, H. M., "Analysis of TLP VIV Responses to Eddy Currents," Offshore Technology Conference, OTC 15289, Houston, Texas, May, 2003

[180] Linton, C. M. and Evans, D. V. (1990), "The interaction of waves with array of vertical circular cylinders," *Journal of Fluid Mechanics,* Vol. 215, pp. 549 to 569

[181] Loh, J., API REPORT 90-56, *Analysis Cylindrical Shell Database and Validation of Design Formulations*, Appendix B, 1993

[182] Lucor D., Imas L. and Karniadakis G. E. (2001), "Vortex Displocations and Force Distribution of Long Flexible Cylinders Subjected to Sheared Flows," *Journal of Fluids and Structures*, Vol. 15, pp. 641 to 650

[183] MacCamy, R. C. and Fuchs, R. A. (1954), *Wave Forces on Piles: A Diffraction Theory*, TM 69, Corps of Engineers, Beach Erosion Board

[184] Macha and Reid (1984), "Semisubmersible Wind Loads and Wind Effects," Paper Presented at the Annual Meeting of the Society of Naval Architects and Marine Engineers, New York, New York, November 7 to 10

[185] Malenica, S. and Molin, B., “Third-harmonic Diffraction by a Vertical Cylinder,” *Journal of Fluid Mechanics*, Volume 302, pp. 203 to 229, 1995

[186] Matlock, H. and Tucker, R. L. (1961), “Lateral-Load Tests of an Instrumented Pile at Sabine, Texas,” A Report to Shell Development Company, Houston, Texas on Research Conducted by Engineering-Science Consultants, Austin, Texas

[187] Matlock, H., (1970), “Correlations for Design of Laterally Loaded Piles in Soft Clay,” Second Annual Offshore Technology Conference, OTC 1204, Houston, May

[188] Mei, C. C. (1983*)*, *The Applied Dynamics of Ocean Surface Waves*, John Wiley and Sons, New York

[189] Mercier, R. S. and Niedzwecki, J. M., “Experimental measurement of second-order diffraction by a truncated vertical cylinder in monochromatic waves,” Proceedings of Seventh International Conference on the Behaviour of Offshore Structures (BOSS ’94), Cambridge, Massachusetts, 1994

[190] Mercier, R. S., Schott, W. E., Howell, C. T., Denison, R., Gopalkrishnan, R., and Ekvall, A. G. C., “Mars Tension Leg Platform—Use of Model Testing in the Global Design,” Offshore Technology Conference, OTC 8354, Houston, Texas, May, 1997

[191] Meyers, Holm, and McAllister (1969), *Handbook of Ocean and Underwater Engineering*, McGraw-Hill

[192] Molin, B. (1979), “Computation of Drift Forces,” Paper No. 3627, OTC, Houston, Texas

[193] Morison, J. R., et al. (1950), “The Forces Exerted by Surface Waves on Piles,” *Journal of Petroleum Technology*

[194] Moses, F., *Tutorial on Load and Resistance Factor Design for Fixed Offshore Platforms*, Final Report for API (American Petroleum Institute) PRAC Project 88-22, Dallas, Texas, October 1989

[195] Naess, A. (1994), “Statistics of Combined Linear and Quadratic Springing Response of a TLP in Random Waves,” *Journal of Offshore Mechanics and Arctic Engineering*, Transactions of the ASME, Vol. 116, No. 3, pp. 127 to 136

[196] Natvig, B. J., “A proposed ringing analysis model for higher-order tether response,” Proceedings of Fourth International Offshore and Polar Engineering Conference (ISOPE), 1994

[197] Naudascher, E. and Rockwell, D., *Flow-Induced Vibrations: An Engineering Guide*, Balkema, Rotterdam, Netherlands, 1994

[198] Newman, J. N., “Second Order Slowly Varying Forces on Vessels in Irregular Waves,” International Symposium on the Dynamics of Marine Vehicles and Structures in Waves, University College of London, April 1974.

[199] Newman, J. N. (1977), *Marine Hydrodynamics*, MIT Press, Cambridge, Massachusetts

[200] Newman, J. N., “To Second Order and Beyond,” Proceedings of Fourth Offshore Symposium on Tension Leg Platform Technology, Society of Naval Architects and Marine Engineers, Houston, Texas, February 23 to 24, 1995

[201] Newman, J. N. (2001), *Wave Effects on Multiple Bodies, Hydrodynamics in Ship and Ocean Engineering*, RIAM, Kyushu University (Copyrighted by RIAM, Kyushu University)

[202] Newman, J. N. and Lee, C.-H. (2001), “Boundary-element Methods in Offshore Structure Analysis,” Proceedings of 20th Offshore Mechanics and Arctic Engineering Conference, Rio de Janeiro, Brazil. Also published in *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 124, pp. 81 to 89 (2002)

[203] Ogilvie, T. F. (1963), “First and Second Order Forces on a Cylinder Submerged under a Free Surface,” *Journal of Fluid Mechanics*, Vol. 16, Part 3, pp. 451-472.

[204] Parkinson, G. V., “Phenomena and Modelling of Flow-induced Vibrations of Bluff Bodies,” *Progress in Aerospace Sciences*, Vol. 26, pp.169 to 224, 1989

[205] Paulling, J. R., “Time Domain Simulation of Semisubmersible Platform Motion with Application to the Tension Leg Platform,” SNAME Spring Meeting, May 25 to 27, 1977

[206] Pearcey, H. H. (1978), “Some Observations on Fundamental Features of Wave-Induced Viscous Flows Past Cylinders,” Proceedings of IAHR Symposium on Mechanics of Wave-Induced Forces on Cylinders, Edited by T.L. Shaw

[207] Pelletier, J. H., Doyle, E.H., and Dutt, R.N. (1997), *Deepwater Geotechnical Investigations in the Gulf of Mexico, Underwater Technology*, Vol. 22, No. 2, pp. 63 to 73, Society for Underwater Technology

[208] Peterson, R. E., *Metal Fatigue, Chapter 13—Notch Sensitivity*, Sines and Waisman (Editors)., McGraw-Hill, 1959

[209] Pinkster, J. A. (1979), “Mean and Low Frequency Wave Drift Forces on Floating Structures,” *Ocean Energy*, Vol. 6, pp. 593 to 615

[210] Pinkster, J. A. (1980), *Low Frequency Second Order Wave Exciting Forces on Floating Structures*, NSMB, Wageningen, Publication No. 650

[211] Rice, S. O. (1944-45), “Mathematical analysis of random noise,” Bell *System Technical Journal 23 and 24*, See also Selected Papers on Noise and Stochastic Processes, Ed. N. Wax, 1954, 133-295, Dover Publ., New York

[212] Rijken, O., Leverette, S. and Davies, K. (2004), “Vortex Induced Motions of Semi Submersible with Four Square Columns,” DOT2004-paper 12-1

[213] Rinehart, A. J. and Buitrago, J. A., “Reliability Assessment of Collapse Safety Factors for Tendon Design,” OMAE2006-92063, 25th International Conference on Offshore Mechanics and Arctic Engineering, Hamburg, Germany, June 2006

[214] Roberts, J. B. and Spanos, P. D., *Random Vibration and Statistical Linearization*, Dover Publications, Inc., Mineola, New York, 2003

[215] Sarpkaya, T. and Isaacson, M. (1981), *Mechanics of Wave Forces on Offshore Structures*, Van Nostrand Rienhold Co., New York, p. 651

[216] Sarpkaya, T*., “*Vortex-induced Oscillations,” ASME, *Journal of Applied Mechanics,* Vol. 46, pp. 241 to 258, 1979

[217] Sarpkaya, T., “A Critical Review of the Intrinsic Nature of Vortex-induced Vibrations,” *Journal of Fluids and Structures*, 19, pp. 389 to 446, 2004

[218] Schaudt, K., Spillane, M., and Cardone, V., “Combined Eddy Current/Hurricane, Design Criteria for Deepwater Gulf of Mexico Structures,” Behavior of Offshore Structures Conference (BOSS ‘92), 1992

[219] Schott, W. E., Mercier, R. S. and Howell, C. T., “Resonant Tendon Tension Response Observed in the Hydrodynamic Scale Model Testing of the Mars Tension Leg Platform,” Proceedings of Fourth Offshore Symposium on Tension Leg Platform Technology, Society of Naval Architects and Marine Engineers, Houston, Texas, February 23 to 24, 1995

[220] Shih W. C. L., Wang C., Coles D., and Roshko, A. (1993), "Experiments on Flow Past Rough Circular Cylinders at Large Reynolds Numbers," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 49, pp. 351 to 368

[221] Simiu, E. and Scanlon, R. H. (1978), *Wind Effects on Structures*, John Wiley and Sons, New York

[222] Simiu, E. and Leigh, S. D., *Turbulent Wind Effects on Tension Leg Platform Surge*, NBS Building Science Series 151 National Bureau of Standards, U.S. Government Printing Office, Washington, March 1983

[223] Skop, R. A.; Griffin, O. M.; Ramberg, S.E. (1977), "Strumming Predictions for the SEACON II Experimental Mooring," Offshore Technology Conference Paper 2491, Houston, Texas

[224] Spillane, M. W., and Leverette, S. J., "Probabilistic Design: A Frequency-Domain Response Methodology," Proceedings of Seventh International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Houston, Texas, February 7 to 12, 1988

[225] Spillane, M. W., and Leverette, S. J., "Efficient Methods for use in Probabilistic Design," Second Offshore Symposium, Design Criteria and Codes, Texas Section of SNAME, Houston, Texas, April 4 and 5, 1991

[226] Spillane, M. W., Haring, R., Irick, J., and Chen, Cheng-Yo, *Response-Based Metocean Criteria Development for GB260 Compliant Tower*, OTC 10916, 1999 OTC, Houston, Texas

[227] Standing, R. G. and Dacunha, N. M. C. (1982), "Slowly-varying and Mean Second-order Wave Forces on Ships and Offshore Structures," Proceedings of 14th ONR Symposium on Naval Hydrodynamics, Ann Arbor, Michigan

[228] Stevenson, A. and Harris, J. A., "Fatigue Life Estimation of Flex Elements for TLP Structures," Proceedings of International Conference on Offshore Mechanics and Arctic Engineering, *Material Engineering*, Vol. III, 1992

[229] Sumer, B. M. and Fredsøe, J., "Hydrodynamics around Cylindrical Structures," *World Scientific*, Singapore, 1997

[230] Sungeun Kim and Paul D. Sclavounos (2001*),* "Fully Coupled Response Simulations of Theme Offshore Structures in Water Depths of up to 10,000 Feet," ISOPE Conference, Stavanger, Norway

[231] Terzaghi, K. and Peck, R. B. (1964), *Soil Mechanics In Engineering Practice*, John Wiley and Sons, New York

[232] Triantafyllou G. S. (1998), "Vortex Induced Vibrations of Flexible Structures," Summer Meeting of the American Society of Mechanical Engineers, Washington, DC

[233] Triantafyllou M. S., Triantafyllou, G. S., Tein D., and Ambrose, B. D. (1999), "Pragmatic Riser VIV Analysis," OTC Paper 10931, Houston, Texas

[234] Tromans, P. S. and Vanderschuren, L., "Response Based Design Conditions in the North Sea: Application of a New Method, Offshore Technology Conference," OTC 7683, Houston, Texas, May, 1995

[235] Tucker, M. J., Challenor, P. G., and Carter, P. S. T., *Numerical Simulation of a Random Sea: A Common Error and its effect on Wave Group Statistics*, *Applied Ocean Research*, 6(2), 1984

[236] Van Oortmerssen, G., *The Motions of a Moored Ship in Waves*, Netherlands Ship Model Basin Publication No. 510, 1976

[237] Vandiver, J. K. (1983), "Drag Coefficients of Long Flexible Cylinders," Offshore Technology Conference Paper 4490, Houston, Texas

[238] Vandiver, J. K., "Dimensionless Parameters Important to the Prediction of Vortex-Induced Vibration of Long, Flexible Cylinders in Ocean Currents," *Journal of Fluids and Structures*, 7, pp. 423 to 455, 1993

[239] Vandiver, J. K., Allen, D. and Li, L., "The Occurrence of Lock-in under Highly Sheared Conditions," *Journal of Fluids and Structures*, Vol. 10, pp. 555 to 561, 1996

[240] Verley, R. L. P. and Moe, G. (1980), "Hydrodynamic Damping of Offshore Structures in Waves and Currents," Proceedings of Offshore Technology Conference, No. 3798, Houston, Texas, May 1980

[241] Waals, O. J; Phadke, A. C.; and Bultema S. (2007), "Flow-induced Motions of Multi-column Floaters," Proceedings of OMAE Conference, Paper OMAE2007-29539

[242] Wen, Y. K. and Banon, H., "Environmental Event Combination Criteria for Tension Leg Platforms," Offshore Technology Conference, OTC 7682, Houston, Texas, May 1995

[243] Whittle, A. J. and Sutabutr, T., (1999), *Prediction of Pile Set-up in Clay*, Transportation Research Record, 1663, pp. 33 to 41

[244] Whittle, A. J. and Sutabutr, T., "Parameters for Average Gulf Clay and Predictions of Pile Set-up in Gulf of Mexico," ASCE Geo-Frontiers Conference, January 2005

[245] Wickers, J. E. W. and Huijsmans, R. M. H. (1984), "On the Low Frequency Hydrodynamic Damping Forces Acting on Offshore Moored Vessels," OTC Paper 4813, OTC, Houston, Texas

[246] Williamson, C. H. K. and Govardhan, R., "Vortex-induced vibrations," *Annual Review of Fluid Mechanics*, Vol. 36, pp. 413 to 455, 2004

[247] Winterstein, S. R., Ude, T., Cornell, C. A., Bjerager, P. and Haver, S., "Environmental Parameters for Extreme Response: Inverse FORM with Omission Factors," Proceedings ICOSSAR-93, Innsbruck, Austria, August 9 to 13, 1993

[248] Winterstein, S. R., Ude, T. C. and Kleiven, G., "Springing and Slow-drift Responses: Predicted Extremes and Fatigue vs. simulation," Proceedings of Seventh International Conference on the Behaviour of Offshore Structures (BOSS '94), Cambridge, Massachusetts, 1994

[249] Wirsching, P. H., *Probability-based Fatigue Design Criteria for Offshore Structures*, Report API-PRAC Project No. 81-15, Dept. of Aerospace and Mechanical Engineering, University of Arizona, Tucson, January 1983

[250] Wirsching, P. H. and Chen Y. N., "Fatigue Design Criteria for TLP Tendons," *Journal of Structural Engineering*, ASCE, August 1986

[251] Young, A. G., Honganen C. D., Silva A. J., and Bryant W. R., 2000, "Comparison of Geotechnical Properties from Large-diameter Long Cores and Borings in Deep Water Gulf of Mexico," 32nd Annual Offshore Technology Conference, Houston, Texas (OTC 12089)

[252] Young, R. W. and Bai, K. J. (1974), "Numerical Solution to Free Surface Flow Problems," 10th Symposium ONR

[253] Yue, D. K., H. S. Chen, and C. C. Mei (1978), "A Hybrid Element Method for Diffraction of Water Waves by Three-Dimensional Bodies*," International Journal for Numerical Methods in Engineering*, Vol. 12, pp. 245 to 266

[254] Zdravkovich M. M. (1997), *Flow around Circular Cylinders*, Oxford University Press: Oxford

[255] Zhu, X. (1997), “A Higher-order Panel Method for Third-Harmonic Diffraction Problem,” Ph.D. Thesis, Dept of Ocean Engineering, MIT

energy API

AMERICAN PETROLEUM INSTITUTE

2010 PUBLICATIONS ORDER FORM

Effective January 1, 2010. API Members receive a 30% discount where applicable. The member discount does not apply to purchases made for the purpose of resale or for incorporation into commercial products, training courses, workshops, or other commercial enterprises.

Ordering Information
Online: **www.api.org/pubs**
Phone: **1-800-854-7179** (Toll-free in the U.S. and Canada) | **(+1) 303-397-7956** (Local and International)
Fax: **(+1) 303-397-2740**

Date: ____________________ ☐ **API Member** (Check if Yes)

Invoice To (☐ Check here if same as "Ship To")		**Ship To** (UPS will not deliver to a P.O. Box)	
Name:		Name:	
Title:		Title:	
Company:		Company:	
Department:		Department:	
Address:		Address:	
City:	State/Province:	City:	State/Province:
Zip/Postal Code:	Country:	Zip/Postal Code:	Country:
Telephone:		Telephone:	
Fax:		Fax:	
Email:		Email:	

Quantity	Title	SO★	Unit Price	Total
	RP 2A-WSD, Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design		$341.00	
	Bull 2INT-DG, Interim Guidance for Design of Offshore Structures for Hurricane Conditions		$55.00	
	Bull 2INT-EX, Interim Guidance for Assessment of Existing Offshore Structures for Hurricane Conditions		$55.00	
	Bull 2INT-MET, Interim Guidance on Hurricane Conditions in the Gulf of Mexico		$82.00	
	RP 2RD, Design of Risers for Floating Production Systems (FPSs) and Tension Leg Platforms (TLPs)		$203.00	
	RP 2SK, Design and Analysis of Stationkeeping Systems for Floating Structures		$123.00	
	Bull 2TD, Guidelines for Tie-does on Offshore Production Facilities for Hurricane Season		$49.00	

☐ Payment Enclosed ☐ P.O. No. (Enclose Copy) ____________

☐ Charge My IHS Account No. ____________

☐ VISA ☐ MasterCard ☐ American Express
☐ Diners Club ☐ Discover

Credit Card No.:

Print Name (As It Appears on Card):

Expiration Date:

Signature:

Subtotal	
Applicable Sales Tax (see below)	
Rush Shipping Fee (see below)	
Shipping and Handling (see below)	
Total (in U.S. Dollars)	

★ To be placed on Standing Order for future editions of this publication, place a check mark in the SO column and sign here:

Pricing and availability subject to change without notice.

Mail Orders – Payment by check or money order in U.S. dollars is required except for established accounts. State and local taxes, $10 processing fee, and 5% shipping must be added. Send mail orders to: **API Publications, IHS, 15 Inverness Way East, c/o Retail Sales, Englewood, CO 80112-5776, USA.**

Purchase Orders – Purchase orders are accepted from established accounts. Invoice will include actual freight cost, a $10 processing fee, plus state and local taxes.

Telephone Orders – If ordering by telephone, a $10 processing fee and actual freight costs will be added to the order.

Sales Tax – All U.S. purchases must include applicable state and local sales tax. Customers claiming tax-exempt status must provide IHS with a copy of their exemption certificate.

Shipping (U.S. Orders) – Orders shipped within the U.S. are sent via traceable means. Most orders are shipped the same day. Subscription updates are sent by First-Class Mail. Other options, including next-day service, air service, and fax transmission are available at additional cost. Call 1-800-854-7179 for more information.

Shipping (International Orders) – Standard international shipping is by air express courier service. Subscription updates are sent by World Mail. Normal delivery is 3-4 days from shipping date.

Rush Shipping Fee – Next Day Delivery orders charge is $20 in addition to the carrier charges. Next Day Delivery orders must be placed by 2:00 p.m. MST to ensure overnight delivery.

Returns – All returns must be pre-approved by calling the IHS Customer Service Department at 1-800-624-3974 for information and assistance. There may be a 15% restocking fee. Special order items, electronic documents, and age-dated materials are non-returnable.

THERE'S MORE
WHERE THIS CAME FROM.

API Monogram® Licensing Program
Sales: (+1) 713-964-2662
Service: (+1) 202-962-4791
Fax: (+1) 202-682-8070
Email: certification@api.org
Web: www.api.org/monogram

API Quality Registrar (APIQR®)
- ISO 9001
- ISO/TS 29001
- ISO 14001
- OHSAS 18001
- API Spec Q1®
- API QualityPlus®
- Dual Registration

Sales: (+1) 713-964-2662
Service: (+1) 202-962-4791
Fax: (+1) 202-682-8070
Email: certification@api.org
Web: www.api.org/apiqr

API Individual Certification Programs (ICP®)
Sales: (+1) 713-964-2662
Service: (+1) 202-682-8064
Fax: (+1) 202-682-8348
Email: icp@api.org
Web: www.api.org/icp

API Engine Oil Licensing and Certification System (EOLCS)
Sales: (+1) 713-964-2662
Service: (+1) 202-682-8516
Fax: (+1) 202-962-4739
Email: eolcs@api.org
Web: www.api.org/eolcs

API Training Provider Certification Program (API TPCP™)
Sales: (+1) 713-964-2662
Service: (+1) 202-682-8075
Fax: (+1) 202-682-8070
Email: tpcp@api.org
Web: www.api.org/tpcp

API Perforator Design Registration Program
Sales: (+1) 713-964-2662
Service: (+1) 202-682-8490
Fax: (+1) 202-682-8070
Email: perfdesign@api.org
Web: www.api.org/perforators

API Credit Exchange (ACE™)
Service: (+1) 202-682-8192
Fax: (+1) 202-682-8070
Email: exchange@api.org
Web: www.api.org/ace

API Diesel Exhaust Fluid Certification Program
Phone: (+1) 202-682-8516
Fax: (+1) 202-962-4739
Email: info@apidef.org
Web: www.apidef.org

API WorkSafe™
Sales: (+1) 713-964-2662
Service: (+1) 202-682-8469
Fax: (+1) 202-682-8348
Email: apiworksafe@api.org
Web: www.api.org/worksafe

API-U
Phone: (+1) 202-682-8053
Fax: (+1) 202-682-8070
Email: training@api.org
Web: www.api-u.org

API Data™
Phone: (+1) 202-682-8499
Fax: (+1) 202-962-4730
Email: apidata@api.org
Web: www.APIDataNow.org

API Publications
Online: www.api.org/pubs
Phone: 1-800-854-7179
(Toll-free: U.S./Canada)
(+1) 303-397-7956
(Local/International)
Fax: (+1) 303-397-2740

API Standards
Phone: (+1) 202-682-8148
Fax: (+1) 202-962-4797
Email: standards.org
Web: www.api.org/standards

Request a Quotation:
www.api.org/quote

---

energy API®
AMERICAN PETROLEUM INSTITUTE

energy API®

AMERICAN PETROLEUM INSTITUTE

1220 L Street, NW
Washington, DC 20005-4070
USA

202-682-8000

Additional copies are available online at www.api.org/pubs

Phone Orders: 1-800-854-7179 (Toll-free in the U.S. and Canada)
303-397-7956 (Local and International)
Fax Orders: 303-397-2740

Information about API publications, programs and services is available on the web at www.api.org.

Product No. G02T03