GUIDE FOR

‘DYNAMIC LOADING APPROACH’ FOR FLOATING PRODUCTION, STORAGE AND OFFLOADING (FPSO) INSTALLATIONS

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Foreword

This Guide provides information about the optional classification notation, Dynamic Loading Approach (**DLA**), which is available to qualifying ship-type "Floating Production Installations" (FPIs). This type of offshore installation is usually referred to as a "Floating Storage and Offloading (FSO) System"; or "Floating Production, Storage and Offloading (FPSO) System", and "FPSO" is the term that will be used herein to denote these ship-type Floating Production Installations. Also, in the text herein, this document is referred to as the "Guide".

Section 1-1-2 of the ABS *Rules for Building and Classing Floating Production Installations* (*FPI Rules*) contains descriptions of the various, basic and optional classification notations available. Part 5A of the *FPI Rules* gives the specific design and analysis criteria applicable to ship-type FPIs (new build ship-type installations and conversions to FPI).

In addition to the Rule design criteria, Dynamic Loading Approach based on first-principle direct calculations is acceptable with respect to the determination of design loads and the establishment of strength criteria for ship-type FPIs. In case of any conflict between this Guide and the *FPI Rules*, the latter has precedence.

This Guide represents the most current and advanced ABS DLA analysis procedure including linear and nonlinear seakeeping analysis. This Guide is issued May 2010, and is an extended edition of the ABS *Guidance Notes on SafeHull-Dynamic Loading Approach for Floating Production, Storage and Offloading (FPSO) Systems*, published in December 2001. Users of this Guide are welcomed to contact ABS with any questions or comments concerning this Guide. Users are advised to check periodically with ABS that this version of this Guide is current.

GUIDE FOR

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SECTION 1 Introduction

1 Background

The design and construction of the hull, superstructure, and deckhouses of a ship-type FPI that can be a new build or conversion are to be based on all applicable requirements of the ABS *Rules for Building and Classing Floating Production Installations* (*FPI Rules*). The design criteria for these structures, as given in the *FPI Rules*, reflect the structural performance and demands expected of a floating production installation which is moored at a particular site on a long-term basis.

The design criteria for a ship-type installation are located in Part 5A, Chapters 1 through 4 of the *FPI Rules*. Part 5A, Chapters 1, 2, and 3 are applicable to vessels of 150 meters (492 feet) or more in length, while Part 5A, Chapter 4, applies to vessels under 150 meters (492 feet) in length.

The FPI criteria contained in Part 5A of the *FPI Rules* entail a two-step procedure. The first step, referred to as the *Initial Scantling Evaluation (ISE)*, is scantling selection to accommodate global and local strength requirements. The scantling selection is accomplished through the application of design equations that reflect combinations of: probable extreme, dynamically induced loads; durability considerations; expected service, survey and maintenance practices; and structural strength considering the failure modes of material yielding and buckling. Also, a part of *ISE* is an assessment of fatigue strength primarily aimed at connections between longitudinal stiffeners and transverse web frames in the hull structure.

The second step of the FPI criteria, referred to as the *Total Strength Assessment (TSA)*, requires the performance of finite structural analysis using either a three cargo tank length model or cargo block length model, to validate the selected scantlings from the initial *ISE* phase. The main purpose of the *TSA* analysis is to confirm that the selected design scantlings are adequate (from a broader structural system point of view) to resist the failure modes of yielding, buckling and ultimate strength, and fatigue.

The Dynamic Loading Approach (DLA) provides an enhanced structural analysis basis to assess the capabilities and sufficiency of a structural design. A fundamental requirement of DLA is that the basic, initial design of the structure is to be in accordance with the Rule criteria as specified in the *FPI Rules*. The results of the DLA Analyses cannot be used to reduce the basic scantlings obtained from the direct application of the Rule criteria scantling equations. However, should the DLA Analysis indicate the need to increase any basic scantling this increase is to be accomplished to meet the DLA criteria.

This Guide is applicable to ship-type installations of all size and proportions including new build ship-type FPI and conversions to FPI.

3 Concepts and Benefits of DLA Analysis

3.1 Concepts

The structural design portions of the *FPI Rules* (i.e., see especially Part 5A, Chapter 3) are intended to provide an appropriate and sufficient basis for the design and analysis of the hull structure of an FPSO. This was done by modifying tanker structural design criteria to reflect site-specific environmental loadings and other design features of an FPSO. The other design features include such items as possible turret based mooring, deck-mounted hydrocarbon processing equipment, etc. The *FPI Rules* includes provisions that address these matters with emphasis on the sequence, process and objectives of design, not on the structural analysis itself.

DLA is an analysis process, rather than the step-wise design oriented process that *FPI Rules* criteria is. The DLA analysis emphasizes the completeness and realism of the analysis model in terms of both the extent of the structure modeled and the loading conditions analyzed. In a manner that is the converse of the *FPI Rules* criteria, in DLA the modeling and analysis process relies on performing multiple levels of analysis that start with an overall or global hull model, and the results of each previous level of analysis are used to establish areas of the structure requiring finer (more detailed) modeling and analysis, the local loading to be re-imposed and the 'boundary conditions' to be imposed on the finer model.

The Load Cases considered in the DLA analysis possess the following attributes:

i) Use of tank-loading patterns, other loading components, and vessel operating drafts that reflect the actual ones intended for the vessel (note that the Load Cases in the *FPI Rules* criteria comprise mainly those intended to produce 'scantling design controlling' situations).

ii) Load components are combined to assemble each DLA Load Case. The dynamic related aspects of the components are incorporated in the model, and the combination of these dynamically considered components is accommodated in the analysis method.

iii) The use of environmental and other load effects for the installation site directly considers the functional role of the FPI as a site-dependent structure, using 'design return' periods appropriate to this function. Also, the phasing and relative directionality that exist between environmental effects and the structure itself can be directly considered.

iv) Because of the required extent of the structural modeling, the direct effects and the interaction between structural subsystems (such as mooring turret and main deck supported equipment modules) can be directly assessed.

3.3 Benefits

The enhanced realism provided by the DLA analysis gives benefits that are of added value to the Operator/Owner. The most important of these is an enhanced and more precise quantification of structural safety based on the attributes mentioned above. Additionally, the more specific knowledge of expected structural behavior and performance is very useful in more realistically evaluating and developing inspection and maintenance plans. The usefulness of such analytical results when discussing the need to provide possible future steel renewals should be apparent. An under-appreciated, but potentially valuable benefit that can arise from the DLA Analysis is that it provides access to a comprehensive and authoritative structural evaluation model, which may be readily employed in the event of emergency situations that might occur during the service life of the FPI, such as structural damage, repairs or modifications, long distance ocean transit to a repair facility or redeployment to another installation site.

3.5 Load Case Development for DLA Analysis

The basic concept, which must be understood to grasp the nature of DLA, concerns the creation of each Load Case used in the analysis. A Load Case considered for analysis comprises combinations of a Dominant Load component and the other significant load components that are considered to be accompanying the Dominant Load component. Each Load Case contains the load components accompanying the Dominant Load component and a Dominant Load component that is characterized by a defining parameter, referred to as the Dominant Load Parameter (DLP).

A load component consists of dynamic and static parts. For example, the load component "external fluid pressure on the FPSO's hull in the presence of waves" has a hydrostatic component that combines with a dynamically considered pressure component. The determination of the static part of the load component is basic. The dynamically considered part reflects the wave induced motion effects, which are the product of an inertial portion of the load and a portion representing the motion induced displacement of the load relative to the structure's axis system.

Note: This Guide considers dynamic effects produced almost exclusively by waves. As appropriate, the effects of wind may need to be combined with waves when developing some Load Cases, such as ones involving the DLP "Maximum Roll Angle." (see 2/7.9)

Examples of Dominant Load Parameters are "Vertical Hull Girder Bending Moment Amidships" and "Lateral Acceleration at the Vessel's Forepeak Frame". The specific Dominant Load Parameters that are recommended for inclusion in the DLA analysis of an FPSO are given in Subsection 2/7. The other significant load components accompanying the Dominant Load component in a Load Case include internal and external fluid pressures, lightship weights including structural self-weight, topside equipment weights, and mooring system forces.

The combination of the load components composing a Load Case is done through a process where each Dominant Load is analyzed to establish its Response Amplitude Operator (RAO). Using a combination of vessel motion analysis, involving ocean wave spectra, and extreme value analysis of the Dominant Load Parameter an equivalent sinusoidal wave is derived. The wave (defined by wave amplitude, frequency, heading and phase angle with respect to a selected reference location) is considered equivalent in the sense that when it is imposed on the structural model it simulates the extreme value of the DLP. The process to perform this derivation is given in Sections 4 and 5.

In this Guide, emphasis is given to the essential elements of Load Case creation using DLPs and the equivalent wave to obtain the other load components accompanying the DLP. It is assumed that the user has the needed background in the procedures and computational tools that are used for Spectral-based Vessel Motion and Wave Induced Load Analysis and Extreme Value Analysis, both of which are required in the establishment of DLPs.

From the RAOs of the dynamic portions of the other load components and the equivalent wave derived for the DLP, the magnitude and spatial distributions of the other load components accompanying the Dominant Load component are obtained. The procedures to establish these load components accompanying the DLP are given for the various other load component types in Sections 7, 8, and 9.

Using the described basic procedure there are many additional considerations and refinements that can be included and accommodated in DLA Analysis. These include items such as the following:

i) Operational considerations of the vessel in extreme waves

ii) Directionality of waves

iii) Energy spreading of sea spectra

iv) Various formulations to characterize the sea spectra

v) Various 'Return Periods' (or 'Exceedance Probability' Levels) to characterize extreme values of Dominant Load Parameters.

The point to bear in mind is that the procedure is robust enough to accommodate these items.

3.7 General Modeling Considerations

In general, it is expected that the inaccuracies and uncertainties, which can arise from use of partial or segmented models, will be minimized by the use of models that are sufficiently comprehensive and complete to meet the goals of the analysis. This specifically means that to the maximum extent practicable, the overall model of the hull structure should comprise the entire hull, the topside equipment support structure and the interface with a turret mooring system. The motion analysis may consider the effect of shallow water depth on vessel motions if its effect turns out to be critical in determining the vessel responses. There is also to be sufficient compatibility between the hydrodynamic and structural models so that the application of fluid pressures onto the Finite Element (FE) mesh of the structural model can be done appropriately.

For the load component types and structural responses of primary interest in the DLA, analysis software formulations derived from linear idealizations are deemed to be sufficient. However, the designer/analyst is encouraged to employ enhanced bases for the analysis, especially to incorporate non-linear loads (for example hull slamming), if this proves to be necessary for the specific design being evaluated. The designer/analyst needs to be aware that the adequacy of the selected software is to be demonstrated to the satisfaction of ABS.

The results of overall (global) model analysis are to be directly employed in the creation and analysis of the required finer mesh, local structural models. Appropriate 'boundary conditions' determined in the larger scale model are to be imposed on the local models to assure appropriate structural continuity and load transfer between the various levels of models.

5 Notations

The **DLA** notation signifies the satisfaction of the DLA analysis procedure of this Guide. The notation DLA signifies:

i) The design is based on an analysis which more explicitly considers the loads acting on structure and their dynamic nature, and

ii) In no case is an offered design scantling to be less than that obtained from other requirements in the *FPI Rules*.

In this regard, all the supporting data analysis procedures and calculated results are to be fully documented and submitted for review. The submittals for review should include:

i) A contract which clearly defines owner's specification other tan standard requirement, or other critical information

ii) Site metocean data

iii) Principal Dimensions, Lines and Trim/Stability booklet

iv) Key drawings (General Arrangement, Midship section, Shell expansion, Construction profile and Deck plan)

v) More drawings for Forebody/Aftbody, Typical bulkhead and Engine room

vi) DLA analysis report detailing findings and identifying any inconsistencies, assumptions, and corrective actions

vii) Seakeeping input/output files including DLPs' RAO and their extreme values

viii) Structural FE model and its analysis results

7 Scope and Overview of the Following Sections

This Guide provides a description of the analysis procedure to be pursued to obtain the optional classification notation 'Dynamic Loading Approach', **DLA**. Emphasis is given here to the determination of dynamic loads rather than the structural FE analysis procedure. This has been done mainly because structural analysis practices are well established and understood among designers, but dynamic load determination is a less familiar subject. Therefore, the procedures for FE analysis are only briefly described for the purpose of ready reference and completeness.

The Dynamic Loading Approach uses explicitly determined dynamic loads, and the results of the analysis are used as the basis to increase scantlings where indicated, but allows no decreases in scantlings form those obtained form the direct application based on *FPI Rules* scantling equations.

While outside the scope of this Guide, any local impact pressure and global whipping loads due to slamming are to be separately addressed for the strength assessment of the hull structure. Also, any green sea loads due to the ingress of green water on deck is to be addressed for scantlings of the forecastle deck and breakwater. For this purpose, the adequacy of the selected software may need to be demonstrated to the satisfaction of ABS.

This Guide systematically introduces the assumptions in the load formulation and the methods used in the response analysis underlying the DLA Analysis for FPSOs. These include the following topics:

i) Specification of the loading conditions

ii) Specification of the Dominant Load Parameters

iii) Response Amplitude Operators and extreme values

iv) Equivalent design waves

v) Wave-induced load components and the assembly of Load Cases

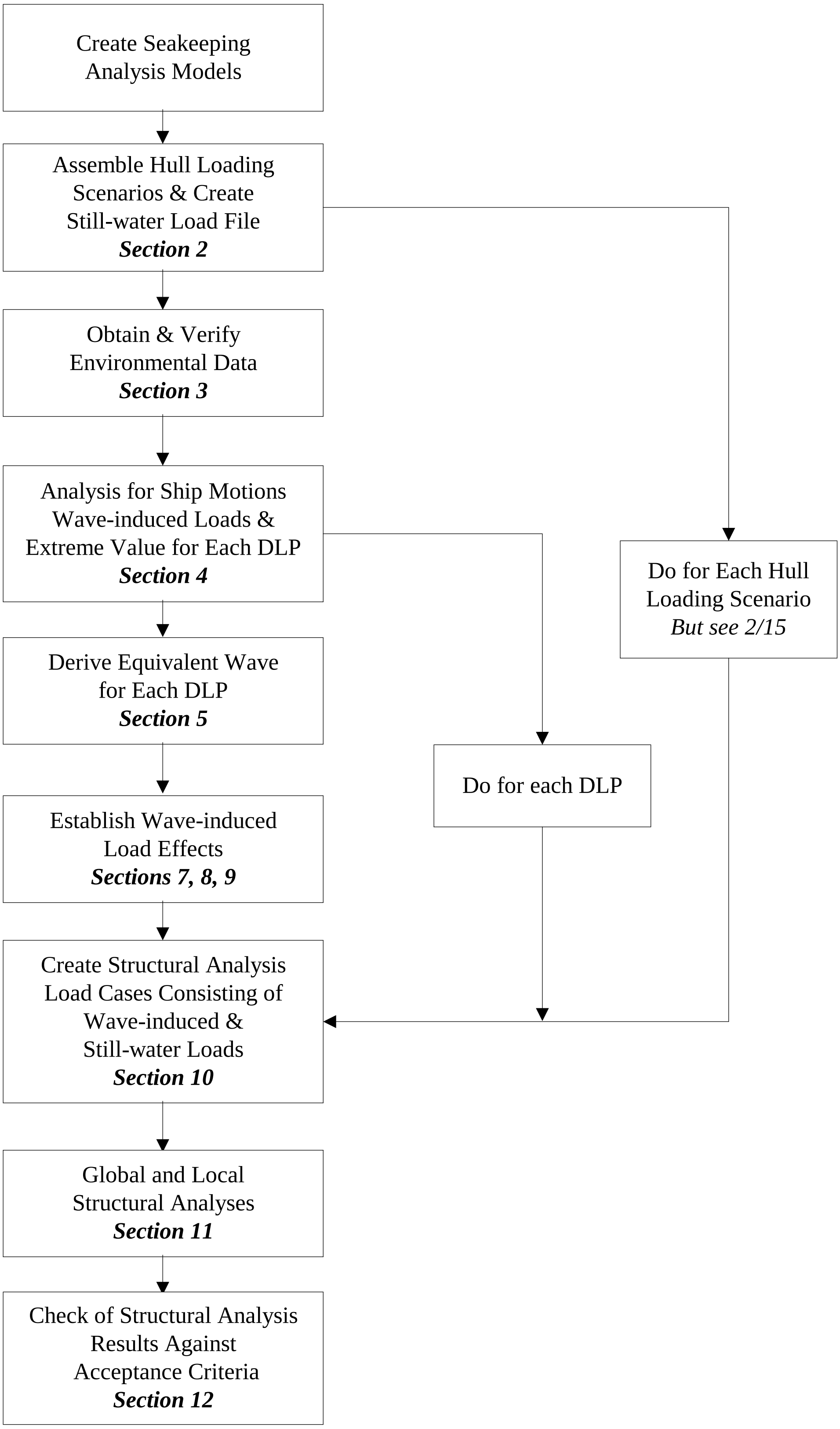
vi) Structural FE model development; and *vii)* Permissible stresses used in the acceptance criteria.

These topics are presented in the following Sections 2 through 12, and Appendix 1 summarizes the DLA analysis procedure.

Refer to Section 1, Figure 1 for a schematic representation of the DLA analysis procedure.

While the DLA can, in principle, be applied to all types of floating offshore structures, the focus of this Guide is on FPSOs. In the case of other ship types, clients should consult with ABS to establish appropriate analysis procedures. This applies particularly to the choice of loading conditions and Dominant Load Parameters. For trading ship types, designers can refer to the ABS *Guide for SafeHull-Dynamic Loading Approach for Vessels*.

FIGURE 1
Schematic Representation of the DLA Analysis Procedure



SECTION 2 Load Cases

1 Basic Considerations

The DLA Analysis requires the development of Load Cases to be investigated using the Finite Element Method (FEM) of structural analysis. The Load Cases are derived mainly based on the operational loading conditions (see Subsection 2/5), Dominant Load Parameters (see Subsection 2/7) and environmental conditions (see Section 3).

For each Load Case, the applied loads to be used for structural FE analysis are to include both the static and dynamic parts of each load component. A Load Case represents the combined effects of a dominant load and other accompanying loads acting simultaneously on the hull structure including external wave pressures, internal tank pressures and inertial loads on the structural components and equipment. In quantifying the dynamic part of a load, it is necessary to consider a range of sea conditions and headings, which produce the considered critical responses of the hull structure. The developed Load Cases are then used in the FE analysis to determine the resulting stresses and other load effects within the hull structure.

3 Vessel Speed

For the DLA analysis of an FPSO, the vessel speed is set to be zero for site-specific design wave conditions after installation and average transit speed for transit condition from the building or outfitting site (or the shipyard where the conversion modifications are made) to the project site.

5 Operational Loading Conditions

The design of an FPSO should consider the production rate, storage capacity and produced fluid's offloading capability. Hence, loading on the hull structure relates to the liquid cargo and ballast patterns, the vessel's draft and trim ranges, the deck loading from processing equipment and the loads resulting from the mooring system.

About five (5) to seven (7) tank loading pattern and hull draft conditions, typically found in the FPSO's Loading Manual, are to be selected as representative conditions in the DLA analysis. Also loading condition(s) representing major transportation phase(s) for the FPSO should be included in the DLA analysis. For example:

i) *On-site Operations:*

- Ballast or minimum draft condition after offloading (all cargo tanks empty)
- 2nd intermediate loading (33% filled)
- 3rd intermediate loading (tanks 50% filled)
- 4th intermediate loading (67% filled)
- Full-load condition at scantling draft or before offloading (tanks full)
- Inspection and repair conditions
- Tank testing conditions – during conversion and after construction (periodic survey)

Other cargo loading conditions that may be deemed critical can also be considered in the DLA analysis. The need to consider the other loading conditions or additional loading conditions is to be determined in consultation with ABS.

ii) *Transit:*

- Vessel Loading Pattern and Draft for the voyage from outfitting yard to the installation site.

Additionally, load conditions representative of other transit conditions, which are anticipated during the life of the FPSO, will need to be included in the scope of the DLA analysis.

7 Dominant Load Parameters

The term, Dominant Load Parameter (DLP) refers to a global load or motion effect of the hull (e.g., hull girder bending or vessel motion) that may yield the maximum structural response for critical structural members. The instantaneous response of the vessel can be judged by one of the several Dominant Load Parameters. These parameters are to be maximized to establish Load Cases for the FE analysis.

Ocean waves produce external dynamic pressures on the hull surface. These waves also induce vessel motions that produce load components in translational and rotational motion modes, and generate inertial forces through the acceleration of the structural, equipment and the internal fluid masses including ballast and cargo. Vessel motion responses in waves are calculated for the hull operational loading conditions. The important range of vessel response can be obtained by the use of a series of Dominant Load Parameters. For the DLA analysis of an FPSO, five Dominant Load Parameters have been identified as necessary to develop the Load Cases for the hull structure. These five DLP's are as follows:

i) Vertical Bending Moment, (*VBM*)

ii) Vertical Shear Force, (*VSF*)

iii) Horizontal Bending Moment

iv) Horizontal Shear Force

v) Vertical acceleration (V_{acc})

vi) Lateral acceleration (L_{acc})

vii) Roll angle (Φ)

The vertical bending moment is to be assessed for both hogging and sagging conditions. Vertical bending moment and shear force are especially to be evaluated in way of an internally mounted mooring turret. Accelerations are to be determined at a sufficient number of process equipment locations to represent accurately the load effects arising from their motion. As appropriate, roll angle calculations may include simultaneous effects of waves and winds.

Other DLPs that may be deemed critical can also be considered in the DLA analysis. The need to consider other DLPs or additional DLPs is to be determined in consultation with ABS.

7.1 Maximum *VBM*

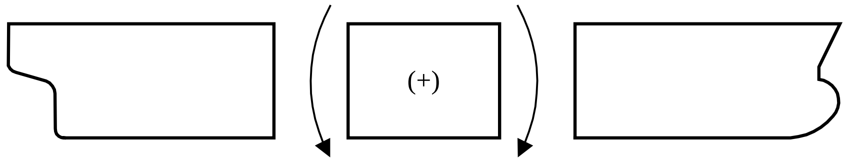
i) Vertical bending moment amidships, (+) hogging (see Section 2, Figure 1)

ii) Vertical bending moment amidships, (–) sagging

This DLP refers to the maximum wave-induced vertical bending moment amidships. For structural analysis load cases including this DLP, it is to be combined with the appropriate still-water VBM.

Note: Due account is to be given to the minimum design wave-induced VBM amidships as specified in Section 5A-1-2 of the *FPI Rules*.

FIGURE 1
Positive Vertical Bending Moment



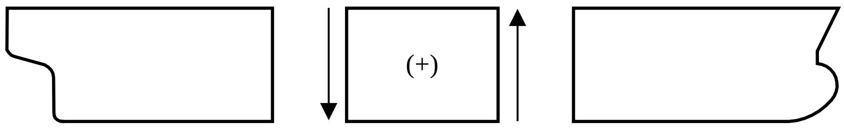
7.3 Maximum *VSF*

i) Vertical shear force, (+) upward shear force on a positive face (see Section 2, Figure 2)

ii) Vertical shear force, (–) downward shear force on a positive face

The shear force location is selected based on the still-water maximum shear force location for the loading condition considered.

FIGURE 2
Positive Vertical Shear Force



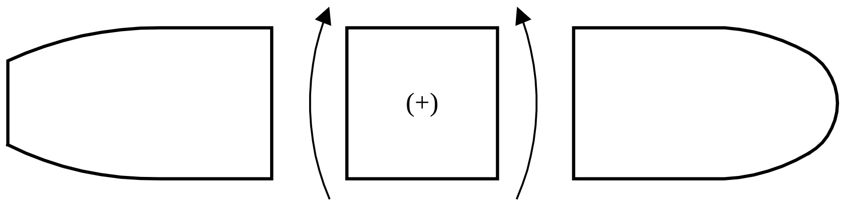
7.5 Maximum *HBM*

i) Horizontal bending moment amidships, (+) tension on the starboard side (see Section 2, Figure 3)

ii) Horizontal bending moment amidships, (–) tension on the port side

This DLP refers to the maximum wave-induced horizontal bending moment amidships

FIGURE 3
Positive Horizontal Bending Moment



7.7 Maximum *HSF*

i) Horizontal shear force, (+) toward port forward

ii) Horizontal shear force, (–) toward starboard aft

This DLP refers to the maximum wave-induced horizontal shear force at two locations ($^1/_4$ and $^3/_4$ of the vessel length).

7.9 Maximum V_{acc}

i) Vertical acceleration at Forward Perpendicular (FP) or turret center, (+) pitching up

ii) Vertical acceleration at Forward Perpendicular (FP) or turret center, (–) pitching down

This DLP refers to the maximum vertical acceleration at bow. Unless otherwise specified, the reference point may be taken at intersection of FP or turret center, centerline and waterline.

7.11 Maximum L_{acc}

i) Lateral acceleration at bow, in way of turret structure or at least to the main deck level, (+) port side;

ii) Lateral acceleration at bow, in way of turret structure or at least to the main deck level, (–) starboard side;

This DLP refers to the maximum lateral acceleration at bow. The lateral acceleration may be taken at the same reference point for vertical acceleration. Additional reference points for accelerations may need to be introduced depending on the configuration of the deck-mounted equipment.

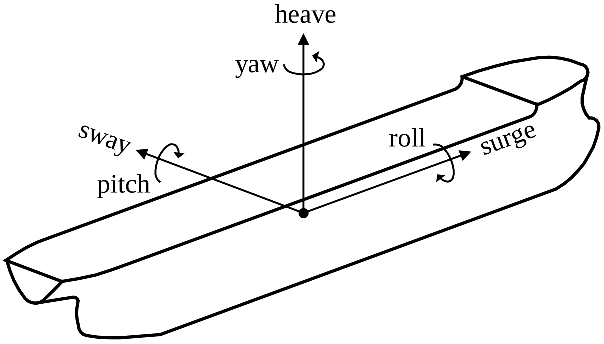
7.13 Maximum Roll Angle

i) Roll angle, (+) starboard down (see Section 2, Figure 4)

ii) Roll angle, (–) starboard up

The DLP refers to the maximum roll angle calculated with respect to the vessel center of gravity. In general, both conditions *i)* and *ii)* should be considered, as condition *i)* may not be exactly opposite to condition *ii)* in terms of the wave profile at the side shell. This may be significant when 'steady' heel angles are considered (say due to persistent winds).

FIGURE 4
Definition of Vessel Motions



9 Other Accompanying Instantaneous Load Components

The other accompanying instantaneous load components are the load components that are considered to be simultaneously acting on the vessel at the instant time when the Dominant Load Parameter reaches its maximum considering the equivalent design wave determined for each Load Case. The method to determine the equivalent wave for each Load Case is presented in Section 5. Calculation methods to develop the accompanying load components are presented in later sections as follows.

- Section 7 – external hydrodynamic pressures on hull,
- Section 8 – internal pressures at cargo and ballast tank wetted boundaries, and
- Section 9 –loads on lightship weight and equipment.

Mooring loads are another significant accompanying instantaneous load component to be included in the DLA Analysis.

11 Mooring Loads

Mooring loads are primarily elastic reactions resisting the combined effects of the wave-induced forces and motions of the FPSO hull. Those loads act as multiple local loads in the case of a spread mooring system, or as a concentrated load in the case of a turret mooring system. The effects of mooring can be considered in three regimes of hull motion: *first-order* (wave frequency), *second order* (low frequency or slowly varying), and *steady offset* due to wind and wave. These frequency-related components are to be obtained using a recognized vessel mooring analysis method. The total mooring line tension is then composed of the appropriate summation of the three component values. The concentrated or multiple loads, representing the turret or spread moorings, are to be applied to the structural analysis model of Section 11. The applied mooring loads are to be established for each loading scenario, wave direction and frequency, etc. The mooring loads can then be resolved into directions corresponding to the global axes of the structural analysis model.

The wave frequency loads on the hull are partially resisted by the applied mooring loads. The other two (lower) frequency-related mooring load components can be balanced by suitable elastic restraints at the ends of the global structural analysis model. The stiffness of each restraint should be based on the results of the vessel mooring analysis so as to produce consistent values of global system displacements.

As appropriate to the FPSO under consideration, determination of the mooring loads should also adequately model the interaction with risers, Dynamic Positioning (DP) System and design controlling shuttle tanker or support vessel mooring operations.

13 Impact and Other Loads

Other loads due to wave impacts on the bow and stern, flare and bottom slamming, tank fluid sloshing, vibrations, temperature gradients, and ice floe impacts affect local structural strength and have to be treated. These are not included in this document, but the loads resulting from these considerations are to be treated in accordance with the current *FPI Rules* requirements.

15 Selection of Load Cases

Load Cases are the cases to be investigated in the required structural analysis for DLA. Each Load Case is defined by a combination of operational loading conditions (Subsection 2/5), individual sets of global load and motion effects established in consideration of each of the specified DLPs (Subsection 2/7), other instantaneous loads accompanying the DLPs (Subsection 2/9), mooring system loads (Subsection 2/11), and an equivalent wave system (Section 5) for the particular DLP of interest.

For the DLP of interest, the equivalent design wave is to be determined for the linear seakeeping analysis and extreme value analysis (Subsection 4/7). With the derived equivalent design wave (Section 5), the instantaneous loads accompanying the DLP are to be determined from linear seakeeping analysis with nonlinear adjustment (Subsection 5/11) or directly from the nonlinear seakeeping analysis (Section 6).

A large number of Load Cases will result (operational loading conditions times the number of DLPs). Each Load Case is to be examined by performing the seakeeping and wave load analyses of Section 4. In general not all the Load Cases may need to be included in the FE structural analysis. If necessary because of computational limitations, the analyst may judiciously screen and select the most critical Load Cases for the comprehensive, global structural FE analyses of Section 11.

SECTION 3 Environmental Conditions

1 Basic Considerations

The Design Environmental Conditions (DEC) for an FPSO are specified in Section 3-2-3 of the *FPI Rules*. For offshore applications, a 100-year return period is ordinarily specified to establish design values for controlling environmentally induced effects.

Note: Environmentally induced effects means loads, environmental events (or actions such as a storm), responses, and combinations of these. The 100-year return period should be considered as a 'return period up to 100-years', since some load effects may reach maximum values for environmental actions with severities less than the 100-year level. Also the use of characterizing return periods reduced to no less than 50-years may be permitted, where a reduced design return period is allowed by the Governmental Authority having jurisdiction for the FPSO.

For an FPSO, environmentally induced loads are dominated by waves, which are characterized by significant heights, spectral shapes and associated wave periods. Design of an FPSO for operation at a selected installation site requires site-specific joint statistics of significant wave heights and periods. The joint statistics are ordinarily given in the form of a scatter diagram, which should be capable of reliably supporting 100-year return period estimates of the wave-induced effect under consideration.

The environmental condition for the transit route from the building or outfitting site (or shipyard where the conversion modifications are made) to the project site are to be determined for the design of a floating installation. As a minimum, a 10-year return period is to be considered, unless a weather routing plan is to be implemented for the voyage.

An FPSO with a **Disconnectable** classification notation is to be disconnected from the mooring system when (or before) reaching the limiting environment (having a return period less than 100-years). Hence, for such an FPSO, the limiting environment is the basis of the DLA Analysis.

The following Subsections provide information on ocean waves and the statistically based parameters that can be used to define the sea states. These include the characterization of a sea-state as spectra comprised of numerous individual wave components, and the use of spectral moments to establish sea state defining parameters such as significant wave height and wave periods.

3 Wave Spectra

The shape of a spectrum supplies useful information about the characteristics of the ocean wave system to which it corresponds. There exist many wave spectral formulations (e.g., Bretschneider spectrum, Pierson-Moskowitz spectrum, ISSC spectrum, ITTC spectrum, JONSWAP spectrum, Ochi-Hubble 6-parameter spectrum, etc.).

The Bretschneider spectrum or two-parameter Pierson-Moskowitz spectrum is the spectrum recommended for open-ocean wave conditions (e.g., the Atlantic Ocean).

$$S_\eta(\omega) = \frac{5H_s^2\omega_p^4}{16\omega^5}\exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right] \quad \text{in m}^2\text{/(rad/s) (ft}^2\text{/(rad/s))}$$

or

$$S_\eta(\omega) = \frac{H_s^2}{4\pi\omega^5}\left(\frac{2\pi}{T_z}\right)^4 \exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4\omega^{-4}\right] \quad \text{in m}^2\text{/(rad/s) (ft}^2\text{/(rad/s))}$$

where

ω_p	=	modal (peak) frequency corresponding to the highest peak of the spectrum , in rad/s
H_s	=	significant wave height, in m (ft)
ω	=	circular frequency of the wave, in rad/s
T_z	=	average zero up-crossing period of the wave, in seconds

The JONSWAP spectrum is derived from the Joint North Sea Wave Project (JONSWAP) and constitutes a modification to the Pierson-Moskowitz spectrum to account for the regions that have geographical boundaries that limit the fetch in the wave generating area (e.g., the North Sea).

$$S_\eta(\omega) = \frac{5H_s^2\omega_p^4}{16\omega^5}\exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^a(1-0.287\ln\gamma) \quad \text{in m}^2/(\text{rad/s}) \ (\text{ft}^2/(\text{rad/s}))$$

where

$$a = \exp\left[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right]$$

$$\sigma = \begin{cases} 0.07 & \text{when } \omega \le \omega_p \\ 0.09 & \text{when } \omega > \omega_p \end{cases}$$

γ	=	peakedness parameter (typically 1~7), representing the ratio of the maximum spectral density to that of the corresponding Pierson-Moskowitz spectrum. This means that for $\gamma = 1$ the JONSWAP spectrum defaults to the Pierson-Moskowitz spectrum

Here, the factor $(1 - 0.287 \ln \gamma)$ limits its practical application, because for $\gamma = 32.6$, the spectral value from above formula becomes zero. For a peakedness larger than 7, it is recommended that an adjustment to the formula has to be made. The formula of the JONSWAP spectrum can be then given by:

$$S_\eta = \frac{\alpha g^2}{\omega^5}\exp\left[-1.25\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^a \quad \text{in m}^2/(\text{rad/s}) \ (\text{ft}^2/(\text{rad/s}))$$

where

γ	=	peakedness parameter, representing the ratio of the maximum spectral density to that of the corresponding Pierson-Moskowitz spectrum. This means that for $\gamma = 1$ the JONSWAP spectrum defaults to the Pierson-Moskowitz spectrum
g	=	gravitational acceleration = 9.8 m/s^2 (32.2 ft/s^2)
α	=	parameter to be determined as a function of the significant wave height, through the expression provided in the formula of H_s below, since the integral is a function of α

$$H_s = 4\sqrt{\int_0^\infty S_\eta(\omega)d\omega} \quad \text{m (ft)}$$

The Ochi-Hubble 6-Parameter spectrum covers shapes of wave spectra associated with the growth and decay of a storm, including swells. As may be seen in some wave records, the variability in the form of spectra can be great. Multi-modal spectra are common, and a single-modal Bretschneider form may not match the shape of such spectrum in an accurate manner. In order to cover a variety of shapes of wave spectra associated with the growth and decay of a storm, including the existence of swell, the following 6-parameter spectrum was developed by Ochi and Hubble:

$$S_\eta(\omega) = \frac{1}{4}\sum_{j=1}^{2}\frac{\left(\frac{4\lambda_j+1}{4}\omega_{pj}^4\right)^{\lambda_j}}{\Gamma(\lambda_j)}\times\frac{H_{sj}^2}{\omega^{4\lambda_j+1}}e^{-\frac{4\lambda_j+1}{4}(\omega_{pj}/\omega)^4} \quad \text{in m}^2\text{/(rad/s) (ft}^2\text{/(rad/s))}$$

where j = 1, 2 stands for lower (swell part) and higher (wind seas part) frequency components. The six parameters, H_{s1}, H_{s2}, ω_{p1}, ω_{p2}, λ_1, λ_2, are determined numerically to minimize the difference between theoretical and observed spectra.

The design sea state may come from intensification of the local wind seas (waves) and/or swell propagating with different directions. In general, both are statistically independent. The wind seas are often characterized with the Bretschneider or the JONSWAP spectrum while the Gaussian distribution function can be used to describe swells. The spectral formulation for the swell can be represented by the Gaussian-Swell spectrum:

$$S_\eta(\omega) = \frac{(H_s/4)^2}{2\pi\delta\sqrt{2\pi}}\exp\left[-\frac{(\omega-\omega_p)^2}{2(2\pi\delta)^2}\right] \quad \text{in m}^2\text{/(rad/s) (ft}^2\text{/(rad/s))}$$

where

H_s	=	significant wave height, in m (ft)
δ	=	peakedness parameter for Gaussian spectral width

5 Wave Spreading

There is a simple case where the observed wave pattern at a fixed point neglects different directions of wave components. This is equivalent to assuming that all wave components travel in the same direction. These waves are called 'long-crested' since the wave motion is two-dimensional and the wave crests are parallel. Waves produced by swell are almost long-crested in many situations since the crests of the wave system observed outside the storm area (beyond the fetch area) which produced them become nearly parallel as the observation point recedes from the storm area.

The waves in the ocean are more likely to travel in many directions; therefore, the combined wave system will be short-crested. The spreading of wave directions should be taken into account to describe the short-crestedness.

The wave energy spectrum can be obtained by integrating the spreading wave spectrum over the range of directions from $-\theta_{max}$ to $+\theta_{max}$ (θ_{max} can be typically taken as 90°). The general expression for wave spreading is given by

$$S_\eta(\omega) = \int_{-\theta_{max}}^{\theta_{max}} S_\eta(\omega,\theta)\,d(\alpha-\theta)$$

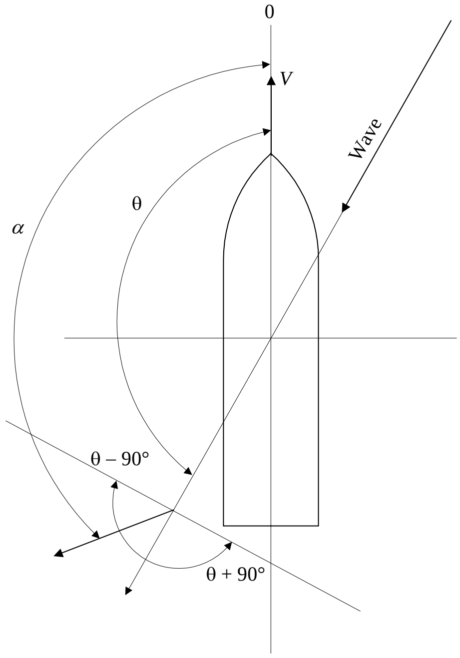
where α denotes the predominant wave direction and θ is the wave spreading angle, as shown in Section 3, Figure 1.

In general, the cosine spreading function for the wave spectrum can be used as:

$$S_\eta(\omega,\theta) = D\cos^n\left[\frac{\pi}{2\theta_{max}}(\alpha-\theta)\right]S_\eta(\omega)$$

where D is a normalizing constant that ensures that the spreading function $G(\omega,\alpha-\theta)$ integrates to 1 and n is the wave spreading parameter, which is a positive integer.

FIGURE 1
Definition of Spreading Angles



7 Environmental Data

7.1 General

Section 1-1-4 of the *FPI Rules* requires the submission of authoritative documentation concerning design environmental data. The environmental data, pertinent resulting environmentally induced effects, and the formulations or models for these are to be appropriately documented. The environmental data and resulting effects are to be given in ways that are compatible with the DLA Analysis method of this Guide. The sources of the data, and the data's expected reliability, and the expected reliability of the predicted environmentally induced load effects should be documented in the submitted report. It is to be noted that, as per Section 1-1-4 of the *FPI Rules*, design environmental data are required for conditions representing both the FPSO transit condition and conditions at the FPSO installation site.

7.3 Special Wave Data Needs

As mentioned in Subsection 3/1, waves ordinarily produce the dominant environmentally induced effects on an FPSO. Therefore the DLA Analysis primarily relies on wave data, and the wave data should be compatible with the stochastic response and extreme value prediction methods applied to ship-type structures. However, given the differences in the operating profiles and design features of an FPSO compared to a ship and site-specific considerations, it should be noted that special emphasis may need to be given to the directionality of waves because of the mooring system, the recognition of 'short-crestedness' (wave energy spreading) effects, and interactions between dominant wave directions and other environmental actions (e.g., persistent ocean current or winds may alter the presumed wave induced 'weathervaning' behavior of the FPSO).

7.5 Wave Data for DLA Analysis

To determine the extreme values of DLPs, two types of wave data may be used (i.e., long-term and short-term wave data). The long-term wave data consists of a wave scatter diagram recorded at a certain location over a long period (years) of time. In general, the wave scatter diagram provides the probability or number of occurrence of sea states in a specified ocean area. For each single sea state, a wave scatter diagram is stored together with its associated directional probability distribution (wave rosette). The short-term wave data (i.e., related to a particular sea state) can be given to represent a design storm condition. Generally, this kind of storm lasts only a certain period of time, say, 3 hours, but the effects of single storms may control the strength design of the FPSO structure. This kind of wave data is to be provided by clients to meet the Design Environmental Condition (DEC) specified in Section 3-2-3 of the *FPI Rules*. A minimum return period of 100 years is typically required. A minimum return period of 50 years may be specially considered if it is accepted by the coastal state, as specified in Section 3-2-3 of the *FPI Rules*.

For transit condition, a minimum return period of 10 years is required. A global wave data may be necessary to provide wave environment conditions along a transit route. Upon client's request, ABS SEAS software with its global wave database may provide a convenient way to obtain the needed wave conditions for transit.

SECTION 4 Analyses for Vessel Motion, Wave Load, and Extreme Value

1 Overview

This Section lists essential features about the calculation of vessel motions and wave induced loads. It is expected that such calculations will be made using the Spectral-based approach, which by definition relies on the use of Response Amplitude Operators (RAO's). Each RAO is to be calculated for regular waves of unit amplitude for ranges of wave frequencies and wave headings that will be given below. These RAOs will also be used to determine the equivalent design wave system.

This Section also specifies the expected outcome of analysis to establish an Extreme Value of a Dominant Load Parameter. Still-water load determination is described first, followed by the seakeeping analysis procedure to determine the dynamic vessel motion and wave load RAOs.

3 Still-water Loads

For each operational loading condition (see Subsection 2/5), with a vessel's hull geometry offset, lightship and deadweight as input data, the hull girder shear force and bending moment distributions in still water are to be computed at a sufficient number of transverse sections along the hull's length, in order to accurately take into account discontinuities in the weight distribution of the vessel.

At a statically balanced loading condition, the displacement, trim and draft, Longitudinal Center of Buoyancy (LCB), transverse metacentric height (GM_T), longitudinal metacentric height (GM_L) and still-water bending moment (SWBM) should be checked to meet the following tolerances:

Displacement:		±1%
Trim:		±0.5 degrees
Draft:		
	Forward	±1 cm (0.4 in.)
	Mean	±1 cm (0.4 in.)
	Aft	±1 cm (0.4 in.)
LCB:		±0.1% of length
GMT:		±2%
GML:		±2%
SWBM:		±5%

Additionally, the longitudinal locations of the maximum and the minimum still-water bending moments and, if appropriate, that of zero SWBM should be checked to assure proper distribution of the SWBM along the vessel's length.

5 Essential Features of Spectral-based Analysis of Motion and Wave Load

5.1 General Modeling Considerations

The model of the hull should include the masses of the topside equipment and the equipment's supporting structure. The model is also to consider the interaction with the mooring system; and as appropriate, the effects of import or export risers, the effects of the Dynamic Positioning system, and the operation of offloading or support vessels. There is also to be sufficient compatibility between the hydrodynamic and structural models (e.g., the ratio of the number of panels not greater than two for the wetted hull surface area) so that the application of fluid pressures onto the finite element mesh of the structural model is done appropriately.

For the load component types and structural responses of primary interest in DLA, analysis software formulations derived from linear idealizations are deemed to be sufficient. However, the designer/ analyst is encouraged to employ enhanced methods, especially to incorporate non-linear loads (for example hull slamming, pressure near and above the mean waterline, hog and sag bending moments, green water on deck), if this proves to be necessary for the specific design being evaluated. The analyst needs to be aware that the adequacy of the selected software is to be demonstrated to the satisfaction of ABS.

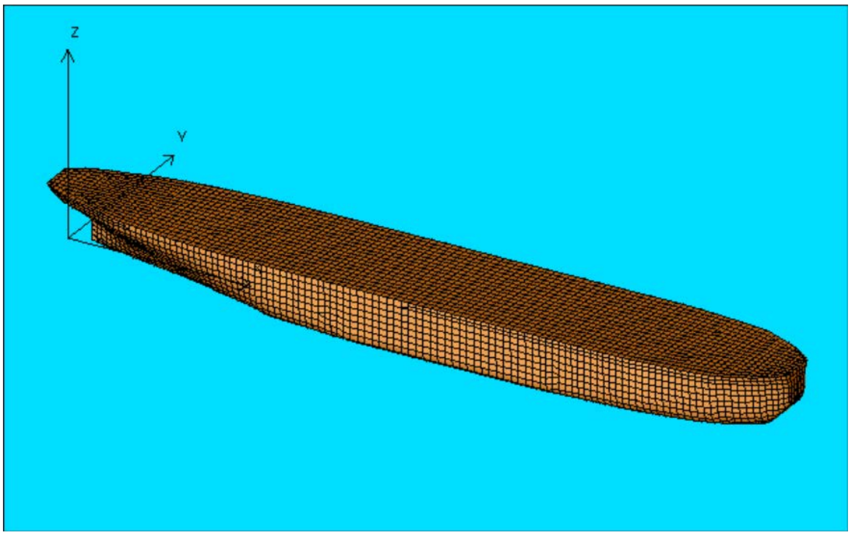
5.3 Diffraction-Radiation Methods

Computations of the wave-induced motions and loads are to be carried out through the application of seakeeping analysis codes utilizing three-dimensional potential flow based diffraction-radiation theory. All six degrees-of-freedom rigid-body motions of the vessel are to be accounted for. The water depth is to be considered if its effect deemed to be critical to determine the vessel responses. These codes, based on linear wave and motion amplitude assumptions, make use of panel methods (or boundary element methods) with source or source/dipole singularities on panels over the mean wetted surface of the hull, on which the hydrodynamic pressures are computed.

5.5 Panel Model Development

Boundary element methods, in general, require that the mean wetted part of the vessel hull surface be discretized into a large number of panels (see Section 4, Figure 1). The panel mesh should be fine enough to resolve the radiation and diffraction waves with reasonable accuracy.

FIGURE 1
Panel Model for Diffraction-Radiation Analysis



5.7 Roll Damping Model

The roll motion of a vessel in beam or oblique seas is greatly affected by the viscous roll damping of the hull and its appendages, especially near the roll resonance. For seakeeping analysis based on the potential flow theory, proper viscous roll damping modeling should be introduced. Experimental data or empirical methods for the roll damping can be used for the determination of viscous roll damping.

In general, viscous damping depends on roll motion and velocity and is thus non-linear in character. Difficulties in predicting roll damping are due to its nonlinear characteristics. For simplicity, the non-linear damping may be replaced by an equivalent linearized damping.

The sources for viscous damping are due to hull friction and appendages such as bilge keels and rudders. Viscous roll damping should consider all these effects in the seakeeping analysis. If this information is not available, 10% of critical damping may be used for the overall viscous roll damping.

5.9 Mooring Line and Riser Modeling

The effects of mooring and riser may be considered in three regimes of vessel motion: first-order (wave frequency), second-order (low frequency or slowly varying), and steady offsets in combination with wind and current actions. In general, the effect of mooring lines and risers may not be significant for determining the RAOs in the wave frequency regime. On the other hand, the low frequency responses affected by the mooring lines dominate the mean offset positions in surge, sway and yaw. This change in the mean offset is not the primary concern for the DLA analysis. As a common practice, if necessary, the additional stiffness due to a mooring system can be modeled as linear elastic springs applied to the vessel.

5.11 Vessel Motion and Wave Load Response Amplitude Operators

RAOs are to be calculated for the DLPs for each Load Case, selected per Subsection 2/15. Only these DLPs need to be considered for the calculation of extreme values. The RAOs should represent the pertinent range of wave headings (β), in increments not exceeding 15 degrees.

It is important that a sufficiently broad range of wave frequencies are considered based on the site-specific wave conditions. The recommended range is 0.2 radians/second (rad/s) to 1.8 rad/s in increments of 0.05 rad/s.

The worst wave frequency-heading (ω,β) combination is to be determined from an examination of the RAOs for each DLP. Only the heading $\beta_{\max}$ and the wave frequency ω_e at which the RAO of the DLP is a maximum need to be used in further analysis. In general, it may be expected that *VBM*, *VSF* and V_{acc} will be maximum in head and bow seas, while maximum L_{acc} and Φ are realized in oblique seas. Precise headings at which these are maximum, can be determined from the RAO analysis output.

In addition, RAOs for the other load components accompanying the DLPs (see Subsection 2/9) are to be determined.

7 Extreme Values for DLA Analysis

Extreme value analysis is to be performed for each DLP to determine maximum values to be used in the DLA Analysis. Preference is given to an Extreme Value method that follows the so-called long-term approach commonly used for ship structures. However, the use of a validated short-term extreme value approach, which is appropriate to the vessel type and installation site's environmental data, should also be considered. The supplementary use of such a short-term approach to confirm or test the sensitivity of the long-term based design values is required. The result of the short-term approach cannot be used to reduce the long-term extreme value. If the short-term result is significantly larger, the long-term extreme value is to be further studied and validated. The environments specified for use in the short-term approach are "response based" (i.e., a 100-year design storm event is one that leads to the maximum responses expected to occur in 100-years).

Note: A useful reference to explain concepts and terminology associated with extreme value analysis is "Wave Statistics for the Design of Ships and Ocean Structures", by M. K. Ochi, SNAME Transactions, Vol. 86, 1978, pp. 47-76.

The procedure for calculating the long-term extreme value corresponding to a particular return period across a combined scatter-diagram-heading distribution of sea states is described below:

For each entry in the wave scatter diagram for each heading, the spectral moment of the response spectra can be given by:

$$m_n = \int_0^\infty \omega^n |H_i(\omega)|^2 S_\eta(\omega) d\omega \qquad n = 0, 1, 2\ldots$$

where $|H_i(\omega)|$ is the RAO of the vessel response. The variance (zeroth moment) of a response spectrum can be generalized to include the direction of vessel heading relative to predominant wave direction α and wave spreading angle θ as follows:

$$\sigma_i^2(\alpha) = m_0 = \int_{-\pi/2}^{\pi/2} \int_0^\infty |H_i(\omega, \alpha - \theta)|^2 S_\eta(\omega, \theta) d\omega d\theta$$

The other spectral moments can be also generalized in a similar manner over the wave spreading angle. The number of positive maxima per unit time for a Gaussian process is given by:

$$\bar{n} = \frac{1}{4\pi}\left(\frac{1+\sqrt{1-\varepsilon^2}}{\sqrt{1-\varepsilon^2}}\right)\sqrt{\frac{m_2}{m_0}}$$

where the bandwidth parameter ε is given by:

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}$$

For any scatter-diagram-heading contribution, the number of response cycles will be calculated during the design lifetime of the vessel. The contribution that any one scatter-diagram-heading contribution makes to the long-term exceedance distribution of the response is then the sum of Gaussian distributions multiplied by the normalized number of response cycles, so that the long-term probability that the response will exceed a particular value $\bar{x}$ is calculated from the equation:

$$\frac{\sum_m \sum_k \bar{n} p_m p_k p_{\bar{x}}(\bar{x})}{\sum_m \sum_k \bar{n} p_m p_k} = \frac{1}{N} = Q$$

where the sum over m and k is over the entire set of scatter diagram and wave heading contributions; $\bar{n}$ depends on each scatter-diagram entry at each heading; p_m is the probability of occurrence from the wave scatter table; and p_k is the weighing factor for heading to waves from the wave rosette in a given site area. The distribution of probability of exceedance $p_{\bar{x}}(\bar{x})$ for wide-banded Gaussian processes given by:

$$p_{\bar{x}}(\bar{x}) = \begin{aligned} &1 - \frac{2}{1+\sqrt{1-\varepsilon^2}}\left[-\frac{1}{2}\left(1-\sqrt{1-\varepsilon^2}\right) + \Phi\left(\frac{\bar{x}}{\varepsilon\sqrt{m_0}}\right) - \sqrt{1-\varepsilon^2}\,\exp\left\{-\frac{1}{2}\left(\frac{\bar{x}}{\sqrt{m_0}}\right)^2\right\}\right. \\ &\left.\times\left\{1 - \Phi\left(-\frac{\sqrt{1-\varepsilon^2}}{\varepsilon}\frac{\bar{x}}{\sqrt{m_0}}\right)\right\}\right] \end{aligned}$$

where

$$\Phi(u) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{u} \exp\left(-\frac{u^2}{2}\right) du = \frac{1}{2} + \frac{1}{\sqrt{2\pi}}\int_0^u \exp\left(-\frac{u^2}{2}\right) du$$

For narrow-banded cases ($\varepsilon = 0$), the exceedance distribution function for the peak values becomes:

$$p_{\bar{x}}(\bar{x}) = \exp\left(-\frac{\bar{x}^2}{2m_0}\right)$$

which is a Rayleigh distribution. Unless specified, the Rayleigh distribution approximation would be good enough in most single-modal spectral situations. However, in the specific site where the environmental condition is described as a combination of swell and wind seas, the wide-banded Gaussian distribution to represent the multi-modal spectra should be appropriately introduced.

To determine the probability level corresponding to the design life time or return period, the total number of response peaks N expected in the design lifetime T (years) is to be calculated from the following formula:

$$N = T \times 365 \times 24 \times 3600 \times \sum_m \sum_k \overline{n} p_m p_k$$

where T is the design return period or total years exposure time to the seas. The long-term extreme values of $\bar{x}$ that make the expression of probability of exceedance equal to Q are those corresponding to the design return period.

The relevant value to be obtained from the above long-term analysis is the long-term extreme value having a 100-year Return Period for site-specific condition, or 10-year Return Period for transit condition, or 1-year Return Period for inspection/repair and tank testing conditions. The return period of 100 years for site is, for example, approximately equivalent to a probability level of $Q = 10^{-8.7}$, assuming an average period to be 7 sec. (Refer to Subsection 3/1 concerning reduced return periods.) However, considering the operational considerations of weathervaning vessels, the long-term probability level of V_{acc}, L_{acc} and roll angle (Φ) may be reduced to $10^{-6.5}$ (equivalent to 1-year return period) in beam or oblique sea conditions

In specific locations, the environmental condition can be given in combination of swell and wind seas with different directionality. In this case, the two response spectra can be added and then the standard deviation of the combined spectrum can be determined by:

$$\sigma_c = \sqrt{m_0} = \sqrt{\sigma_{wave}^2 + \sigma_{swell}^2}$$

This procedure tends to be rational in evaluating the extreme response calculation compared to the simple summation in which the extreme values from the two processes are simply added.

SECTION 5 Equivalent Design Wave

1 General

An equivalent design wave is a regular sinusoidal wave that simulates the extreme value of the Dominant Load Parameter under consideration. The equivalent design wave is characterized by its: amplitude, length (or frequency), heading, and crest position (or phase angle) relative to the Longitudinal Center of Gravity (LCG) of the hull. For each Load Case, an equivalent design wave is determined which simulates the magnitude and location of the extreme value of the Dominant Load Component of the Load Case.

The procedure to be used to determine the equivalent design wave's characterizing parameters is given below in Subsections 5/3 to 5/7. Subsection 5/9 describes the formulations to establish the magnitude and distribution of the other load components accompanying the extreme value of the Dominant Load Component in a Load Case.

3 Equivalent Wave Amplitude

The amplitude of the equivalent design wave is to be determined by dividing the extreme value of a DLP (see Subsection 4/7) under consideration by the RAO value of that DLP occurring at the wave frequency and wave heading corresponding to the maximum amplitude of the RAO.

The Equivalent Wave Amplitude (EWA) for the j-th Dominant Load Parameter is given by:

$$a_w = \frac{MPEV_j}{\max RAO_j}$$

where

a_w	=	equivalent wave amplitude of the j-th Dominant Load Parameter, see Section 5, Figure 1
$MPEV_j$	=	Most Probable Extreme Value of the j-th DLP at a probability level equivalent to the design Return Period (e.g., 100-years for site and 10-years for transit), See Section 4
$Max.\ RAO_j$	=	maximum amplitude of the j-th Dominant Load Parameter's RAO

5 Wave Frequency and Length

The equivalent wave frequency and length for each DLP are determined from the lifetime maximum value of the DLP's RAO for each considered heading angle. When the RAO is maximum, the corresponding peak frequency is denoted, ω. The wavelength of the equivalent wave system can be determined from deep water approximation by:

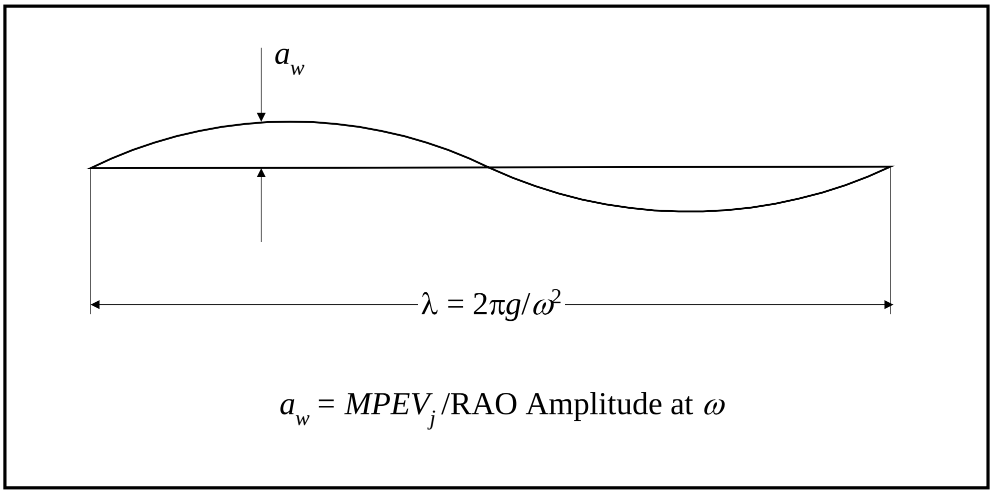
$$\lambda = (2\pi g)/\omega^2$$

where

λ	=	wavelength
g	=	gravitational acceleration = 9.8 m/s^2 (32.2 ft/s^2)
ω	=	wave frequency

For finite or shallow water depth, if necessary, the equivalent wave length can be calculated by the corresponding dispersion relation, which determines wave length for given values of the water depth and frequency.

FIGURE 1
Determination of Equivalent Wave Amplitude



7 Phase Angle and Wave Crest Position

With the wavelength, amplitude and direction from Subsections 5/3 and 5/5, the wave crest position is calculated with respect to the LCG of the hull by:

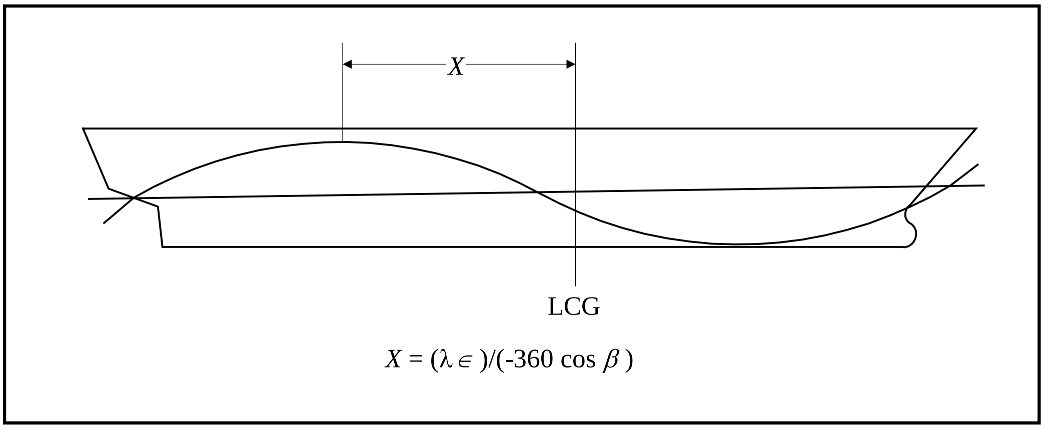
$X = (\lambda \in)/(-360 \cos \beta)$

where

X	=	wave crest position with respect to the LCG for which the DLP is at its extreme value
λ	=	wave length
$\in$	=	phase angle of DLP in degrees
β	=	wave heading

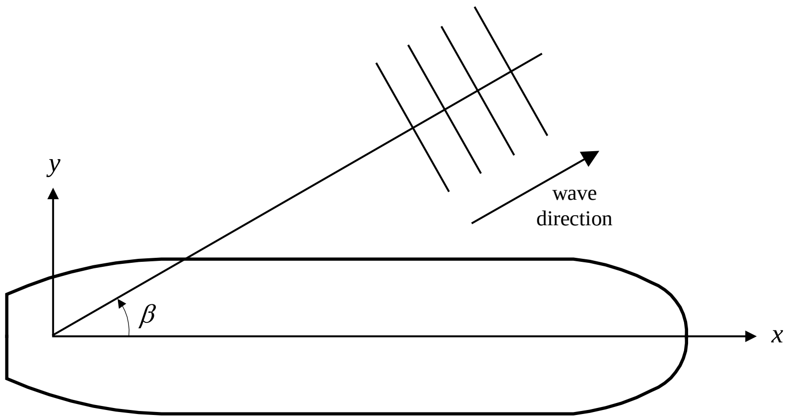
Section 5, Figure 2 illustrates the crest position X.

FIGURE 2
Equivalent Wave Length and Crest Position



The definition of wave heading is illustrated in Section 5, Figure 3.

FIGURE 3
Definition of Wave Heading



It should be noted that X is undefined in beam seas (β = 90° or 270°). Instead the wave crest position from the centerline of the vessel in the y (transverse) direction is given by:

$Y \quad = \quad (\lambda \in)/(-360 \sin \beta)$

9 Instantaneous Load Components in a Load Case

In this Guide, nonlinear seakeeping analysis (see Section 6) can be used to determine loads on the vessel subject to the equivalent design waves. As an alternative to the standard approach, the vessel motion and wave load RAOs can be used to determine instantaneous design loads based on linear seakeeping theory. In this case, for the equivalent wave, the longitudinal distribution of the other wave-induced motions, accelerations and the other instantaneous Load Components accompanying the Dominant Load Component in a Load Case are calculated using the following equation:

$$M_i = RAO_i\, a_w \cos(\in_j - \in_i)$$

where

M_i	=	instantaneous *i*-th (other) load effect being considered (i.e., vertical bending moment and shear force, external and internal pressures, or acceleration at selected points)
RAO_i	=	amplitude of the *i*-th (other) load component's RAO
a_w	=	equivalent wave amplitude of the *j*-th Dominant Load Parameter
$\in_i$	=	RAQ phase angle of the *i*-th accompanying load component
$\in_j$	=	RAO phase angle of the *j*-th Dominant Load Parameter

The above equation is to be applied to motions, accelerations, hydrodynamic pressures, and the bending moments and shear forces at the selected stations and the internal tank pressures. The specific use of this approach for particular load components is given in the next several sections.

11 Nonlinear Pressure Adjustment Near the Waterline

In case the vessel motion and wave loads RAOs are used to determine the design loads, the linear seakeeping theory may provide the hydrodynamic pressure distribution below the mean waterline only. In this case, the linear pressure distribution will result in wave-induced hogging and sagging moments having the same magnitude with opposite signs. Therefore, a suitable adjustment is required for the linear pressure distribution, especially near the mean waterline in order to better reflect the nonlinear nature of the pressure distribution above and below the mean waterline.

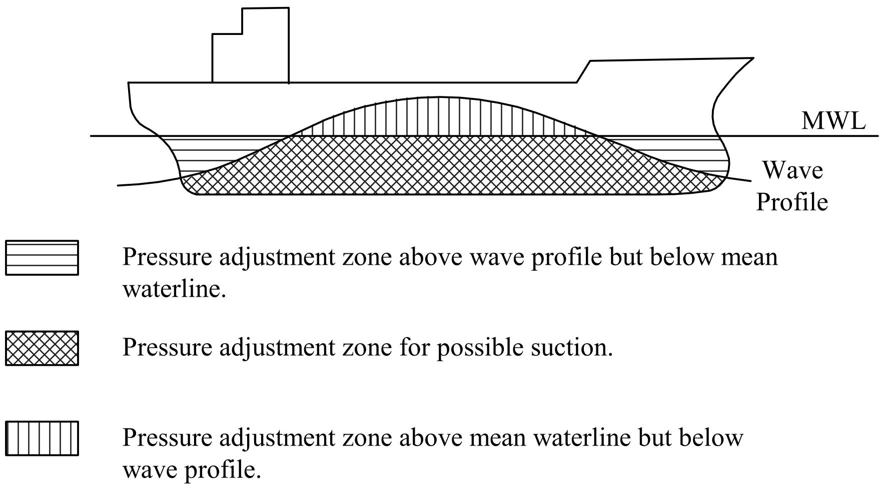
i) The pressure value must be set to zero at any pressure point above the wave surface profile but below the mean waterline.

ii) Total (hydrostatic plus hydrodynamic) suction pressure at any pressure point below the mean waterline must be set to zero. This adjustment can be done by simply setting the hydrodynamic pressure to the negative value of the hydrostatic pressure at the same point.

iii) The pressure at any point above the mean waterline but below the wave surface profile needs to be accounted for in wave load calculations. This adjustment can be achieved by adding in a hydrostatic pressure calculated based on the water head measured from the wave surface profile to the pressure point. This pressure addition will be treated as wave induced pressure although it is calculated from a static pressure formula.

Section 5, Figure 4 illustrates the aforementioned pressure adjustment zones below and above the mean waterline. The wave-induced hogging and sagging moments will usually be different in both values and signs after these pressure adjustments. It should be noted that the above pressure adjustments need to be applied to all load cases, regardless of the DLPs defining the load cases.

FIGURE 4
Pressure Adjustment Zones



SECTION 6 Nonlinear Vessel Motion and Wave Load

1 General

For the equivalent design waves defined in Section 5, a nonlinear seakeeping analysis may be performed to calculate the nonlinear vessel motions and wave loads. In this Guide, nonlinear time-domain seakeeping analysis is recommended to effectively account for instantaneous nonlinear effects during the time simulation. ABS NLOAD3D or equivalent computer programs may be used to perform these calculations.

3 Nonlinear Seakeeping Analysis

3.1 Concept

Under severe design wave conditions, the vessel motions and wave loads are expected to be highly nonlinear, mainly due to the hydrodynamic interaction of the incident waves with the hull geometry above the mean waterline.

Linear seakeeping analysis considers only the hull geometry below the mean waterline as a linear approximation. Nonlinear seakeeping analysis, as a minimum requirement, is to consider the hull geometry above the mean waterline in consideration of:

i) Nonlinear hydrostatic restoring force, and

ii) Nonlinear Froude-Krylov force

which are acting on the instantaneous wetted hull surface below the exact wave surface at every time step during the time simulation.

3.3 Benefits of Nonlinear Seakeeping Analysis

In general, linear seakeeping analysis provides hydrodynamic pressure on the hull surface below the mean waterline only. The linear hydrodynamic pressure will give the wave-induced hogging and sagging moments with same magnitudes but opposite signs. Therefore, an appropriate nonlinear correction on the hydrodynamic pressure is required to be used as hydrodynamic loadings for DLA analysis. In the DLA based on linear seakeeping analysis, a quasi-static wave profile correction (described in Subsection 5/11) is required to adjust the pressure distribution near the mean waterline.

In the advanced DLA analysis based on nonlinear seakeeping analysis, however, the quasi-static wave profile correction is not required. The instantaneous nonlinear hydrostatic and Froude-Krylov forces are directly accounted for during the time simulation, which provides a more accurate calculation of the hydrodynamic pressure distribution on the actual wetted surface.

5 Modeling Consideration

5.1 Mathematical Model

For nonlinear seakeeping analysis in the time domain, two alternative mathematical formulations may be used: the mixed-source formulation and the Rankine source formulation. The mixed-source formulation requires a matching surface, which is the outer surface surrounding the hull and free surfaces. In the mixed-source formulation, the inner fluid domain inside the matching surface is formulated by a Rankine source, while the outer fluid domain outside the matching surface is formulated by a transient Green function. The velocity potentials of the inner and outer domains should be continuous at the matching surface.

The Rankine source formulation requires Rankine source distribution on the hull and free surfaces only. The Rankine source formulation requires a numerical damping beach around the outer edge of the free surface in order to absorb the outgoing waves generated by the hull. The size and strength of the damping beach are to be determined to effectively absorb the outgoing waves with a broad range of wave frequencies.

The Rankine source formulation may require larger free surface domain than the mixed-source formulation. The entire free surface domain of the Rankine source formulation is to be at least four times the vessel length, including the damping beach. In terms of computational effort, however, the Rankine source formulation can be more efficient than the mixed-source formulation because it does not require the use of the time-consuming transient Green function on the matching surface

5.3 Numerical Station-keeping Model

For the time-domain seakeeping analysis, a numerical station-keeping model is required for the simulation of surge, sway and yaw motions. In general, the surge, sway and yaw motions of the vessel occur in the horizontal plane where there exists no hydrostatic restoring force or moment. Without any restoring mechanism, the time simulation of the surge, sway and yaw motions may result in drift motions due to any small transient disturbances or drift forces. In order to prevent unrealistic drift motions in the horizontal plane, a numerical station-keeping model is to be introduced for the motion simulation in the time domain.

As a numerical station-keeping model, a soft-spring system may be used for simplicity. The numerical soft springs are similar to the soft springs used in the experimental setup connecting a model to the towing carriage. These springs are to provide restoring forces and moments sufficient to prevent large drift motion of the model without affecting the wave-induced vessel motions. The stiffness of the soft spring is determined so that the natural frequencies of surge, sway and yaw modes fall far below the wave frequency range. Unlike the rudder-control system, the soft-spring system can be more reliable and effective in the extreme design wave conditions.

7 Nonlinear Instantaneous Load Components

From the nonlinear seakeeping analysis, the nonlinear instantaneous vessel motions and wave loads are to be determined at the instant when each DLP under consideration reaches its maximum.

The vessel motions are to include all six degrees-of-freedom rigid-body motions. For FPSOs, the following DLPs are to be considered: vertical acceleration at bow, lateral acceleration at bow, and roll motion (see Subsection 2/7).

The wave loads are the sectional loads acting on the hull along the vessel length. The nonlinear wave loads are obtained by integrating the nonlinear hydrostatic and hydrodynamic pressure acting on the instantaneous wetted hull surface and the inertial forces acting on the mass distribution of the cargo and lightship structure along the vessel length. For FPSOs, the following DLPs are to be considered: vertical bending moment amidships and vertical shear force at the still-water maximum shear force location (see Subsection 2/7).

To determine the nonlinear instantaneous load components accompanying the DLP, a specific instant of time is to be selected when the DLP under consideration reaches its maximum from the response time history of the DLP. The duration of time simulation is to be sufficiently long enough so that the response of the DLP reaches a steady state. It is recommended that the time simulation length is to be longer than twenty response cycles and that the first half of the time history be treated as transient response.

SECTION 7 External Hydrodynamic Pressure

1 General

The external hydrodynamic pressures on the wetted hull surface are to be calculated for each Load Case defined by the DLP under consideration (see Subsection 2/7). The external hydrodynamic pressure is to include the pressure components due to undisturbed incoming waves, diffracted waves due to existence of the vessel and the radiated wave components due to vessel motion. The components of the hydrodynamic pressure are to be calculated from the seakeeping analysis of Subsection 4/5.

3 External Hydrodynamic Pressures Accompanying the Dominant Load Component

For each Load Case, the simultaneously-acting external pressures accompanying the DLP are to be calculated at the specific time instant when the DLP reaches its maximum value. The simultaneously-acting pressures are to be calculated from the linear seakeeping analysis with nonlinear pressure adjustments (see Subsections 5/9 and 5/11) or directly from the nonlinear seakeeping analysis (see Section 6).

The external pressure is calculated either as a complex number or in terms of the amplitude and phase. Then, 'simultaneously' acting pressures over the wetted surface can be represented in the form:

$$P = A\, a_w \cos\left(\epsilon_j - \epsilon_i\right)$$

where

P	=	'simultaneous' external hydrodynamic pressure
A	=	amplitude of the external hydrodynamic pressure RAO
a_w	=	equivalent wave amplitude of the j-th Dominant Load Parameter
ϵ_i	=	phase angle of external hydrodynamic pressure RAO
ϵ_j	=	RAO phase angle of the j-th Dominant Load Parameter

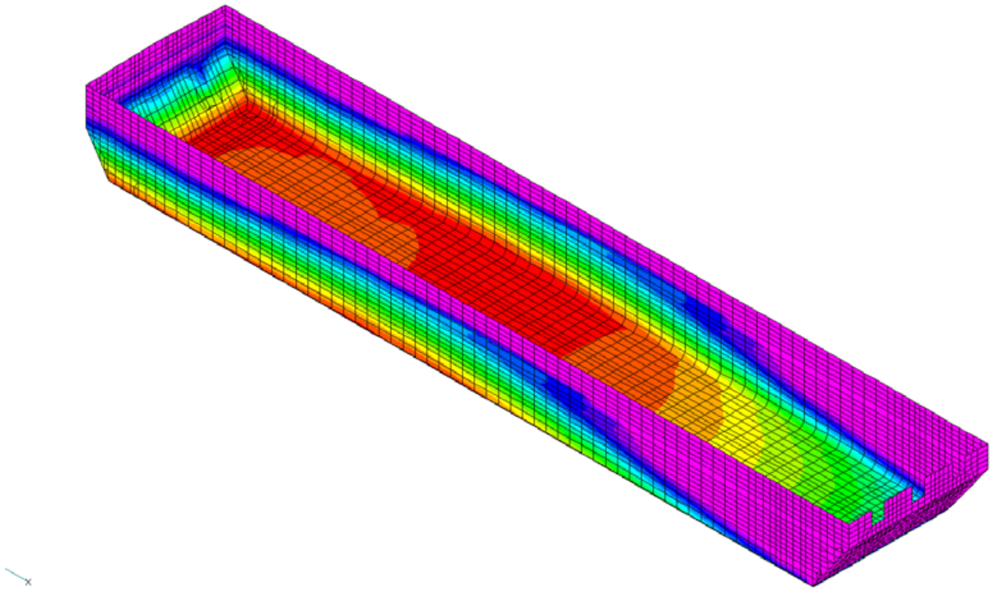
5 Pressure Loading on the Structural FE Analysis Model

The pressure distribution over a hydrodynamic panel model may be too coarse to be used in the structural FE analysis. Therefore, it is necessary to calculate the pressures over the finer structural mesh. Hydrodynamic pressure determined from seakeeping analysis may be linearly interpolated to obtain the pressures at the nodes of the structural FE analysis model.

Section 7, Figure 1 shows an example of the external hydrodynamic pressure distribution mapped on the structural FE model of an FPSO. The pressure distribution is a simultaneously-acting pressure accompanying the DLP of maximum hogging moment amidships at the instant time when the DLP reaches its maximum.

The external pressure distribution mapped over the structural FE model should contain both hydrostatic and hydrodynamic pressures.

FIGURE 1
External Hydrodynamic Pressure Mapping for a Load Case



SECTION 8 Internal Liquid Tank Pressure

1 General

The liquid pressures acting on the internal surfaces of liquid cargo and ballast tanks are to be calculated and applied to the structural FE model for DLA analysis. Static and dynamic pressures on completely filled and/or partially filled tanks are to be considered in the analysis assuming that there is no relative motion between the tank and the contained liquid. Tank sloshing loads are not included in DLA analysis. These sloshing loads are to be separately treated in accordance with the current *FPI Rules* requirements (see 5A-3-2/11 of the *FPI Rules*).

3 Pressure Components

The internal liquid tank pressure is composed of static and dynamic components. The static pressure component results from gravity. The dynamic pressure component can be further decomposed into quasi-static and inertial components. The quasi-static component results from gravity due to roll and pitch inclinations of the tank. The direction of gravitational forces in the vessel-fixed coordinate system varies with roll and pitch motion, resulting in a change of internal pressure.

The internal tank pressure for each of the tank boundary points can be calculated from the following equation, which is expressed in a combined formula of the static and dynamic pressure components:

$$p = p_o + \rho\, h_i\, [(g + a_V)^2 + (g_T + a_T)^2 + (g_L + a_L)^2\,]^{1/2}$$

where

p	=	internal tank pressure at a tank boundary point
p_o	=	either the vapor pressure or the pressure setting on pressure/vacuum relief valve
ρ	=	liquid density, cargo or ballast
h_i	=	internal pressure head defined by the height of projected liquid column in the direction of a resultant acceleration vector. For a completely filled tank, the pressure head is to be measured from the highest point of the tank to the load point (see Section 8, Figure 1). For a partially filled tank, the pressure head is to be measured from the free surface level to the load point (see Section 8, Figure 2). The free surface is defined as the liquid surface normal to the resultant acceleration vector. In Section 8, Figures 1 and 2, only vertical and transverse accelerations are considered for illustration purpose. Here, the angle θ_e is instantaneous effective inclination angle, which can be calculated from magnitudes of vertical and transverse accelerations.
g	=	acceleration of gravity = 9.8 m/s^2 (32.2 ft/s^2)
g_L, g_T	=	longitudinal and transverse components of gravitational acceleration relative to the vessel-fixed coordinate system due to roll and pitch inclinations
	=	$(-g \sin \phi,\, g \sin \theta)$
θ	=	roll angle
ϕ	=	pitch angle
a_L, a_T, a_V	=	longitudinal, transverse and vertical components of local accelerations caused by vessel motions relative to the vessel-fixed coordinate system at the center of gravity of tank contents

Here, the local acceleration at the CG of tank content due to vessel motions may be expressed by the following equation:

$$(a_L, a_T, a_V) = \vec{a} + \vec{\Theta} \times \vec{R}$$

where

(a_L, a_T, a_V) = longitudinal, transverse and vertical components of local accelerations at the CG of tank content

$\vec{a}$ = surge, sway and heave acceleration vector

$\vec{\Theta}$ = roll, pitch and yaw acceleration vector

$\vec{R}$ = distance vector from the vessel's center of gravity to the CG of tank content

5 Pressure Head Change due to Roll and Pitch Motions

As reflected in the previous formulations, the inclination of the tank due to vessel roll and pitch is to be considered in the calculation of the hydrostatic pressure. The direction of gravitational forces in the vessel-fixed coordinate system varies with roll and pitch, resulting in a change in pressure head and a corresponding change in the static pressure.

7 'Simultaneously' Acting Tank Pressure

For each load case described in Subsection 2/15, 'simultaneously' acting tank pressures (quasi-static and inertial) are to be calculated. Each Load Case is defined by equivalent wave amplitude, frequency, heading angle and wave crest position explained in Section 4. Using the wave amplitude and phase angle determined based on the RAO of a DLP, the 'simultaneously' acting tank pressure is calculated at the time corresponding to the maximum value of the RAO of the DLP. These internal tank pressures are to be used in the structural FE model.

9 Partially Filled Tanks

The previous Subsections deal with filled, pressurized tanks, whether due to an overflow head or vapor pressure. For the FPSO Operational Loadings (Subsection 2/5) to be analyzed, some tanks may be partially filled. In order to make the FE model loading procedure manageable, potential "sloshing" pressure in a partially filled tank is itself treated in accordance with the Rule-based approach given in 5A-3-2/11 of the *FPI Rules*. But as needed in the FE model, the liquid free surface will be considered as a planar surface and calculated relative to the tank boundaries using the roll and pitch motions when the DLP is maximized for the Load Case being considered. The total pressure to be applied to the FE model is calculated by the equation of Subsection 8/3 with $p_o = 0$.

FIGURE 1
Internal Pressure on a Completely Filled Tank

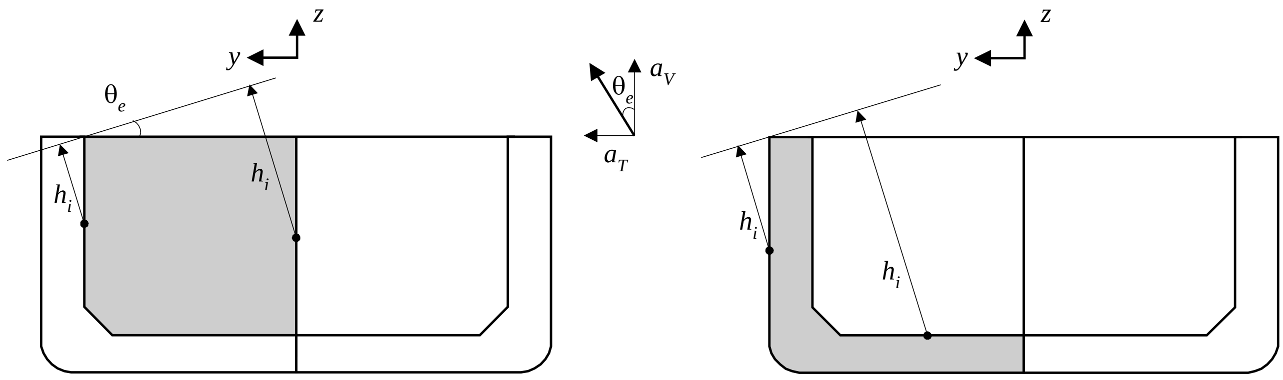
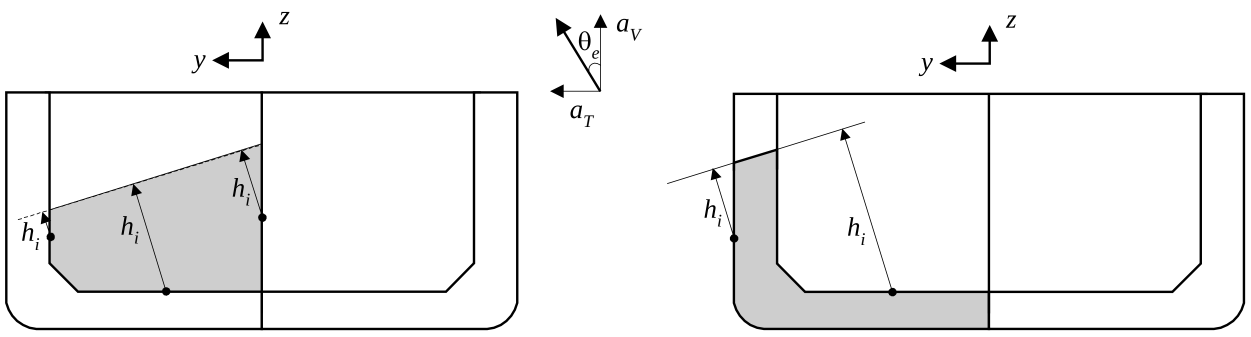


FIGURE 2
Internal Pressure on a Partially Filled Tank



SECTION 9 Local Acceleration and Motion-induced Loads for Lightship Weights and Equipment

1 General

The static and dynamic loads of the lightship structure and equipment are to be calculated and applied to the structural FE model for DLA analysis. Local accelerations at points where the weight of the lightship structure (non-liquid cargo) is located including deck-mounted equipment should be calculated to determine the motion-induced dynamic loads.

3 Load Components

The loads from the lightship structure and equipment are composed of static and dynamic components. The static load results from gravity. The dynamic load can be further decomposed into quasi-static and inertial components. The quasi-static load results from gravity, considering the instantaneous roll and pitch inclinations of the vessel. The inertial load results from the instantaneous local accelerations of the lightship structure and equipment caused by the vessel motions in six degrees-of-freedom. The static and dynamic loads of top-side equipment and facilities are to be applied to the topside module support structure (e.g., support stools) located on the main deck of the FPI installation

3.1 Static Load

The static load due to gravity acting of the lightship structure and equipment can be expressed as:

$$F_S = mg$$

where

m	=	mass of the structural member or equipment
g	=	acceleration of gravity

3.3 Dynamic Load

The dynamic load consists of quasi-static and inertial components. The quasi-static load is due to the roll and pitch inclinations of the vessel. The direction of gravitational forces in the vessel-fixed coordinate system varies with the roll and pitch motions resulting in a change of the dynamic load.

The inertial load is due to the instantaneous local acceleration of the lightship structure and equipment. In the procedure, the vertical, transverse and longitudinal components of local accelerations are defined in the vessel-fixed coordinate system.

The acceleration is often calculated as a complex number or in terms of the amplitude and phase in real numbers. Using the amplitude and phase of the acceleration, 'simultaneously' acting three acceleration components should be determined.

The dynamic load can be calculated from the following equation, which is expressed in a combined formula of the quasi-static and inertial components, as described below.

The vertical component of dynamic load due to vertical acceleration may be expressed by the following equation:

$$F_V = ma_V$$

where

m = mass of the structural member or equipment

a_V = local vertical acceleration

The transverse component of dynamic load due to transverse acceleration may be expressed by the following equation:

$$F_T = m(g_T + a_T)$$

where

g_T = transverse component of gravitational acceleration relative to the vessel-fixed coordinate system due to roll inclination

= $g \sin \theta$

a_T = local transverse acceleration

The longitudinal component of dynamic load due to longitudinal acceleration may be expressed by the following equation:

$$F_L = m(g_L + a_L)$$

where

g_L = longitudinal component of gravitational acceleration relative to the vessel-fixed coordinate system due to pitch inclination

= $-g \sin \phi$

a_L = local longitudinal acceleration

5 Local Acceleration

The local acceleration RAO at a location of interest can be calculated by the following formula:

$$(a_L, a_T, a_V) = \vec{a} + \vec{\Theta} \times \vec{R}$$

where

(a_L, a_T, a_V) = longitudinal, transverse and vertical components of local acceleration

gravitational terms due to quasi-static inclination of vessel motion, such as pitch and roll, should be accounted for structural loads for FE analysis

$\vec{a}$ = surge, sway and heave acceleration vector

$\vec{\Theta}$ = roll, pitch and yaw acceleration vector

$\vec{R}$ = distance vector from the vessel's center of gravity to the location of interest

The components of the gravitational acceleration in the vessel's coordinate system are to be included. If non-linear analysis is used, non-linear terms in the acceleration should also be added.

7 Simultaneously-acting Loads of Lightship Structure and Equipment

For each DLP, the simultaneously-acting static and dynamic loads of lightship structure and equipment are to be calculated at the time instant when the DLP under consideration reaches its maximum value. These simultaneously-acting inertial loads of the lightship structure and equipment are to be applied to each node of the structural FE model in the structural analysis.

SECTION 10 Loading for FEM Global Structural Model

1 General

The Load Cases of Subsection 2/15 are to be applied to the global (whole vessel) structural analysis model described in Section 11. Each load case needs to also include the hydrostatic and still-water load components that have not been otherwise directly included in the load component determination performed in accordance with Sections 7 and 9. These hydrostatic or still-water components are those caused, for example, by buoyancy and gravity, respectively, and should be included in the structural FE analysis.

In the application of loads to the structural model, caution should be taken in the interpolation of the pressure loading near regions where pressure changes sign.

3 Equilibrium Check

The model of the hull girder structure should be close to equilibrium when all the loads (static and dynamic) are applied.

The unbalanced forces in the model's global axis system for each Load Case need to be determined and resolved. For the head sea condition, the unbalanced force should not exceed one percent of the displacement. For oblique and beam sea conditions, it should not exceed two percent of the displacement. These residual forces could be balanced out by adding suitably distributed inertial forces (so called "inertial relief") before carrying out the FE structural analysis. The magnitudes of the unbalanced forces and the procedure used to balance the structural model in equilibrium prior to solution should be fully documented.

5 Boundary Forces and Moments

When the FE analysis model considers only a portion of the vessel, boundary conditions are required at the end sections of the partial model. These conditions are represented by the instantaneous vertical and lateral shear forces and three moments at the instant of time when the Dominant Load Parameter reaches its maximum. The method to calculate the instantaneous loads is described in Subsection 5/9.

SECTION 11 Structural Analysis of the Hull Structure

1 General

The structural adequacy of the hull is to be examined by the Finite Element Method (FEM) using a three-dimensional (3-D) model representing the entire hull girder structure, and as applicable the topside equipment support structure, and the interface with a mooring system (e.g., turret configuration). Results of nodal displacements obtained from the 3-D analysis are to be used as boundary conditions in the subsequent (typically finer mesh) analyses of local structure.

For the critical areas with high stress levels, a local FE analysis is recommended using a local finer mesh model representing the structural details. In this case, the results of nodal displacements or forces obtained from the global FE analysis are to be used as boundary conditions in the subsequent local FE analysis.

The DLA strength assessment procedures in this Guide are based on the use of net scantlings, which are defined as gross scantlings minus the Nominal Design Corrosion Values specified in Subsection A3/3. For more details of global FE modeling, refer to Appendix 5A-3-A4 of the *FPI Rules*.

For modeling convenience, FE modeling based on gross or as-built scantling can be used as an option in DLA analysis. The acceptance criteria in Section 12 have been modified to taking into account the stress differences between gross scantling model and net scantling model.

3 Structural Members

The following structural components are listed to indicate the important regions to be investigated in detail in the DLA Analysis.

i) Deck plating, longitudinal stiffeners and girders

ii) Bottom and inner bottom plating longitudinal stiffeners and girders

iii) Bulkheads

- longitudinal
- transverse
- stringers

iv) Side shell plating, longitudinal stiffeners, and frames

- midship
- forward
- aft

v) Web frames

vi) Turret supporting structure

vii) Topside supporting structure and hull underdeck structure

5 3-D Global Analysis Modeling

The global structural and load modeling should be as detailed and complete as practicable. In making the FE model, a judicious selection of nodes, elements and degrees of freedom is to be made to represent the stiffness and mass properties of the hull, while keeping the size of the model and required data generation within manageable limits. Lumping of plating stiffeners, use of equivalent plate thickness and other techniques may be used for this purpose. The finite elements, whose geometry, configuration and stiffness closely approximate the actual structure, can typically be of three types: 1) truss or bar elements with axial stiffness only, 2) beam elements with axial, shear and bending stiffness, and 3) membrane and bending plate elements, either triangular or quadrilateral. For more details of global FE modeling, refer to 5A-1-4/3 and 5A-3-4/11 of the *FPI Rules*.

7 Analyses of Local Structure

More detailed local stresses are to be determined by fine mesh FE analysis of local structures, based on the results of the global 3-D analysis. In the fine mesh models, care is to be taken to represent the structure's stiffness as well as its geometry accurately. Boundary displacements obtained from the 3-D global analysis are to be used as boundary conditions in the fine mesh analysis. In addition to the boundary constraints, the pertinent local loads should be reapplied to the fine-mesh models.

As applicable, the fine mesh models are to include at least the following local structures:

i) Two transverse web frames, one at mid-tank and the other adjacent to a typical watertight transverse bulkhead;

ii) Centerline longitudinal girder;

iii) Side longitudinal girders, expected to carry relatively high loads;

iv) Horizontal stringers of watertight transverse bulkhead;

v) Turret supporting structure and its interaction with the hull structure;

vi) Topside equipment supporting structures and their connections to the main supports to the hull, including hull underdeck structure;

vii) Other areas of high stress indicated from the 3-D global analysis.

Reference is to be made to 5A-1-4/3 of the *FPI Rules*, regarding additional modeling and analysis considerations for Mooring System/Hull interaction.

Where the 3-D global analysis is not comprehensive enough to determine adequately the total stress in the longitudinal plating (e.g., deck and shell) and transverse bulkhead plating of the vessel, additional analyses may be required. Such analyses may not require the performance of fine mesh FE analysis, where the needed results can be provided by another acceptable method.

SECTION 12 Acceptance Criteria

1 General

For assessing the results of the finite element analyses, two failure modes of the structural detail are to be considered:

i) Yielding

ii) Buckling and Ultimate Strength

Fatigue assessment of the vessels in critical areas such as hopper knuckles is important. The fatigue analysis is outside the scope of the DLA analysis. The global and local FE models developed for DLA analysis may be utilized in spectral fatigue analysis. Detailed procedures for spectral fatigue analysis and the **SFA** notation are described in the ABS *Guide for Spectral-based Fatigue Analysis for Floating Production, Storage and Offloading (FPSO) Installations*.

The evaluation for yielding and buckling of the main supporting structure of the vessel should be based mainly on the results of local finer mesh models where more accurate determination of local stress is required.

3 Yielding

For a plate element subjected to biaxial stress, a specific combination of stress components, rather than a single maximum normal stress component constitutes the limiting condition. In this regard, the following equivalent stress, given by the Hencky von-Mises theory, is to be compared to a maximum allowable percentage of the material's yield strength:

$$\sigma_{HVM} = [\sigma_X^2 + \sigma_Y^2 - \sigma_X\sigma_Y + 3\,\tau_{XY}^2\,]^{1/2}$$

where

σ_X = normal stress in the X direction (local axis system of the element)

σ_Y = normal stress in the Y direction

τ_{XY} = shear stress

or using principal stresses, σ_1 and σ_2:

$$\sigma_{HVM} = [\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2]^{1/2}$$

The von-Mises stress (obtained from the finite element stress components), is not to exceed a certain portion of the material's yield strength.

It is generally expected that finer finite element mesh induces higher resultant stress from a linear elastic analysis. However, the increase in stress is not just a function of finite element mesh size. It may also depend on the relative stiffness of adjoining structural members and the loading pattern. When a flexible member is connected to a stiff member, the increase in stress will be higher than when two flexible members are joined together. The increase in stress is also higher when bending is applied as compared to axial loads. In other words, the increase in stress due to a reduction in mesh size depends mainly on the expected stress gradient in the connection joint.

Given the recommended basic mesh of one longitudinal spacing for hull structures and finer meshing for critical structural areas such as openings and bracket toes, the resulting stresses may be categorized into the following three levels of stresses.

3.1 Field Stress

Field stresses are indicative of stress severity sufficiently away from structural details such as hopper knuckles, openings and bracket toes. The recommended basic mesh size for capturing field stresses is one longitudinal spacing. Element stresses directly obtained from 3D finite element models of one longitudinal spacing can be considered as field stresses. For main supporting members, field stresses are primarily due to primary hull girder deformation and secondary bending between watertight boundaries. In practice, mesh size up to $^1/_3$ longitudinal spacing is often used to calculate field stresses in main supporting members.

3.3 Local Stress

Local stresses reflect stress variation due to the presence of structural openings, details and discontinuities. Local stresses can be determined from elements having a mesh size in the range of $^1/_5$ to $^1/_{10}$ longitudinal spacing. This mesh size is finer than that used for determining the field stresses, but is still relatively coarse for determining stress concentration factors.

3.5 Hot-Spot Stress

A hot-spot stress is defined at one particular hot spot in a structural detail where fatigue cracking is expected to initiate. The hot-spot stress includes stress risers due to structural discontinuities and presence of attachments, but excludes the effects of welds. To determine hot-spot stresses, the mesh size needs to be finer than $^1/_{10}$ longitudinal spacing, but not finer than plate thickness.

3.7 Allowable Stresses for Watertight Boundaries

The allowable stresses, defined in Section 12, Table 1, are applicable to plating and longitudinal stiffeners on watertight boundaries. For the recommended basic mesh size of one longitudinal spacing, each allowable stress is defined as a percentage of the minimum specified yield stress f_y times the strength reduction factor S_m. Application of this allowable stress to rod and beam elements is based on axial stress while von-Mises membrane stresses for quadrilateral elements are checked.

TABLE 1
Allowable Stresses for Watertight Boundaries

Stress Limit	*Ordinary Strength Steel* ($S_m = 1.000$)	*HT27* ($S_m = 0.980$)	*HT32* ($S_m = 0.950$)	*HT36* ($S_m = 0.908$)	*HT40* ($S_m = 0.875$)	
$c_\ell \times c_f S_m f_y$	$23534 \times c_\ell c_f$	$25947 \times c_\ell c_f$	$29810 \times c_\ell c_f$	$32056 \times c_\ell c_f$	$34321 \times c_\ell c_f$	N/cm²
	$2400 \times c_\ell c_f$	$2646 \times c_\ell c_f$	$3040 \times c_\ell c_f$	$3269 \times c_\ell c_f$	$3500 \times c_\ell c_f$	kgf/cm²
	$34138 \times c_\ell c_f$	$37637 \times c_\ell c_f$	$43241 \times c_\ell c_f$	$46498 \times c_\ell c_f$	$49784 \times c_\ell c_f$	lbf/in²

Note: c_f is to be taken as 0.95 for FE model with gross scantlings.
c_f is to be taken as 1.0 for FE model with net scantlings.

The coefficient c_ℓ is 0.9 for upper deck, side shell and longitudinal bulkheads where the combined total stress is dominated by the stresses components caused by hull-girder bending/shear, primary support member deflection and concentration loads of topside modules. The coefficient c_ℓ suggested to be 0.80 for outer bottom, inner bottom and transverse bulkheads where the tertiary plate bending stresses have a relatively higher contribution to the total stress.

3.9 Allowable Stresses for Main Supporting Members and Structural Details

The allowable stresses, defined in Section 12, Table 2, are applicable to main supporting members and structural details. The allowable stress for the recommended basic mesh size is defined as a percentage of the minimum specified yield stress f_y times the strength reduction factor S_m. Application of this allowable stress to rod and beam elements is based on axial stress while von-Mises membrane stresses for quadrilateral elements are checked.

To calculate the local stress distribution in a main supporting member, it is often necessary to model openings, details and discontinuities using various mesh sizes. In areas of high stress gradient, the allowable stresses are to be adjusted according to mesh sizes and are listed in Section 12, Table 2.

TABLE 2
Allowable Stresses for Various Finite Element Mesh Sizes (Non-tight Structural Members), in N/cm^2 (kgf/cm^2, lbf/in^2)

Mesh Size	*Stress Limit*	*Ordinary Strength Steel (S_m = 1.000)*	*HT27 (S_m = 0.980)*	*HT32 (S_m = 0.950)*	*HT36 (S_m = 0.908)*	*HT40 (S_m = 0.875)*
1 × LS	1.00 × $c_f S_m f_y$	23534 × c_f 2400 × c_f 34138 × c_f	25947 × c_f 2646 × c_f 37637 × c_f	29810 × c_f 3040 × c_f 43241 × c_f	32056 × c_f 3269 × c_f 46498 × c_f	34321 × c_f 3500 × c_f 49784 × c_f
$^1/_2$ × LS (1)	1.06 × $c_f S_m f_y$	24946 × c_f 2544 × c_f 36186 × c_f	27506 × c_f 2805 × c_f 39898 × c_f	31595 × c_f 3222 × c_f 45830 × c_f	33978 × c_f 3465 × c_f 49286 × c_f	36380 × c_f 3710 × c_f 52771 × c_f
$^1/_3$ × LS (1)	1.12 × $c_f S_m f_y$	26359 × c_f 2688 × c_f 38234 × c_f	29055 × c_f 2963 × c_f 42146 × c_f	33380 × c_f 3404 × c_f 48418 × c_f	35900 × c_f 3661 × c_f 52074 × c_f	38440 × c_f 3920 × c_f 55758 × c_f
$^1/_4$ × LS (1)	1.18 × $c_f S_m f_y$	27771 × c_f 2832 × c_f 40282 × c_f	30614 × c_f 3122 × c_f 44407 × c_f	35174 × c_f 3587 × c_f 51021 × c_f	37822 × c_f 3857 × c_f 54862 × c_f	40499 × c_f 4130 × c_f 58745 × c_f
$^1/_5$ × LS ~ $^1/_{10}$ × LS (1)	1.25 × $c_f S_m f_y$	29418 × c_f 3000 × c_f 42672 × c_f	32438 × c_f 3308 × c_f 47053 × c_f	37263 × c_f 3800 × c_f 54051 × c_f	40067 × c_f 4086 × c_f 58119 × c_f	42901 × c_f 4375 × c_f 62230 × c_f
Thickness (1, 2)	$c_f f_u$ or 1.50 × $c_f S_m f_y$	40205 × c_f 4100 × c_f 58318 × c_f	$c_f f_u$ or 1.50 × $c_f S_m f_y$	44127 × c_f 4500 × c_f 64008 × c_f	48079 × c_f 4903 × c_f 69740 × c_f	51482 × c_f 5250 × c_f 74676 × c_f

Notes:

1. Stress limits greater than 1.00 × $c_f S_m f_y$ are to be restricted to small areas in way of structural discontinuities.
2. When the fatigue strength of the detail is found satisfactory, the hot spot stress in the detail may be allowed up to the minimum tensile strength of the material.
3. c_f is to be taken as 0.95 for FE model with gross scantlings.
   c_f is to be taken as 1.0 for FE model with net scantlings.
4. For intermediate mesh size, the stress may be obtained by linear interpolation.
5. LS = stiffener spacing

5 Buckling and Ultimate Strength

Plate panels and primary supporting members are to be checked against buckling (serviceability state limit) and ultimate state limit using stresses obtained from the FE analyses. For this purpose, established analytical or empirical formulas suitable to the hull structure are to be used.

Appendix 2 provides the buckling and ultimate strength criteria for plate panels and primary supporting members of the vessels, which are taken from the *FPI Rules*. The criteria given in Appendix 2 are to be used for DLA analysis after appropriate modification. Such modification is required because the *FPI Rules* criteria are to be applied to the stresses obtained from analysis employing net structural scantlings with component strength formulations expressed in terms of net scantlings, while the stresses obtained from DLA analysis are based on gross scantlings.

Therefore, in using the *FPI Rules* buckling criteria, the appropriate modification entails:

i) Increase the normal and shear stress components obtained from the DLA analysis (σ_x, σ_y, τ_{xy}) proportional to the ratio of gross and net scantlings, i.e.:

For plate: $$\frac{t_{gross}}{t_{net}} \times (\sigma_x, \sigma_y, \tau_{xy})$$

For stiffener: $$\frac{A_{gross}}{A_{net}} \times (\sigma_x, \sigma_y, \tau_{xy})$$

ii) Use net scantlings, for the buckling and ultimate strength formulations given in Appendix 2, that are determined as equal to the gross thickness minus nominal design corrosion values as described in Appendix 3.

APPENDIX 1 Summary of DLA Analysis Procedure

1 General

The concepts and analysis procedure presented in this Guide are summarized in this Appendix. The general procedure outlined below is recommended for the Dynamic Loading Approach (DLA) analysis of the vessels. The DLA analysis carried out in accordance with this procedure and considering the load cases as defined in Section 2 is deemed to be adequate to determine the controlling dynamic loadings acting on the hull structure of the vessels.

3 Basic Data Required

The following geometric and loading information is required to perform the prescribed analysis:

i) Principal Dimensions

ii) General Arrangement

iii) Lightship weight curve

iv) Cargo weight distribution for each loading condition

v) Lines Plan and/or Offset Table

vi) Drafts (forward and aft) for each loading condition

vii) Longitudinal Center of Gravity (LCG) for each loading condition

viii) Vertical Center of Gravity (VCG) for each loading condition

ix) Roll radius of gyration (k_r) for each loading condition

If this information is not available, the roll radius of gyration may be estimated by:

$k_r = 0.35B$ for full load

$k_r = 0.45B$ for ballast load

x) Radii of gyration in pitch and yaw for each loading condition

5 Hydrostatic Calculations

The steps involved in the hydrostatic calculations are as follows:

i) Prepare hull offset file of the vessel utilizing the offsets from the Offset Table

ii) Discretize the lightship weight distribution curve along the vessel's length into a series of trapezoidal weight blocks. It should be noted that the finer the discretization, the more accurate the numerical modeling of the lightship weight distribution would be.

iii) Based on the loading manual for the particular loading condition, discretize the cargo weight distribution curve along the vessel's length into a series of trapezoidal weight blocks.

iv) Calculate the displacement, trim, drafts (at FP and AP), longitudinal center of gravity and longitudinal distribution of still-water vertical shear force and bending moment using a seakeeping program based on the information obtained above.

v) The results of the hydrostatic calculations should be within acceptable tolerances specified in Subsection 4/3.

vi) The DLA criteria require the investigation of a set of Operational Loading Conditions as outlined in Subsection 2/5. The above hydrostatic calculations are to be repeated for each of these Loading Conditions.

7 Response Amplitude Operators (RAOs)

i) Determine the response amplitude operators for each Dominant Load Parameter (DLP) as specified in Subsection 2/7. A computer program that employs linear potential theory using panel method may be adequate for the determination of the RAOs.

ii) It is important that a broad range of wave frequencies and headings is considered in this calculation. It is recommended that the RAOs be calculated for wave headings, in increments of 15 degrees from head seas (180 degrees) to following seas (0 degrees). The range of wave frequencies is to include at least from 0.2 rad/s to 1.80 rad/s in increment of 0.05 rad/s.

iii) The offset data, drafts and trim determined from the hydrostatic analysis described above are to be used in the determination of the RAOs.

iv) The RAOs are to be calculated for each of the Operational Loading Conditions as outlined in Subsection 2/5.

9 Extreme Values

i) Establish the appropriate wave environment for the intended vessel service. (This may be for either a site specific service or unrestricted service depending on which is more appropriate for the vessel's required classification). For unrestricted service vessels, the wave data should be representative of realistic sea conditions in the North Atlantic Ocean. It is recommended that IACS Recommendation No.34 be used for unrestricted service vessels. For unrestricted service, equal probability of wave headings may be used.

ii) Determine the extreme values of the Dominant Load Parameters as specified in Section 4. Following the operational considerations, the probability level for extreme values of V_{acc}, L_{acc} and *Roll* may be reduced in beam or oblique sea condition. The extreme value predictions are to be carried out for each of the Operational Loading Conditions.

11 Equivalent Design Waves

Determine an equivalent design wave system for each DLP. In conjunction with the equivalent design wave system, the linear instantaneous load components accompanying the DLP may be obtained at the instant of time when the DLP under consideration reaches its maximum. This wave system is determined by using the results of the RAO calculations and the extreme value predictions. To determine this wave system, the following information must be captured from the RAO calculations:

i) Maximum amplitude of the RAO for each DLP

ii) Wave heading corresponding to the maximum of the RAO

iii) Wave frequency corresponding to the maximum of the RAO

iv) Wave amplitude that is equivalent to the extreme value divided by the maximum amplitude of the RAO.

13 Nonlinear Seakeeping Analysis

For the equivalent design waves defined in Section 5, nonlinear seakeeping analysis may be performed for the calculation of nonlinear vessel motions and wave loads. The nonlinear seakeeping analysis is to consider nonlinear hydrostatic restoring and Froude-Krylov forces. The computer program ABS NLOAD3D or equivalent computer programs may be used for this purpose.

From the response time history of each DLP, a specific instant of time is to be determined when the DLP under consideration reaches its maximum. The duration of time simulation is to be sufficiently long enough so that the response of the DLP reaches a steady state. Nonlinear instantaneous load components accompanying the DLP are to be obtained at the specific instant of time when the DLP reaches its maximum. It is recommended that the time simulation length be longer than twenty response cycles and the first half of the time history may be treated as transient response.

15 External Pressure

Determine the instantaneous external hydrodynamic pressure on the wetted hull surface corresponding to the time instant when the Dominant Load Parameter under consideration reaches its maximum. The external pressures at the nodes of FE model are to be determined by interpolating the external pressures calculated at the nodes of hydrodynamic panel model. A computer program which employs 3D linear interpolation techniques will be adequate for the determination of the external pressures on the FE model.

17 Internal Liquid Tank Pressure

Determine the instantaneous internal liquid tank pressure on liquid cargo and ballast tank boundaries corresponding to the time instant when the Dominant Load Parameter being considered reaches its maximum. The formulae to calculate the internal tank pressure are defined in Subsection 8/3.

19 Loads on Lightship Structure and Equipment

Determine the instantaneous inertial loads on the lightship structure and equipment induced by local acceleration corresponding to the time instant when the Dominant Load Parameter being considered reaches its maximum. The formulae to calculate the static and inertial loads are defined in Subsection 9/3.

21 Loadings for Structural FE Analysis

The instantaneous static and dynamic load components are to be applied to the FE model for each of the Load Cases defined in Section 2. The instantaneous static and dynamic load components to be applied in the FE analysis may include:

i) External pressure on the FE shell model

ii) Internal liquid tank pressure on the liquid cargo and ballast tank boundaries

iii) Static and dynamic loads from lightship structure and equipment

An equilibrium check for the unbalanced forces from the application of the instantaneous static and dynamic loads on the FE model is to be performed to determine whether or not they are within the following recommended allowable limits:

i) Load Cases for head sea conditions are to be within 1% of the vessel's displacement

ii) Load Cases for beam or oblique sea conditions are to be within 2% of the vessel's displacement

These unbalanced forces, if any, are to be accounted for by adding a suitably distributed and negligibly small inertial force system to the vessel's loading prior to carrying out the FE analysis. This check of unbalanced force is performed to assure that the structure is in dynamic equilibrium with the applied instantaneous static and dynamic loads.

23 Global FE Analysis

i) Prepare a global FE model of the vessel taking into account the structural and material properties of the vessel. It is recommended that the entire hull girder and main supporting members be modeled with one-longitudinal spacing mesh size. The global FE analysis allows detailed investigation of the structure at any location, thereby providing assurance that potential problem areas are identified at the earliest possible stage.

ii) The input loading to the global FE analysis consists of both static and dynamic components. The static components considered are the external pressures exerted on the hull in still water, liquid or bulk cargo, ballast water and the weight of the lightship structure and equipment.

iii) The global FE analysis is carried out to determine the global stresses and deflections due to the aforementioned static and dynamic loads. The global stresses are reviewed to determine which structural components are highly stressed. The high stress areas are identified as candidate structural components for in-depth examination via local FE analysis using finer mesh model, wherein the global deflections from the global FE analysis, are applied as input.

iv) A series of Load Cases, as given in Section 2, is to be investigated in the global FE analysis.

25 Local FE Analysis

i) Prepare the finer mesh models as determined from the global FE analysis. These local FE models are to represent the specific structural components taking into account the actual geometry and stiffness characteristics of the local structure.

ii) The input to such analysis consists of the deflection and boundary conditions identified from the global FE analysis.

iii) The finer mesh local FE analysis for each structural detail is to be carried out to accurately identify the local stresses. These results from local FE analysis can be used to refine the design of the structure while assuring the structural integrity of the vessel. The criteria to which the stresses are reviewed depend on the structural components and FE mesh size, which are outlined in Section 11.

iv) The maximum stresses determined for each structural detail are to govern the design and determination of the structure's integrity.

27 Closing Comments

The primary intent of this Guide is to provide the necessary steps needed to generate the dynamic loads to be used in the structural FE analysis for the strength assessment of an FPSO. The analysis procedure for the Dynamic Loading Approach analysis of an FPSO described above outlines the "state-of-the-art" methods presently employed by ABS. As research in hydrodynamics identifies more advanced methods of analysis and as experience with newer designs for FPSOs increases, modification of this procedure may be issued.

APPENDIX 2 Buckling and Ultimate Strength Criteria

1 General

1.1 Approach

The strength criteria given here correspond to either serviceability (buckling) state limit or ultimate state limit for structural members and panels, according to the intended functions and buckling resistance capability of the structure. For plate panels between stiffeners of decks, shell or plane bulkhead, buckling in the elastic range is acceptable, provided that the ultimate strength of the structure satisfies the specified design limits. The critical buckling stresses and ultimate strength of structural elements and members may be determined based on either well documented experimental data or a calibrated analytical approach. When a detailed analysis is not available, the equations given in Appendix 5A-3-4 of the *FPI Rules* may be used to assess the buckling strength.

1.3 Buckling Control Concepts

The strength criteria given in Section are based on the following assumptions and limitations with respect to buckling control in the design.

i) The buckling strength of longitudinals and stiffeners is generally greater than that of the plate panels being supported by the stiffeners.

ii) All of the longitudinals and stiffeners are designed to have moments of inertia with the associated effective plating not less than i_o, given in 5A-3-4/7.9.1 of the *FPI Rules*.

iii) The main supporting members, including transverses, girders and floors with the effective associated plating, are to have the moment of inertia not less than is given in 5A-3-4/7.9.3 of the *FPI Rules*.

iv) Face plates and flanges of girders, longitudinals and stiffeners are proportioned such that local instability is prevented (5A-3-4/7.9.4 of the *FPI Rules*).

v) Webs of longitudinals and stiffeners are proportioned such that local instability is prevented (5A-3-4/7.9.5 of the *FPI Rules*).

vi) Webs of girders, floors and transverses are designed with proper proportions and stiffening systems to prevent local instability. Critical buckling stresses of the webs may be calculated from equations given in 5A-3-4/7.3 of the *FPI Rules*.

For structures which do not satisfy these assumptions, a detailed analysis of buckling strength using an acceptable method is to be submitted for review.

3 Plate Panels

3.1 Buckling State Limit

The buckling state limit for plate panels between stiffeners is defined by the following equation:

$$(f_L/f_{cL})^2 + (f_T/f_{cT})^2 + (f_{LT}/f_{cLT})^2 \le 1.0$$

where

f_L = calculated total compressive stress in the longitudinal direction for the plate, in N/cm^2 (kgf/cm^2, lbf/in^2), induced by bending and torsion of the hull girder and large stiffened panels between bulkheads

f_T = calculated total compressive stress in the transverse/vertical direction, in N/cm^2 (kgf/cm^2, lbf/in^2)

f_{LT} = calculated total shear stresses in the horizontal/vertical plane, in N/cm^2 (kgf/cm^2, lbf/in^2)

f_{cL}, f_{cT} and f_{cLT} are the critical buckling stresses corresponding to uniaxial compression in the longitudinal, transverse/vertical direction and edge shear, respectively, in N/cm^2 (kgf/cm^2, lbf/in^2), and may be determined from the equations given in 5A-3-4/7.3 of the *FPI Rules*.

3.3 Effective Width

When the buckling state limit specified in A2/3.1 is not satisfied, the effective width b_{wL} or b_{wT} of the plating given below is to be used instead of the full width between longitudinals, s, for verifying the ultimate strength as specified in A2/3.5 below. When the buckling state limit in A2/3.1 is satisfied, the full width between longitudinals, s, may be used as the effective width b_{wL} for verifying the ultimate strength of longitudinals and stiffeners specified in Subsection A2/5.

3.3.1 For Long Plate (compression on the short edges)

$$b_{wL}/s = C_e$$

where

C_e = $2.25/\beta - 1.25/\beta^2$ for $\beta > 1.25$

= 1.0 for $\beta \le 1.25$

β = $(f_y/E)^{1/2} s/t_n$

f_y = specified minimum yield point of the material, in N/cm^2 (kgf/cm^2, lbf/in^2)

s = stiffeners spacing, in mm (in.)

t_n = net plate thickness, in mm (in.)

E = Young's modulus for steel, 2.06×10^7 N/cm^2 (2.1×10^6 kgf/cm^2, 30×10^6 lbf/in^2)

3.3.2 For Wide Plate (compression on the long edges)

$$b_{wT}/\ell = C_e s/\ell + 0.115\,(1 - s/\ell)\,(1 + 1/\beta^2)^2 \le 1.0$$

where

ℓ = spacing of transverses/girders

C_e and s are as defined in A2/3.3.1.

3.5 Ultimate Strength

The ultimate strength of a plate panel between stiffeners is to satisfy all of the following equations:

$$(f_L/f_{uL})^2 + (f_{LT}/f_{uLT})^2 \le S_m;$$

$$(f_T/f_{uT})^2 + (f_{LT}/f_{uLT})^2 \le S_m;$$

$$(f_L/f_{uL})^2 + (f_T/f_{uT})^2 - \eta\,(f_L/f_{uL})(f_T/f_{uT}) + (f_{LT}/f_{uLT})^2 \le S_m$$

where

η = $(1/2)(3 - \beta) \ge 0$

S_m = strength reduction factor for plating under consideration

= 1.0 for ordinary strength steel

= 0.95 for Grade H32 steel

= 0.908 for Grade H36 steel

= 0.875 for Grade H40 steel

f_L, f_T and f_{LT} are as defined in A2/3.1.

β is as defined in A2/3.3.

f_{uL}, f_{uT} and f_{uLT} are the ultimate strengths with respect to uniaxial compression and edge shear, respectively, and may be obtained from the following equations and do not need to be taken less than the corresponding critical buckling stresses specified in A2/3.1:

$f_{uL} = f_y\, b_{wL}/s \geq f_{cL}$, $f_{uT} = f_y\, b_{wT}/\ell \geq f_{cT}$ for plating longitudinally stiffened

$f_{uL} = f_y\, b_{wT}/\ell \geq f_{cL}$, $f_{uT} = f_y\, b_{wL}/s \geq f_{cT}$ for plating transversely stiffened

$$f_{uLT} = f_{cLT} + 0.5(f_y - 1.73 f_{cLT})/(1 + \alpha + \alpha^2)^{1/2} \geq f_{cLT}$$

where

α = ℓ/s

f_y, b_{wL}, b_{wT}, s, ℓ, f_{cL}, f_{cT} and f_{cLT} as defined above.

When assessing the ultimate strength of plate panels between stiffeners, special attention is to be paid to the longitudinal bulkhead plating in the regions of high hull girder shear forces, and the bottom and inner bottom plating in the mid region of cargo holds subject to bi-axial compression.

5 Longitudinals and Stiffeners

5.1 Beam-Column Buckling State Limits and Ultimate Strength

The buckling state limit for longitudinals and stiffeners are considered as the ultimate state limit for these members and, in combination with the effective plating, are to be determined as follows:

$$f_a/(f_{ca} A_e/A) + m\, f_b/f_y \leq S_m$$

where

f_a = nominal calculated compressive stress, in N/cm^2 (kgf/cm^2, lbf/in^2)

= P/A

P = total compressive load, in N (kgf, lbf)

f_{ca} = critical buckling stress, as given in 5A-3-4/7.5.1 of the *FPI Rules*, in N/cm^2 (kgf/cm^2, lbf/in^2)

A = total net sectional area, in cm^2 (in^2)

= $A_s + s t_n$

A_s = net sectional area of the longitudinal, excluding the associated plating, in cm^2 (in^2)

A_e = effective net sectional area, in cm^2 (in^2)

= $A_s + b_{wL} t_n$

E = Young's modulus for steel, 2.06×10^7 N/cm^2 (2.1×10^6 kgf/cm^2, 30×10^6 lbf/in^2)

f_y = minimum specified yield point of the longitudinal or stiffener under consideration, N/cm^2 (kgf/cm^2, lbf/in^2)

f_b = effective bending stress, N/cm^2 (kgf/cm^2, lbf/in^2)

= M/SM_e

M = maximum total bending moment induced by lateral loads, in N-cm (kgf-cm, lbf-in)

= $C_m\, p s \ell^2/12$

C_m = moment adjustment coefficient and may be taken as 0.75

p = lateral pressure for the region considered, in N/cm^2 (kgf/cm^2, lbf/in^2)

s = spacing of the longitudinals, cm (in.)

SM_e = effective net section modulus of the longitudinal at flange, including the effective plating b_e, in cm^3 (in^3).

b_e = effective breadth as specified in 5A-3-3/Figure 6, line b of the *FPI Rules*

m = amplification factor

= $1/[1 - f_a/(\pi^2 E\,(r/\ell)^2] \geq 1.0$

t_n and b_{wL} are as defined in A2/3.3.1

S_m is as defined in A2/3.5

r and ℓ are as defined in 5A-3-4/7.5.1 of the *FPI Rules*.

5.3 Torsional-Flexural Buckling State Limit

In general, the torsional-flexural buckling state limit of longitudinals and stiffeners is to satisfy the ultimate state limits given below:

$$f_a/(f_{ct}\,A_e/A) \leq S_m$$

where

f_a = nominal calculated compressive stress, in N/cm^2 (kgf/cm^2, lbf/in^2), as defined in A2/5.1

f_{ct} = critical torsional-flexural buckling stress, in N/cm^2 (kgf/cm^2, lbf/in^2), and may be determined by equations given in 5A-3-4/7.5.2 of the *FPI Rules*.

A_e and A are as defined in A2/5.1 and S_m is as defined in A2/3.5.

7 Stiffened Panels

7.1 Large Stiffened Panels between Bulkheads

For a vessel under the assumptions made in A2/1.3 with respect to the buckling control concepts, the large stiffened panels of the double bottom and double side structures between transverse bulkheads should automatically satisfy the design limits, provided that each individual plate panel and longitudinally and uniaxially stiffened panel satisfy the specified ultimate state limits. Assessments of the buckling state limits are to be performed for large stiffened panels of the single side shell and plane transverse bulkheads. In this regard, the buckling strength is to satisfy the following condition for uniaxially or orthogonally stiffened panels.

$$(f_L/f_{cL})^2 + (f_T/f_{cT})^2 \leq S_m$$

where

f_L, f_T = calculated average compressive stresses in the longitudinal and transverse/vertical directions, respectively, in N/cm^2 (kgf/cm^2, lbf/in^2).

f_{cL}, f_{cT} = critical buckling stresses for uniaxial compression in the longitudinal and transverse direction, respectively, and may be determined in accordance with 5A-3-4/7.7 of the *FPI Rules*, in N/cm^2 (kgf/cm^2, lbf/in^2)

S_m = strength reduction factor, as defined in A2/3.5

7.3 Uniaxially Stiffened Panels between Transverses and Girders

The buckling strength of uniaxially stiffened panels between deep transverses and girders is also to be examined in accordance with the specifications given in A2/7.1.

9 Deep Girders and Webs

9.1 Buckling Criteria

In general, the stiffness of the web stiffeners along the depth of the web plating is to be in compliance with the requirements of 5A-3-4/7.9.2 of the *FPI Rules*. Web stiffeners which are oriented parallel to and near the face plate and thus subject to axial compression are also to satisfy the limits specified in Subsection A2/5, considering the combined effect of the compressive and bending stresses in the web. In this case, the unsupported span of these parallel stiffeners may be taken between tripping brackets, as applicable.

The buckling strength of the web plate between stiffeners and flange/face plate is to satisfy the limits specified below:

9.1.1 Web Plate

$$(f_L/f_{cL})^2 + (f_b/f_{cb})^2 + (f_{LT}/f_{cLT})^2 \le S_m$$

where

f_L = calculated uniform compressive stress along the length of the girder, in N/cm^2 (kgf/cm^2, lbf/in^2).

f_b = calculated ideal bending stress, in N/cm^2 (kgf/cm^2, lbf/in^2).

f_{LT} = calculated total shear stress, including hull girder and local loads where applicable, in N/cm^2 (kgf/cm^2, lbf/in^2).

f_L, f_b and f_{LT} are to be calculated for the panel in question under each load case. f_{cL}, f_{cb} and f_{cLT} are critical buckling stresses with respect to uniform compression, ideal bending and shear, respectively, and may be determined in accordance with 5A-3-4/7 of the *FPI Rules*.

S_m is as defined in A2/3.5.

In the determination of f_{cL} and f_{cLT}, the effects of openings are to be appropriately considered.

9.1.2 Face Plate and Flange

The breadth to thickness ratio of face plate and flange is to satisfy the limits given in 5A-3-4/7.9 of the *FPI Rules*.

9.1.3 Large Brackets and Sloping Webs

The buckling strength is to satisfy the limits specified in A2/9.1.2 for web plate.

11 Corrugated Bulkheads

11.1 Local Plate Panels

11.1.1 Buckling Criteria

The buckling strength of the flange and web plate panels is not to be less than that specified below.

$$(f_{Lb}/R_\ell f_{cL})^2 + (f_{Tb}/R_t f_{cT})^2 + (f_{LT}/f_{cLT})^2 \le S_m \qquad \text{for flange panels}$$

$$(f_{Lb}/R_\ell f_{cL})^2 + (f_b/f_{cb})^2 + (f_{LT}/f_{cLT})^2 \le S_m \qquad \text{for web panels}$$

where

R_t = reduction factor accounting for lateral load effects, and may be approximated by:

= $1.0 - 0.45(q - 0.5)$

q = lateral load parameter

= $p_n(s/t_n)^4/\pi^2 E$, 0.5 minimum

p_n = lateral pressure for the combined load case considered, in N/cm^2 (kgf/cm^2, lbf/in^2)

s = longitudinal spacing, in mm (in.)

t_n = net thickness of the plate, in mm (in.)

E = Young's modulus, in N/cm^2 (kgf/cm^2, lbf/in^2), for steel 2.06×10^7 (2.10×10^6, 30×10^6)

All of the parameter definitions and calculations are as specified in 5A-3-4/5.3.1 and 5A-3-4/5.9.1(a) of the *FPI Rules*, except that f_{Lb} is the average compressive stress at the upper and lower ends of the corrugation, and an average value of f_{Tb}, f_{LT} and f_b, calculated along the entire length of the panel, should be used in the above equation.

11.1.2 Ultimate Strength

The ultimate strength of flange panels in the middle one-third of the depth are to satisfy the following criteria, considering a portion of flange panel having a length of three times the panel width, *a*, with the worst bending moments in the mid-depth region for all load cases.

$$(f_{Lb}/f_{uL})^2 + (f_{Tb}/f_{uT})^2 \leq S_m$$

where

f_{Lb} = calculated average compressive bending stress in the region within 3*a* in length, N/cm^2 (kgf/cm^2, lbf/in^2)

f_{Tb} = horizontal compressive stresses, as specified in 5A-3-4/5.11.1(a) of the *FPI Rules*

f_{uL} and f_{uT} may be calculated in accordance with 5A-3-4/5.3.3 of the *FPI Rules*.

11.3 Unit Corrugation

Any unit corrugation of the bulkhead may be treated as a beam column and is to satisfy the buckling criteria (same as the ultimate strength) specified in 5A-3-4/5.5.1 of the *FPI Rules*. The ultimate bending stress is to be determined in accordance with 5A-3-4/7.5.3 of the *FPI Rules*.

11.5 Overall Buckling

The buckling strength of the entire corrugation is to satisfy the equation given in 5A-3-4/5.7.1 of the *FPI Rules* with respect to the biaxial compression by replacing the subscripts "*L*" and "*T*" with "*V*" and "*H*" for the vertical and horizontal directions, respectively.

APPENDIX 3 **Nominal Design Corrosion Values (NDCV) for FPSOs**

1 General

The DLA strength assessment procedures in this Guide are based on the use of net scantlings, which are defined as gross scantlings minus the Nominal Design Corrosion Values specified in Subsection A3/3.

3 Nominal Design Corrosion Values

3.1 Double Hull Ship-type Installations

From Section 5A-3-1 in the *FPI Rules*, the nominal design corrosion values for FPSOs are given in Appendix 3, Figure 1 and Appendix 3, Table 1 of this Guide.

FIGURE 1
Nominal Design Corrosion Values

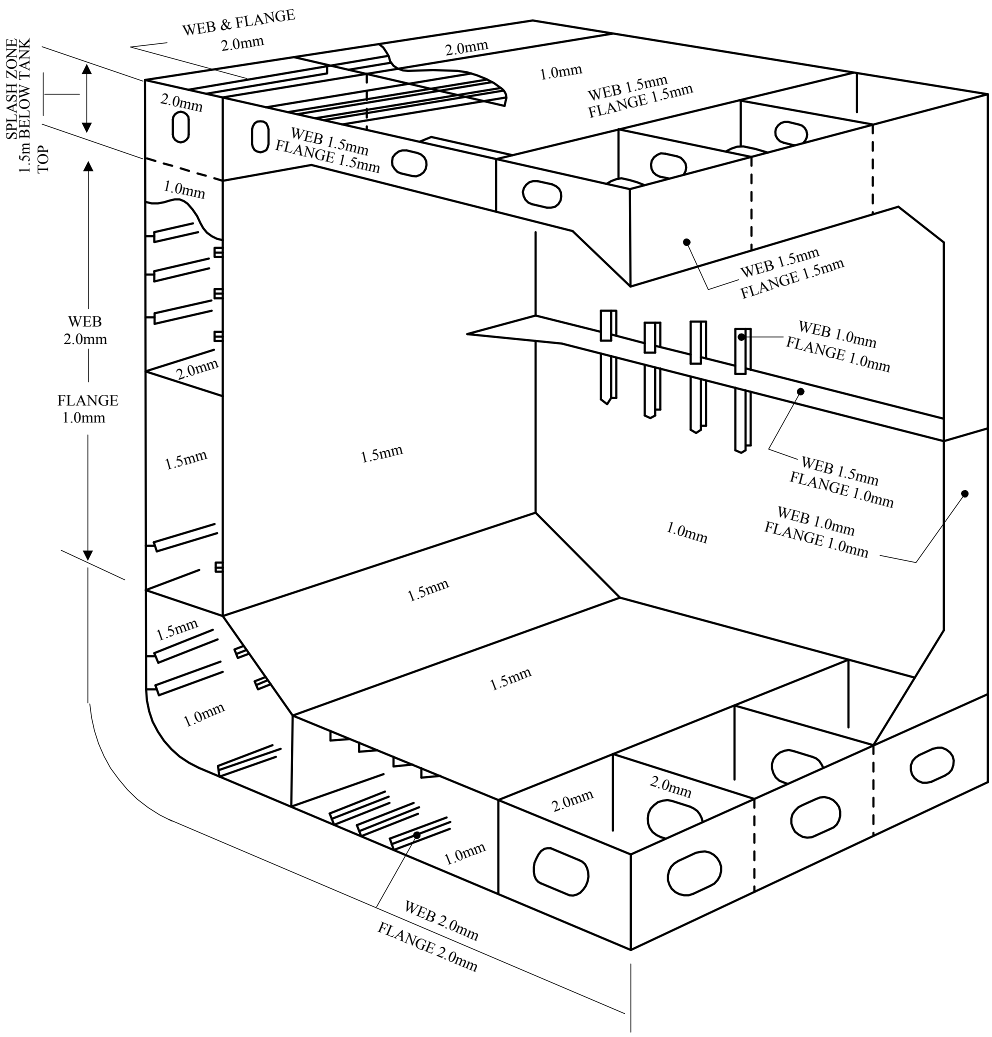


TABLE 1
Nominal Design Corrosion Values

Structural Element/Location		*Nominal Design Corrosion Values in mm (in.)* — *Cargo Tank*	*Ballast Tank Effectively Coated*
Deck Plating		1.0 (0.04)	2.0 (0.08)
Side Shell Plating		NA	1.5 (0.06)
Bottom Plating		NA	1.0 (0.04)
Inner Bottom Plating		1.5 (0.06)	
Longitudinal Bulkhead Plating	Between cargo tanks	1.0 (0.04)	N.A.
	Other Plating	1.5 (0.06)	
Transverse Bulkhead Plating	Between cargo tanks	1.0 (0.04)	N.A.
	Other Plating	1.5 (0.06)	
Transverse and Longitudinal Deck Supporting Members		1.5 (0.06)	2.0 (0.08)
Double Bottom Tanks Internals (Stiffeners, Floors and Girders)		N.A.	2.0 (0.08)
Vertical Stiffeners and Supporting Members Elsewhere		1.0 (0.04)	1.0 (0.04)
Non-vertical Longitudinals/Stiffeners and Supporting Members Elsewhere		1.5 (0.06)	2.0 (0.08)

Notes:

1 It is recognized that corrosion depends on many factors including coating properties, cargo composition, inert gas properties and temperature of carriage, and that actual wastage rates observed may be appreciably different from those given here.

2 Pitting and grooving are regarded as localized phenomena and are not covered in this table.

3.3 Single Hull and Double Side Single Bottom Ship-type Installations

Except as modified by the following, the nominal design corrosion values given in Appendix 3, Table 1 above are applicable to the corresponding structural elements of single hull ship-type installations based on the proposed usage of the individual space.

For bottom plating and contiguously attached structures, the nominal design corrosion values to be used are:

Wing Ballast Tanks

Bottom Plating	1.00 mm (0.04 in.)
Bottom Longitudinals, Transverses and Girders (Web and Flange)	1.50 mm (0.06 in.)

Center or Wing Cargo Tanks

Bottom Plating	1.00 mm (0.04 in.)
Bottom Longitudinals, Transverses and Girders (Web and Flange)	1.00 mm (0.04 in.)

Consideration may be given for modifying the nominal design corrosion values, depending upon the degree of cargo corrosiveness.