GUIDANCE NOTES ON

'SAFEHULL-DYNAMIC LOADING APPROACH' FOR FLOATING PRODUCTION, STORAGE AND OFFLOADING (FPSO) SYSTEMS

(FOR THE 'SH-DLA' CLASSIFICATION NOTATION)

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Foreword

This Guide provides information about the optional classification notation, SafeHull-Dynamic Loading Approach (**SH-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, this guidance document is referred to herein as "this Guide".

Chapter 1, Section 3 of the ABS *Guide for Building and Classing Floating Production Installations* (*FPI Guide*) contains descriptions of the various, basic and optional classification notations available. Chapter 4, Section 2 of the *FPI Guid*e gives the specific design and analysis criteria applicable to ship-type FPIs (FPSOs, etc.). In case of a conflict between this Guide and the *FPI Guide*, the latter has precedence.

This Guide is issued 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.

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CONTENTS

SECTION 1 Introduction

1 Background

The design and construction of the hull, superstructure, and deckhouses of a ship-type installation are to be based on all applicable requirements of the ABS *Rules for Building and Classing Steel Vessels* (*Steel Vessel Rules*). However, the design criteria for those structures, as given in the *Steel Vessel Rules*, can be modified to reflect the different structural performance and demands expected of a trading vessel engaged in unrestricted service compared to a floating production vessel positioned at a particular site on a long-term basis or a vessel with a specific and invariant route.

The design criteria for an oil tanker type vessel are located in the *Steel Vessel Rules*, Part 5, Chapters 1 and 2. Part 5, Chapter 1 is applicable to vessels of 150 meters (492 feet) or more in length, while Part 5, Chapter 2, applies to vessels under 150 meters in length.

The oil tanker criteria in Part 5, Chapter 1 of the *Steel Vessel Rules* are referred to as ABS *SafeHull* based criteria. The basic design criteria applicable to FPSOs have been derived from the *Steel Vessel Rules* and are published in the ABS *FPI Guide*. The most significant modifications of the criteria in the *FPI Guide* arise over the moored and site-dependent nature of the FPSOs design versus the traditional 'unrestricted ocean service' design basis for a tanker. These modifications are accomplished through the introduction of Environmental Severity Factors (ESF's).

The SafeHull criteria in the *Steel Vessel Rules* and the *FPI Guide* entail a two-step procedure. The main objective of the first step, referred to as Phase A, 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 Phase A 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 SafeHull criteria, referred to as Phase B, entails the performance of structural analyses using the primary design Loading Cases of Phase A. The main purpose of the Phase B analyses 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 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 *Steel Vessel Rules* and the *FPI Guide*. 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 indicates the need to increase any basic scantling this increase is to be accomplished to meet the DLA criteria. The **SH-DLA** notation signifies the satisfaction of the DLA analysis procedure of this Guide.

3 The Concepts and Benefits of DLA Analysis

3.1 General

The structural design portions of the ABS *FPI Guide* (i.e. see especially Chapter 4, Section 2) 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 things as possible turret based mooring, deck-mounted hydrocarbon processing equipment, etc. The *FPI Guide* 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 SafeHull 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 SafeHull, 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 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 SafeHull comprise mainly those intended to produce 'scantling design controlling' situations).

ii) Load components are combined to assemble each DLA Analysis 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 ship’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 ocean 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 2/5.9)

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 2/5. 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 ship 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 Ship 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 6, 7 and 8.

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) Directionality of waves

ii) Energy spreading of sea spectra

iii) Various formulations to characterize the sea spectra

iv) 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 – Structural and Hydrodynamic

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 should consider the effect of shallow water on vessel motions. There is also to be sufficient compatibility between the hydrodynamic and structural models so that the application of fluid pressures onto the finite element 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 Overview of the Following Sections

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 Dominant Load Parameters;

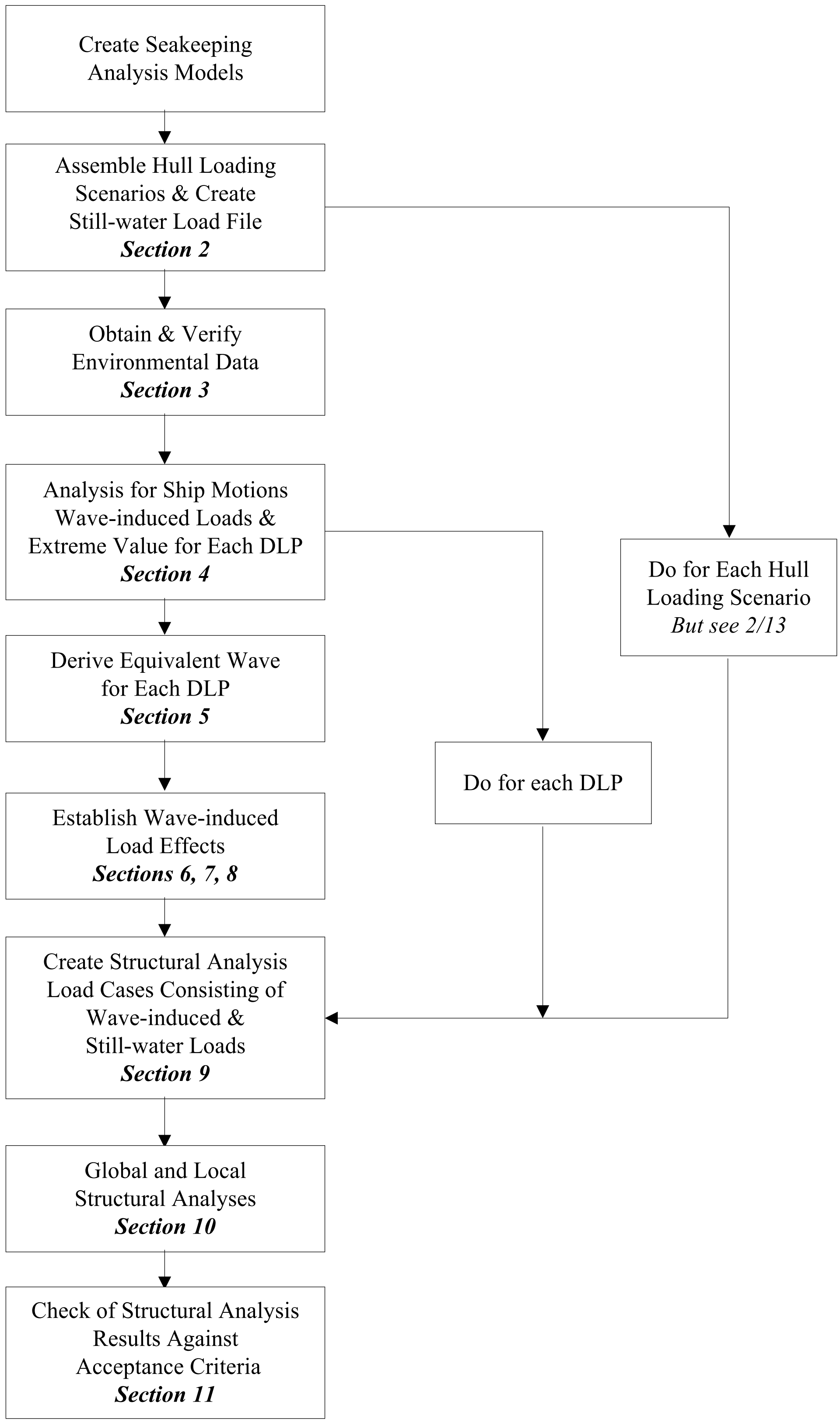
ii) wave-induced load components and the assembly of Load Cases;

iii) structural model development; and

iv) the permissible stresses used in the acceptance criteria.

These topics are presented in the following Sections 2 through 11. Refer to Section 1, Figure 1 for a schematic representation of the DLA Analysis Procedure.

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 hull loading (see Subsection 2/3), dominant load parameters (see Subsection 2/5) and environmental conditions (see Section 3). The loads 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 due to 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 structure. The developed Load Cases are then used in the FEM analysis to determine the resulting stresses and other load effects within the hull structure.

3 Hull Operational Loading

The design of an FPSO should consider the production rate, storage capacity and produced fluid's offloading capability. Hence, hull loading 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 Load Case(s) representing major transportation phase(s) for the FPSO should be included in the DLA Analysis. For example:

After Installation:

Ballast after offloading (all cargo tanks empty)

2nd intermediate loading (less than 50% filled)

3rd intermediate loading (tanks 50% filled)

4th intermediate loading (more than 50% filled)

Full-load before offloading (tanks full)

Transit:

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

Additionally, Load Cases 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.

5 Dominant Load Parameters (DLPs)

The term, Dominant Load Parameter (DLP) refers to a global load or motion effect of the hull (such as hull girder bending or roll motion). These parameters are to be maximized to establish Load Cases for the FEM analysis.

Sea waves produce external dynamic pressures on the hull surface. These waves also induce vessel motions that produce load component translation and rotation and generate inertial forces through the acceleration of the structural, equipment and the internal fluid masses including ballast and cargo. 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 structure. These five DLP's are as follows:

i) Vertical Bending Moment, (*VBM*)

ii) Vertical Shear Force, (*VSF*)

iii) Vertical acceleration (V_{acc})

iv) Lateral acceleration (L_{acc})

v) Roll angle (Φ)

The vertical bending moments are to be assessed for both hogging and sagging conditions. Bending moments and shear forces 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 should include simultaneous effects of waves and winds.

5.1 Maximum *VBM*

i) hogging moment amidships;

ii) sagging moment amidships;

What is being referred to here is the DLP: maximum wave-induced VBM. 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 as specified in 4-2/5 of the FPI Guide.

5.3 Maximum *VSF*

i) vertical shear force, (+) up

ii) vertical shear force, (–) down

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

5.5 Maximum V_{acc}

i) pitching up at FP or turret center;

ii) pitching down at FP or turret center;

5.7 Maximum L_{acc}

i) In way of turret structure or at least to the main deck level, starboard down;

ii) In way of turret structure or at least to the main deck level, starboard up;

In general, both conditions *i)* and *ii)* need to be considered, as the starboard down condition may not be exactly opposite to the starboard up condition. Additional reference points for accelerations may need to be introduced depending on the configuration of the deck-mounted equipment.

5.9 Maximum Roll Angle

i) starboard down

ii) starboard up

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).

7 Other Accompanying Load Components

The other accompanying load components are the load components that are considered to be acting when the Dominant Load Parameter reaches its maximum for the derived, equivalent wave. 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 6 – external hull pressures,

Section 7 – internal pressures at cargo and ballast tank wetted boundaries, and

Section 8 – motion induced loads from the structural components and process equipment.

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

9 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 10. The applied mooring loads are to be established for each hull 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 from Section 6 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 System and design controlling shuttle tanker or support vessel mooring operations.

11 Miscellaneous Loads

Other loads due to wave impacts on the bow and stern, flare and bottom slamming, tank fluid sloshing (see also Subsection 7/9), 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 ABS *Steel Vessel Rules* and *FPI Guide* requirements.

13 Structural Load Cases (SLCs)

Structural Load Cases are the cases to be investigated in the required structural analysis for DLA. Each SLC is defined by a combination of a hull loading condition (Subsection 2/3), individual sets of global load and motion effects established in consideration of each of the specified DLPs (Subsection 2/5), other loads accompanying the DLPs (Subsection 2/7), mooring system loads (Subsection 2/9), and a wave system (Section 5) for the particular DLP of interest.

A large number of SLCs will result (hull loading conditions times the number of DLPs). Each SLC is to be examined by performing the seakeeping and load analyses of Section 4. In general not all the SLCs may need to be included in the FEM structural analysis. If necessary because of computational limitations, the analyst may judiciously screen and select the most critical SLCs for the comprehensive, global structural analyses of Section 10.

SECTION 3 Environmental Condition

1 Basic Considerations

The Design Environmental Conditions (DEC) for an FPSO are specified in Section 3 of the ABS *FPI Guide*. 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 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.

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.

3 Environmental Data

3.1 General

Chapter 3 of the ABS *FPI Guide* 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 Chapter 3 of the *FPI Guide,* design environmental data are required for conditions representing both the FPSO transit condition and conditions at the FPSO installation site.

3.3 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' (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 'weathervane' behavior of the FPSO).

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

1 Overview

This section lists essential features about the calculation of ship 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. This section also specifies the expected outcome of analysis to establish an Extreme Value of a Dominant Load Parameter.

3 Still-water Loads

With the input of Hull Loadings (see Subsection 2/3), 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. A recognized hydrostatic analysis program is to be used to perform these calculations. By iteration, the convergence of the displacement, Longitudinal Center of Gravity (LCG), and trim should be checked to meet the following tolerances:

Displacement:		$\pm$ 1%
Trim:		$\pm$ 0.5 degrees
Draft:		
	Forward	$\pm$ 1 cm
	Mean	$\pm$ 1 cm.
	Aft	$\pm$ 1 cm
LCG:		$\pm$ 0.1% of length
SWBM:		$\pm$ 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 can be 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 and the water depth is to be considered. These codes, based on linear wave and motion amplitude assumptions, make use of boundary element methods with constant-source panels over the entire 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 wetted surface of the vessel be discretized into a large number of panels.

5.7 Vessel Motion and Wave Load Response Amplitude Operators

RAOs are to be calculated for the DLPs for each Load Case, selected per Subsection 2/13. 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 2/7) 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 structure. However, the use of a validated short-term extreme value approach, which is appropriate to the vessel type and installation site's environmental data, will 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 encouraged.

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 relevant value to be obtained from the Long-term Analysis is the Most Probable Extreme Value (MPEV) having a Return Period of 100-years. This return period is ordinarily considered to be equivalent to a probability of level of $10^{-8.7}$. (Refer to Subsection 3/1 concerning reduced return periods.)

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SECTION 5 Equivalent Wave

1 General

An equivalent wave is a sinusoidal wave 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 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 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 wave amplitude of the equivalent 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 wave amplitude of the sinusoidal wave is given by:

$$a_w = \frac{MPEV_j}{Max.\,RAO_j}$$

where

a_w = wave amplitude, 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 (i.e. 100-years), See Section 4

$Max.\,RAO_j$ = maximum amplitude of the j-th DLP's RAO

5 Wave Frequency and Length

The equivalent wave frequency and length for each DLP are determined from the peak value of the DLP's RAO for each considered heading angle. When the RAO is maximum, the corresponding peak frequency is denoted, ω_e. The wavelength of the equivalent wave system is calculated by:

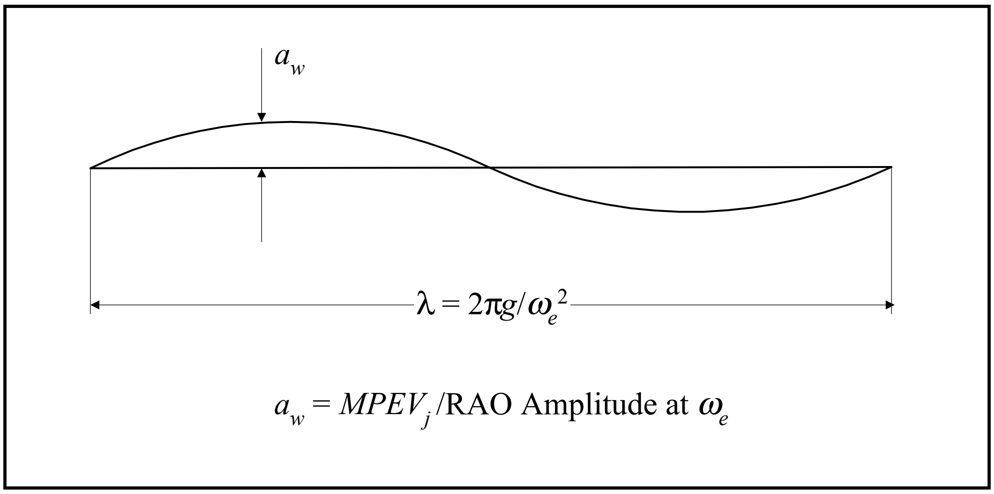
$$\lambda = (2\pi g)/\omega_e^2$$

where:

λ = wavelength

g = gravitational acceleration

FIGURE 1
Determination of 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:

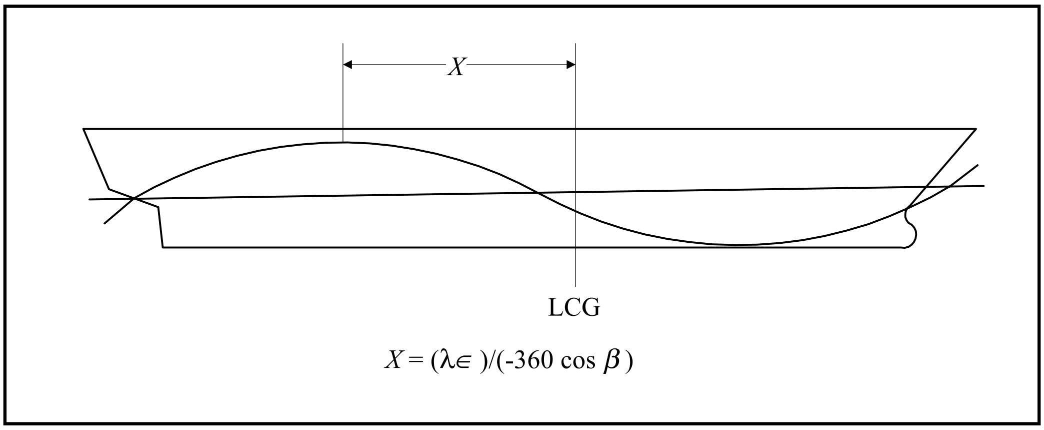
$X = (\lambda \in) / (-360 \cos \beta)$

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
Wavelength and Crest Position



It should be noted that X is undefined in beam seas ($\beta = 90^{o}$ or 270^{o}). Instead the wave crest position from the centerline of the ship in the y (transverse) direction is given by:

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

9 General Procedure to Determine Other Accompanying Load Components in a Load Case

For the equivalent wave, the longitudinal distribution of the other wave-induced motions and the other Load Components accompanying the Dominant Load Component in a Load Case are calculated using the following equation:

$$M_i = (A_i)\,(a_w)\,\sin(\omega_e t + \in_I)$$

where

M_i	=	i-th (other) load effect being considered (i.e., vertical bending moment and shear force, external and internal pressures, or acceleration at selected points)
A_i	=	amplitude of the other load component's RAO
ω_e	=	frequency of the equivalent wave when the RAO of the Dominant Load Component of the Load Case reaches its maximum
a_w	=	equivalent wave amplitude
$\in_I$	=	phase angle of the other load component's RAO
t	=	specific time that DLP under consideration reaches the maximum value

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.

SECTION 6 External Hydrodynamic Pressure

1 General

The hydrodynamic pressure Response Amplitude Operator (RAO) at selected points on the external contours of the designated hull sections are to be calculated for the FPSO in regular waves.

3 External Pressure Components

The total hydrodynamic pressure is to include the pressure components due to waves and the components due to vessel motion. Components of the hydrodynamic pressure are to be calculated from the panel model analysis of Subsection 4/5.

5 Pressures Accompanying the Dominant Load Component and Their Distribution

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:

$$P = A\, a_w \sin(\omega_e t + \in_I)$$

where

P = 'simultaneous' pressure

A = amplitude of the pressure RAO

a_w, ω_e, $\in_I$ and t are as defined in Subsection 5/9.

7 Pressure Loading on the Structural FEM Analysis Model

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

SECTION 7 Internal Tank Pressure

1 General

The fluid pressure in cargo tanks is to be calculated and applied to the structural model for FEM analysis. Static and dynamic pressures should be included in the analysis assuming that there is no relative motion between the tank and the contained fluid.

3 Pressure Components

The internal tank pressure is to account for the motion-induced pressure components; there is a 'quasi-static' component arising from rigid body rotation, and an 'inertial' component. The quasi-static component results from gravity for vessel roll and pitch rotations. The inertial component is due to the acceleration of the fluid caused by the hull's motions in six degrees of freedom. These are to be obtained from the motion analysis discussed in Section 4.

The inertial component is due to the instantaneous accelerations (longitudinal, lateral, and vertical) at the tank boundary points, calculated in conjunction with the load effect component (e.g., acceleration in this case) RAOs and the DLP RAOs. The total instantaneous internal tank pressure for each of the tank boundary points is calculated by combining the inertial and quasi-static components as follows:

$$P = P_o + \rho h_t [(g_x + a_x)^2 + (g_y + a_y)^2 + (g_z + a_z)^2]^{1/2}$$

where

P = total instantaneous internal tank pressure at a tank boundary point

P_o = either the vapor pressure or the relief valve pressure setting

ρ = fluid density, cargo or ballast

h_t = total pressure head defined by the height of the projected fluid column in the direction of the total instantaneous acceleration vector

a_x, a_y, a_z = longitudinal, lateral and vertical wave-induced accelerations relative to the vessel's axis system at a point on a tank's boundary

g_x, g_y, g_z = longitudinal, lateral and vertical components of gravitational accelerations relative to the vessel's axis system at a tank boundary point

5 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 ship-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 the wave condition, for each load case described in Subsection 2/13, 'simultaneously' acting tank pressures (quasi-static and inertial) are to be calculated. Each wave condition is defined by wave amplitude, frequency, heading angle, 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 FEM 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 Hull Loadings (Subsection 2/3) to be analyzed, some tanks may be partially filled. In order to make the FEM model loading procedure manageable, potential "sloshing" pressure in a partially filled tank is itself treated in accordance with the Rule-based approach given in the *FPI Guide*. But as needed in the FEM model, the fluid 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 for the Load Case being considered is maximized. The total pressure to be applied to the FEM model is calculated by the equation of Subsection 7/3 with $P_o = 0$.

SECTION 8 Local Acceleration and Motion-induced Loads for Lightship Weights

1 General

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 loads.

3 Local Acceleration

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

$$A = (R \times \theta)\, \omega_e^2 + a$$

where:

R = distance vector from the vessel's center of gravity (CG) to the point of interest

θ = rotational motion vector

x = cross product between the vectors

a = translational acceleration vector

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

ω_e is as defined in Subsection 5/9.

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.

5 Inertial Loads in the FEM Structural Model

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-component accelerations, A_t, can be determined by an equation of the following form:

$$A_t = A_i\, a_w \sin(\omega_e t + \in_I)$$

where

A_i = amplitude of the acceleration RAO

a_w, $\in_I$, and t are as defined in Subsection 5/9.

Once the acceleration is calculated, the inertial load is computed by:

$F = m\ (A_t)$

where

m = mass of the lumped weight of structural member, item of deck mounted equipment, etc.

A_t = 'simultaneously' acting three-component accelerations as determined in Subsection 8/5

The inertial forces in three (global) directions are to be calculated and applied to the structural FEM model.

SECTION 9 Loading for FEM Global Structural Model

1 General

The Load Cases of Subsection 2/13 are to be applied to the global (whole vessel) structural analysis model described in Section 10 of this Guide. 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 6 and 8. These hydrostatic or still-water components are those caused, for example, by buoyancy or gravity, and included in the hydrostatics analysis computer program mentioned in Subsection 4/3.

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. The magnitudes of the unbalanced forces and the procedure used to balance the structural model in equilibrium prior to solution should be fully documented.

SECTION 10 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 turret mooring system. 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.

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

5 3-D Global Analysis Modeling

The global structural and load modeling should be as detailed and complete as practicable. In making the 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. The DLA procedure is based on the use of gross or as-built scantlings.

7 Analyses of Local Structure

More detailed local stresses are to be determined by fine mesh FEM 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;

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

Reference is to be made to the ABS *FPI Guide*, 4-2/15.1.1 and 5-4/13 and 5-4/15, 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 FEM analysis, where the needed results can be provided by another acceptable method.

SECTION 11 Acceptance Criteria

1 General

The adequacy of the FEM analysis results is to be assessed for the failure modes of material yielding and buckling. Criteria for fatigue strength are provided in other ABS publications.

The evaluation for yielding and buckling of the primary internal supporting structure of the vessel should be based mainly on the results of fine 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 90 percent of the material's yield strength.

Special consideration will be given to the configuration of contour brackets and cut out details. The allowable (local) edge stress with reinforced or unreinforced contours, is the yield stress for Higher Tensile Strength material and 1.25 times the yield stress for mild steel.

5 Buckling

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

For instance, the criteria given in 5-1-5/5.3.1 and 5-1-5/5.3.2 of the ABS *Steel Vessel Rules* (SafeHull criteria) can be used for this purpose after modification. Modification is required because the SafeHull criteria are meant to be applied to stresses obtained from analysis employing net structural scantlings, and component strength formulations expressed in terms of net scantlings. Therefore sufficiently appropriate modification entails:

i) Increasing the normal and shear stress components from the DLA FEM Analysis by 10 percent, and

ii) Using in the SafeHull buckling strength formulations, net scantlings that are determined as equal to the gross thickness minus a value that is the lesser of 10 percent of the gross thickness, or 1.5 mm.

The local stiffness and geometric proportions given in 5-1-A2/11 of the *Steel Vessel Rules* to limit local buckling failures are to be observed in highly stressed areas.

Reference can also be made to Appendix 3-2-A4 of the *Steel Vessel Rules*, for situations where these more limited criteria can be validly applied.