GUIDANCE NOTES ON

‘DYNAMIC LOAD APPROACH’ AND DIRECT ANALYSIS FOR HIGH SPEED CRAFT

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Foreword

This Guide provides information about the optional classification notation, Dynamic Load Approach (**DLA**), which is available to qualifying high-speed craft and ships for DLA certification. In addition, it provides guidance to be followed when submitting required direct analyses or such analyses submitted in place of standard calculations. In the text herein, this document is referred to as "this Guide".

Part 1, Section 1 of the ABS *Guide for Building and Classing High-Speed Craft*, 2001 contains descriptions of the various basic and optional classification notations available. Part 3 of the *HSC Guid*e gives specific design and analysis criteria applicable to these craft.

Revision 1 of this draft Guide was issued in August 2002. 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 their version of this Guide is current.

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SECTION 1 Introduction

1 Background

1.1 Types of High-Speed Craft

Over the past decade (1990-2000), craft length, craft speed and installed engine power on high-speed craft have steadily increased. Most of the craft built over this period can be categorized into the three following groups:

Monohulls

Catamarans

Wave-piercing catamarans

An important trend in the above types of high-speed craft, in recent years, has been an increase in the length of craft that are being built. Most early high-speed craft were of the planing and semi-planing type, while the latter and most recent builds have been shifting into the domain of the semi-planing and displacement type. Although this has given rise to new technological challenges, it has also made it possible to apply well-established methods developed for conventional vessels to the design and analysis of these craft with novel hull forms. Distinct from the design criteria used for planing or dynamically supported craft, where hydrodynamic impact loads governed the loading criteria, these changes have brought about a shift of emphasis in load types and combinations, with global loads playing a more significant role than before. The trend towards larger craft sizes has also seen an increase in the range of different concepts such as “trimaran” hulls, foil-assisted hulls, asymmetric (unequal hull) catamarans and other novel designs.

1.3 Current Regulations on High-Speed Craft

The *International Code of Safety for High-Speed Craft* (IMO, 2000) is the only IMO document addressing high-speed craft. It applies to all types of craft operating internationally, but Chapter 3 of the IMO document deals with structures only in a basic manner. The requirements for direct analyses to be performed, based on craft length, speed and other special features, are stipulated in the following documents:

i) ABS *Guide for Building and Classing High-Speed Craft* (*HSC Guide*)

ii) ABS *Guide for Building and Classing High-Speed Naval Craft* (*HSNC Guide*)

1.5 Naval Requirements

ABS and the U.S. Navy have jointly developed the *HSNC Guide* for high-speed craft for a range of operations. Currently, this document is being validated with several existing commercial and naval high-speed craft.

Naval requirements specify that high-speed craft be built, modified or leased according to technical standards that will assure the safety and operational effectiveness required for the intended mission. Currently, most high-speed craft are designed, built or classed for restricted service. Use of any high-speed craft with a mission that requires unrestricted open-ocean operations should be evaluated for safety using the requirements of the *HSNC Guide*, especially if initially designed or classed for restricted service. This safety evaluation will invariably require a structural assessment that involves direct calculations designed to identify the operational limits.

3 The Concept and Benefits of DLA Analysis

The Dynamic Load Approach (DLA) was formally introduced in 1992 as an optional classification notation for large vessels. DLA provides enhanced structural analyses to assess the capabilities and sufficiency of a structural design. In the present case, a fundamental requirement of DLA is that the preliminary design of the structure be in accordance with the ABS *HSC Guide* criteria. Should a **DLA** notation be desired, the results of the DLA Analyses could not be used to reduce the basic scantlings obtained from the *HSC Guide*. However, should the DLA Analysis indicate the need to increase any basic scantling, this increase is to be accomplished to meet the DLA criteria. If, however, this Guide is being used for alternative direct analysis, scantling reductions justified by the results of the analysis may be considered.

The structural design portions of the *HSC Guide* (i.e. see especially Part 3, Chapter 2) are intended to provide the basis for a preliminary step-by-step design of the hull structure of a high-speed craft. DLA, on the other hand, is a direct analysis process that emphasizes completeness and realism in both the extent of the structure modeled and the loading conditions considered. In DLA, the modeling and analysis process utilize multiple levels that start with a global model of the structure. Results of each previous level of analysis are used to establish: i) areas of the structure requiring finer (more detailed) modeling and analysis, ii) the local loading to be re-imposed and the 'boundary conditions' to be imposed on the finer model. Central to the method is the use of a computational tool based upon linear seakeeping theory for calculating the Dominant Load Parameters (load and motion parameters that best characterize extreme ship response behavior) for the critical craft loading conditions.

The enhanced realism provided by the DLA Analysis has benefits that are of added value to 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 especially for aluminum and FRP hulls. A potentially valuable benefit that can arise from the DLA Analysis is that it provides access to a comprehensive structural evaluation model, which may be readily employed in the event of emergency situations that might arise during the service life of the craft, such as structural damage, repairs or modifications; ocean transit to a repair facility or redeployment to another operating route.

5 Types of Structural Assessments

5.1 Strength

In general, structural assessments of high-speed craft will require the application of direct analysis methods, as their preliminary designs will invariably be based on craft service record or previous experience. This is discussed further in detail in this Guide.

An alternative to direct analysis would be to derive structural loads from physical scale model tests. Rigid segmented models with stiff backbones are adequate for direct measurements of external forces, which are not significantly affected by elastic deformations. If flexibility and dynamics of the hull structure are important, use of a flexible model, which is dynamically scaled to represent structural response, is recommended. This can be realized using either a continuous elastic model or a segmented model with springs between stiff sections.

5.3 Fatigue

As high-speed craft often operate close to their design limits, fatigue is a more pronounced design factor than for conventional vessels. The accumulation of fatigue damage due to cyclic loading must be considered in the design of HSC structural components. The principal source of cyclic stresses in the structure will be motion- and wave-induced loads occurring at high encounter frequencies due to the high forward speeds.

Additional potential sources of structural fatigue are:

i) whipping response as a result of bottom and flare slamming for monohulls (global) and wet deck slamming for multihulls

ii) vibrations caused by pulsating pressures from water-jet propulsion system (local)

The increased flexibility of modern high-speed craft would tend to accelerate fatigue damage resulting from the above secondary effects. Detailed fatigue assessment is recommended for craft with novel hull forms, as few service records are available.

5.5 Vibration

It is not a condition of classification that the craft is demonstrated to be free of undesirable or harmful vibrations. However, in some high-speed craft designs involving increased flexibility of structures, especially those involving water-jet propulsion, flow-induced vibrations could significantly contribute to structural responses that result in accelerated fatigue damage. For high-speed craft, the methods for dynamic response analysis developed for conventional vessels can be applied to vibration problems on high-speed craft. However, the significantly different structural damping characteristics of FRP hulls (relative to steel hulls) must be taken into account. It is recommended that these methods be utilized to investigate vibration-induced fatigue of fast craft fitted with water-jet propulsion.

5.7 Hydroelastic Considerations

Global loads on monohull craft are not significantly affected by elastic deformations, because the rigid body motions are dominant. In this case, the external loads, such as those due to bottom slamming, can be first determined through motion analysis and then applied to the structure to obtain the elastic responses. In some cases, especially in multi-hull craft made of lightweight structural materials such as aluminum, there is true interaction of loads and responses, in which case, they cannot be treated separately. This is particularly the case when the craft operate at high speeds, which are associated with high encounter frequencies resulting in large dynamic amplification. Some cases of slamming impact on local flexible structures are also truly hydroelastic problems. In these cases, the loads can only be specified if the flexibility of the structure is incorporated into the load formulation. For high-speed craft, typical hydroelastic phenomena that require close attention are:

i) Wave-induced springing, as in the “squeezing/prying” mode of multi-hulls (global)

ii) Dynamic response of panels to slam impact pressures (local)

It has been shown through experiments that hydroelastic effects are most important for impacts with short duration. Such impacts occur when a large area of the structure comes in contact with the water surface, as in the case of slamming on the wet deck of a catamaran. Here, as in other nearly flat structures (deadrise angles in the range 0 to 5 degrees), air entrapment effects will be significant, which tend to lengthen the duration of impact. It has also been found through experiments that there is almost no influence of hydroelasticity on bow flare slamming.

As preliminary guidance, the following recommendation with respect to the role of hydroelasticity in local structural response can be given. If the ratio of the duration of the impact to the first natural period of vibration of the dry panel structure is greater than 2.0, the effect of hydroelasticity can be neglected. On the other hand, if the ratio is less than 2.0, structural response of the panel should be taken into account in the calculation of impact loads on the panel.

7 Scope and Overview of the Guide

The DLA procedure is a first-principles based strength assessment methodology. In this regard, acceptance criteria are applied to ensure that predicted stress levels do not exceed a specified percentage of yield strength and do not exceed buckling and ultimate strength. This analysis satisfies the requirements of Required Analyses specified in 1/1.5.2a in the ABS *HSC Guide*. The *HSC Guide* also notes in 1/1.5.2b that Supplementary Analyses may be required. The most likely such requirements are fatigue and vibration analyses. While outside the scope of this Guide, they are, nevertheless, discussed in this Guide in general terms. However, this Guide does not provide specific guidance for assessing these failure modes. Section 1, Figure 1 shows an overview of the analysis requirements for high-speed craft, wherein the strength assessment addressed in this Guide is highlighted and the supplementary analyses are shown shaded.

This Guide systematically introduces the assumptions in the load formulation, and the methodology underlying the response analysis procedures used in applying DLA Direct Analysis to high-speed craft. These include the following topics: specification of the Dominant Load Parameters, wave-induced load components, formulation of load cases, structural model development and the permissible stresses used in the acceptance criteria. These topics are presented in the following Sections 2 through 11. Refer to Section 1, Figure 2 for a schematic representation of the steps involved in DLA Analysis Procedure or alternative direct analysis.

FIGURE 1
Overview of the Analysis Requirements for High-Speed Craft

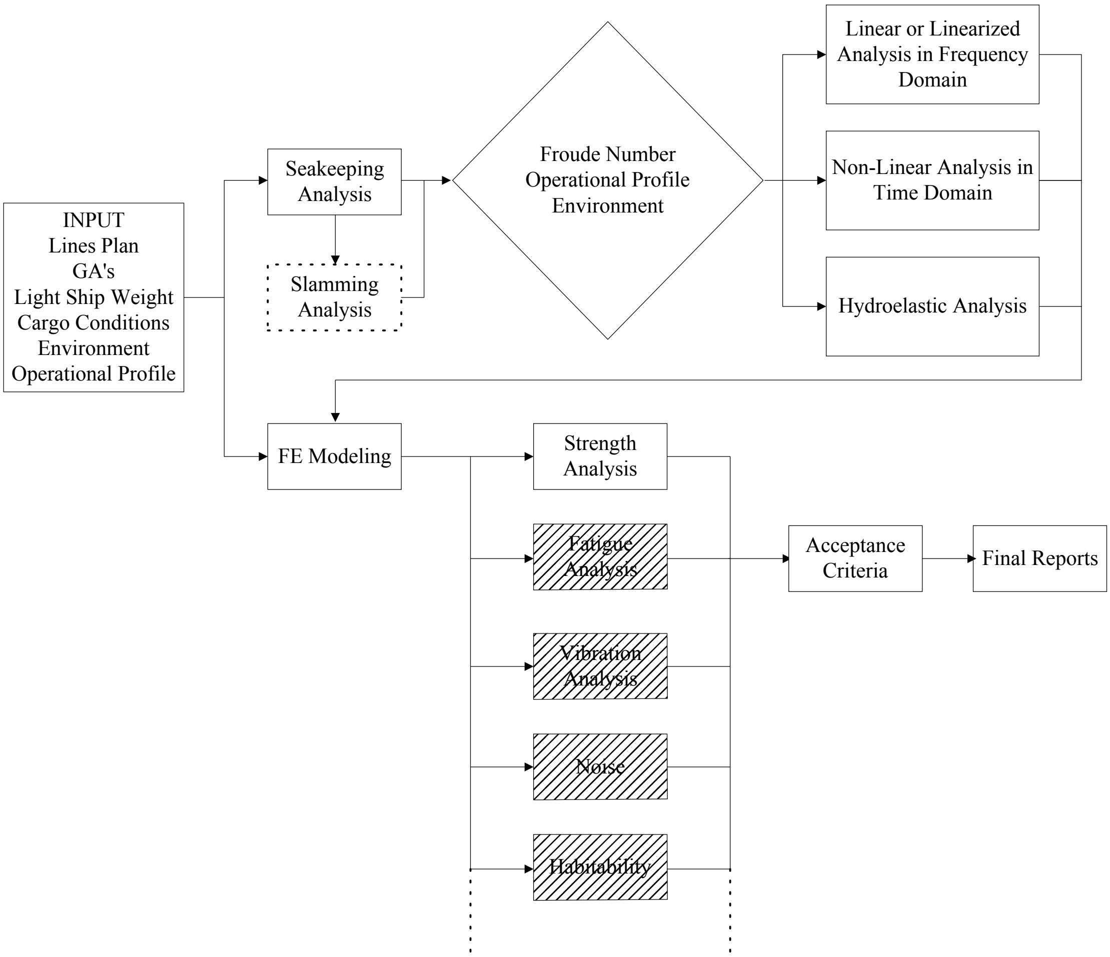
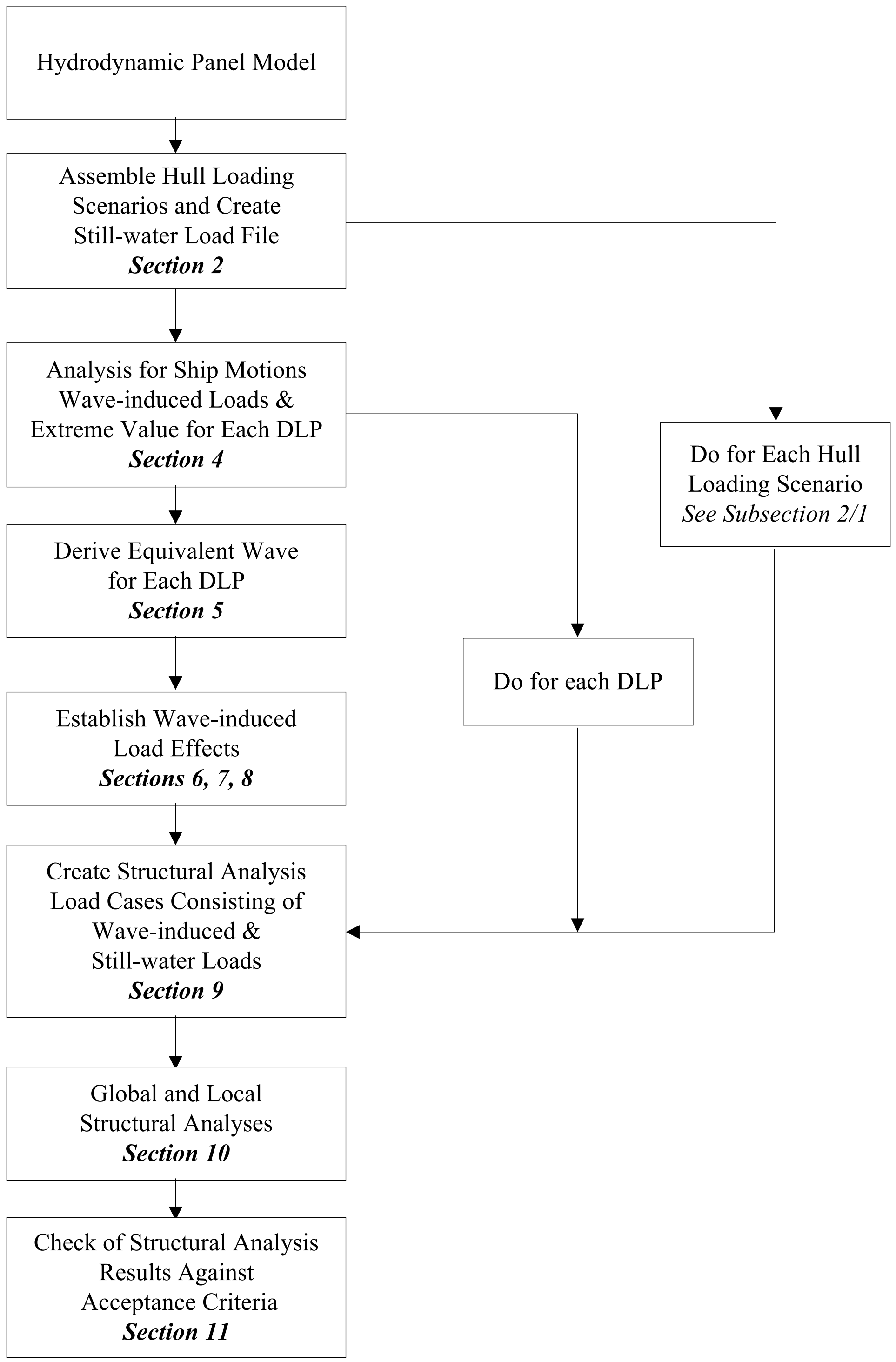


FIGURE 2
Schematic of the DLA Procedure of Alternative Direct Analysis



SECTION 2 Loading Conditions and Load Cases

1 Craft Loading Conditions

Design of a high-speed craft should consider the operational profile, craft load capacity and structural arrangement. Hence, hull loading would relate to the cargo and ballast patterns, the craft's draft and trim ranges.

A number of tank loading patterns and hull draft conditions typically found in high-speed craft Loading Manuals are to be selected as representative conditions in the DLA Direct Analysis. Also load case(s) representing major transportation phase(s) should be included in the DLA and Direct Analysis.

3 Dominant Load Parameters (DLPs)

As indicated earlier, the term *Dominant Load Parameter* (DLP) refers to a global motion or load effect of the hull (such as vertical acceleration or vertical bending moment in hull girder). For DLA and Direct Analysis of a high-speed craft, examples of Dominant Load Parameters would include:

i) Vertical Bending Moment, Shear (monohulls)

ii) Vertical acceleration (monohulls, multi-hulls)

iii) Roll angle (monohulls and multi-hulls)

iv) Vertical Shear at center of connecting structure (for multi-hulls)

v) Longitudinal Shear along centerline of connecting structure (for multi-hulls)

vi) Lateral Shear at the haunch (multi-hulls)

vii) Squeezing/Prying moment (for multi-hulls)

viii) Pitch torsion (connecting) moment (for multi-hulls)

ix) Yaw splitting moment (multi-hulls)

x) Relative velocity at center of wet deck (multi-hulls)

5 Load Cases

5.1 Basic Considerations

DLA and Direct Analysis require 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 craft loading (see Subsection 2/1 above), dominant load parameters (see Subsection 2/3) 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 vehicles. 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 within the hull structure.

5.3 Selection of Load Cases

Each load case is defined by a combination of a hull loading condition (Subsection 2/1), a set of global motion and load effect parameters [established in connection with each of the specified DLPs (Subsection 2/3)], other loads accompanying the DLPs (Subsection 2/7) and an equivalent wave system (Section 5) for the particular DLP. A large number of load cases will result from the hull loading conditions and the number of DLPs considered. In general, not all the load cases 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 load cases, for the comprehensive global structural analyses outlined in Section 10.

The load cases considered possess the following attributes:

i) They use drafts, loading patterns and other load components that reflect the craft's operating conditions.

ii) Load components are combined to build each load case.

The basic task involves the development of each load case used in the analysis. A load case selected for analysis is comprised of combinations of a Dominant Load component and the other significant load components that are considered to be accompanying the Dominant Load component that is characterized by a DLP.

A load component, in general, consists of dynamic and static parts. For example, external fluid pressure on the craft's hull in the presence of waves has a hydrostatic component that combines with a dynamically induced pressure component. The hydrostatic component should also account for variations in the immersion of the hull resulting from motions in waves (for example: combined pitch, heave and roll). The dynamic component should reflect contributions from the incident wave effects (Froude-Krylov), the diffracted and radiation wave effects.

Typical DLPs that are recommended for inclusion in the DLA Analysis of a high-speed craft are given in Subsection 2/3. The other significant load components accompanying the Dominant Load component in a load case include internal (tank) fluid pressures, weights including structural self-weight, weights of vehicles and external forces from the actuation of control surfaces such as those from canards, fins, rudders, etc.

Magnitude of the load components composing a load case is determined through a process where each Dominant Load is analyzed to establish its *Response Amplitude Operator* (RAO). Through a combination of ship motion analysis involving the use of ocean wave spectra and extreme-value analysis of the DLP, an equivalent sinusoidal wave is derived. The wave (defined by the amplitude, frequency, heading, and phase angle with respect to a selected reference on the hull) is considered equivalent in the sense that, when it is imposed on the structural model, it produces 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 hydrodynamics-based ship motion and wave-induced load analysis and spectral and extreme value analysis, both of which are required in the determination of DLPs.

From the RAOs of the other load components and the equivalent wave derived for the DLP, the magnitudes 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 in Sections 6, 7 and 8.

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. The calculation techniques to develop the accompanying load components are presented in later sections as follows:

i) Section 6 – external hull pressures,

ii) Section 7 – internal pressures due to liquid fuel and cargo ballast tank wetted boundaries,

iii) Concentrated wheel loads from vehicles,

iv) Section 8 – motion-induced loads from the structural components.

9 Miscellaneous Loads

Other loads, such as those due to wave impacts on the bow and stern, flare and bottom slamming, wet-deck slamming on multi-hulls and vibration effects on local structures are only briefly discussed in this document (see Section 12). The loads resulting from these are to be treated using independent analysis or, if applicable, in accordance with the current ABS *High-Speed Craft Guide* and ABS *High-Speed Naval Craft Guide* requirements.

Additional considerations that can be accommodated in DLA and direct analysis include:

i) Directionality of waves (waves and swell coming from different directions)

ii) Short-crested waves (energy spreading)

iii) Alternate formulations to characterize sea spectra

iv) Large amplitude waves

v) Various exceedance probabilities to characterize extreme values of DLPs.

SECTION 3 Environmental and Service Conditions

1 Basic Considerations

The need for Design Environmental Conditions (DEC) for a high-speed craft is outlined in Section 3 of the ABS *High-Speed Craft Guide*. Analysis methodology discussed in this document is not limited to determination of loads resulting from operations of the craft in deep water. Many high-speed craft operate in coastal areas where shallow-water characteristics of the waves need to be considered.

For high-speed craft, environmentally induced loads are dominated by motions in waves that are characterized by significant heights, average zero-crossing periods and associated spectral shapes. Design of high-speed craft, for operation on a selected route, requires route-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 one-in-twenty-five year estimates of the wave-induced motions and load-effects under consideration.

3 Environmental Data

3.1 General

The environmental data and resulting effects are to be selected and documented in ways that are compatible with the DLA and Direct 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 also be documented in the submitted report.

3.3 Special Wave Data Needs

As mentioned in Subsection 3/1, waves usually produce the dominant environmentally induced effects. Therefore, DLA and Direct Analysis primarily relies on wave data that is compatible with the stochastic response and extreme value prediction methods used.

As high-speed craft, in general, operate in route-specific coastal or regional environments, it would be appropriate to use spectra developed for the specific route or regions. These environments may include fetch-limited, shallow-water seas. The objective is to use realistic measured or observed wave conditions that include the effects of bathymetry, wind field, current field, coastal contours of the area, etc. and to derive a suitable spectrum that would represent the near-shore wave frequencies. Typically, the Goda-JONSWAP spectrum may be used as it allows control of the shape of the spectrum by adjusting the peak enhancement factor γ, without changing the significant wave height. If the swell and wave components are known to interact, a bi-modal Ochi-Hubble spectrum is to be used. Directional spreading appropriate to coastal conditions is also to be applied.

SECTION 4 Analysis of Ship Motions, Wave Loads and Extreme Values

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 loading (see Subsection 2/1), 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, convergence of the calculated displacement, longitudinal center of gravity (LCG), and trim should be checked to meet the required tolerances.

The maximum and the minimum still-water bending moment (SWBM) and shear force and their distribution along the craft's length are to be documented.

5 Essential Features of Spectral-based Analysis of Motions and Loads

5.1 General Modeling Considerations

The model of the hull should include the masses of all equipment and supporting structure. 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 DLA and Direct Analysis method, software formulations derived from linear idealizations are deemed to be sufficient. However, the designer/analyst is encouraged to employ advanced methods if appropriate, especially to incorporate non-linear loads (such as those due to slamming). The analyst needs to be aware of the capabilities and limitations of the software, and in cases where the software is not known to ABS, it will be necessary to demonstrate the adequacy of the software.

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. These codes may be based either on linear (small) wave and motion amplitude assumptions or nonlinear (large) amplitude motion and wave formulations. Computation of the hydrodynamic pressures should take account of, as a minimum, all six degree-of-freedom rigid-body motions of the hull. The effect of hull lift on motions may be conveniently modeled using panel methods (see below), so that the lifting flow can be directly coupled with the surface. For small control surfaces (fins, rudders, skegs, etc.) a separate lift model can be applied that decouples the wave flow and lift.

5.5 Panel Model Development

Diffraction-radiation methods make use of boundary element methods with constant-source panels, which in general, require that the wetted surface of the hull be discretized into a number of panels. For high-speed craft, use of Rankine source panel method is recommended for solving the hydrodynamic boundary value problem. As the Rankine source, Green's function does not satisfy the free surface boundary condition and the rigid-body boundary condition on the hull. The Rankine sources have to be distributed not only on the hull surface, but also on the free surface and the matching surface, so as to satisfy both boundary conditions.

5.7 Ship Motion and Wave Load Response Amplitude Operators

For each loading condition, selected per Subsection 2/1, the RAOs of all six modes of motion and those of the DLPs are to be calculated. The RAOs should represent the pertinent range of wave headings (β), in increments not exceeding 15 degrees. It is important that a range of wave frequencies are used in the computations, that take account of the coastal routes of operations and the relatively high forward speed of the craft. Considering the relatively high encounter frequencies, the recommended frequency range is 0.5 rad/s to 2.5 rad/s in increments of 0.05 rad/s.

The worst 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 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 output.

In addition, RAOs for the other load components accompanying the DLPs are to be determined.

7 Extreme Values Analysis

Extreme value analysis is to be performed for each DLP to determine the maximum values for use in DLA and Direct 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 craft type and route-specific 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.

The relevant value to be obtained from the long-term response analysis is the most probable extreme value (MPEV) having a probability of level of 10^{-8} in terms of wave encounters.

SECTION 5 Equivalent Wave

1 General

An equivalent wave in deep water 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 parameters is given below in Subsections 5/3 through 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 amplitude of the equivalent wave is given by:

$$a_{wj} = \frac{MPEV_j}{Max\, RAO_j}$$

where

a_{wj} = 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 criterion, See Subsection 4/7.

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

5 Wave Frequency and Length

The frequency and length of the equivalent wave 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:

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

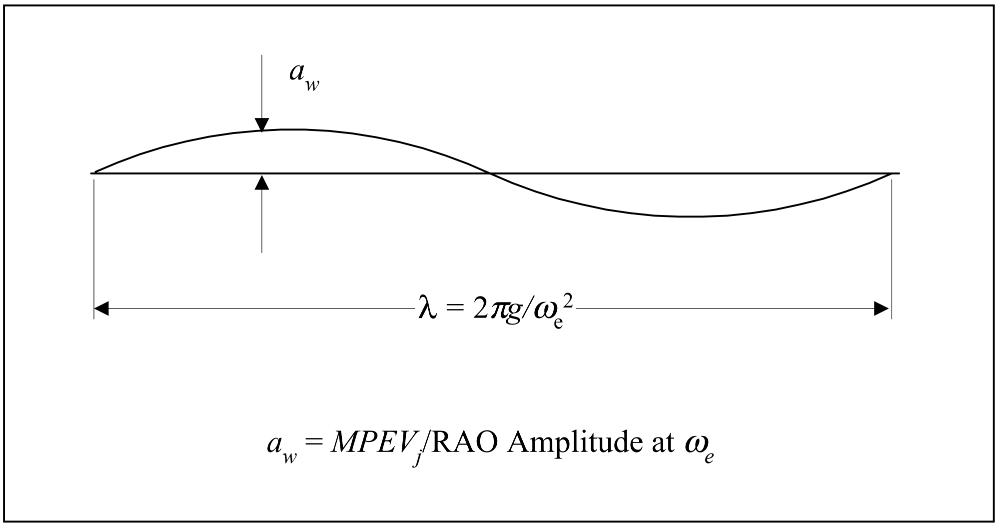
where

λ = wave length.

g = acceleration due to gravity.

ω_e = frequency of the equivalent wave

FIGURE 1
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 = wavelength

$\in$ = phase angle of DLP in degrees with respect to the wave crest

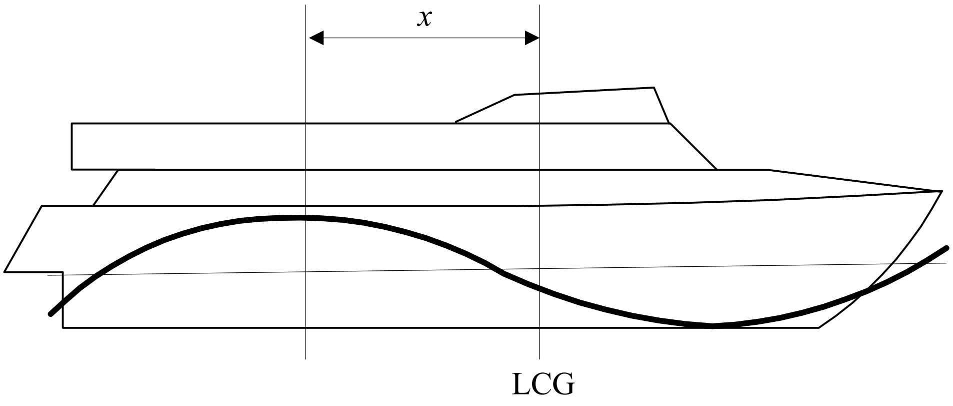
β = wave heading

Section 5, Figure 2 illustrates the crest position X.

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

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

FIGURE 2
Wavelength and Crest Position



$$x = \lambda\varepsilon/-360\cos\beta$$

9 General Procedure to Determine Other 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 = time under consideration.

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 RAO, at selected points on the external contours of the hull sections, are to be calculated 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 craft motion. Components of the hydrodynamic pressure are to be calculated from the panel model analysis of 4/5.5.

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 FE 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 FE 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 craft 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 craft'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 craft's axis system at a tank boundary point

5 Roll and Pitch Motions

The influence of ship motions on the tank pressures is to be taken into account using the maximum pitch and roll angles. As reflected in the previous formulations, the inclination of the tank due to craft 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

At each wave condition, for each load case described in Subsection 2/5, 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.

SECTION 8 Acceleration and Motion-induced Loads

1 General

Local accelerations at points where the lightship weight of the structure, (non-liquid cargo), are located including deck mounted equipment, should be calculated to determine the motion induced loads. For vehicle decks, wheel loading should be applied on hull structures. An evenly distributed load equivalent to the weight of the vehicles may be used.

3 Local Acceleration

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

$$A = (R \text{ x } \theta)\ \omega_e^2 + a$$

where

R = distance vector from the craft's center of gravity CG to the point of interest

θ = rotational motion vector

x = cross product between the vectors

a = translational acceleration vector

ω_e is as defined in Subsection 5/9.

The components of the gravitational acceleration in the craft's coordinate system are to be included.

5 Inertial Loads in the Structural FE 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 defined in Subsection 5/9.

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

$$F = m(A_t)$$

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

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

SECTION 9 Loading for Global Finite Element Model

1 General

The load cases of Subsection 2/5 are to be applied to the global (whole craft) 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 are to be included in the hydrostatics 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. The magnitudes of the unbalanced forces, and the procedure used to balance the structural model in equilibrium should be fully documented.

5 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 be comprised of the entire hull. 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 such as those due to hull slamming, that are critical for high-speed craft. 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 in the local models to assure appropriate structural continuity and load transfer between the various levels of models.

SECTION 10 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 a number of finer mesh models for local structures. 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

5 3-D Global Modeling

The global structural and load modeling should be as detailed and complete as possible. The stress results of the global model are used only to assess the hull girder plating of the deck, side shell, bottom, inner bottom, longitudinal bulkheads, transverse bulkheads and stools or deck box girders. The assessment of the main supporting members of the hull girder is performed using 2-D fine-mesh local models. Therefore, in developing the 3-D global finite element model, special attention should be paid to the following general rules:

i) The finite element model should include all primary load-carrying members. Secondary structural members which may affect the overall load distribution should also be appropriately accounted for.

ii) Structural idealization should be based on the stiffness and anticipated response of the structure, not wholly on the geometry of the structure itself. A common mistake is to simply match the finite element mesh with the structural configuration. Very often a finite element model created this way "looks good" and represents the structural geometry well, but in reality represents the structural properties and performance poorly.

iii) It is important to consider the relative stiffness between associated structural members and their anticipated response under the specified loading.

iv) In general, the finer the mesh, the more accurate are the results. (A coarse mesh tends to be stiffer.) 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.

v) The finite elements, whose geometry, configuration, and stiffness closely approximate the actual structure, can typically be of three types:

truss or bar elements with axial stiffness only,

beam elements with axial, shear, and bending stiffness, and

membrane plate elements, either triangular or quadrilateral.

vi) 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.

It is useful to lay out grids and key points directly on the structural drawings. Definition of elements as to their types, scantlings, and connectivity can also be best accomplished directly on the drawings. In doing so, the possible high stress areas where finer meshes are desired, and locations where boundary displacements need to be applied are also more readily identified.

The general rules for developing the 3-D coarse mesh global model, indicated in Subsection 10/5, are also applicable to the development of the 2-D fine-mesh models. In addition, the following general rules concerning modeling techniques for the 2-D models should also be closely observed:

i) The mesh size of the 2-D finite element model can best be determined by adequately modeling the stiffness of the individual structural members forming the local structure.

ii) In modeling a local transverse structure, the web plating is modeled by membrane plates, using both quadrilateral and triangular elements. Stiffeners on the web plating such as panel breakers, tripping brackets, flat bar stiffeners, etc., and the face plates of the webs are modeled by rod elements of equivalent cross sectional areas. Where face plates on brackets are tapered at the ends, the area of the rod elements should be reduced accordingly. The out-of-plane hull girder plating (i.e. deck, side shell, bottom shell, girders, etc.) is also modeled by rod elements, using an appropriate effective width.

iii) The mesh size used should be adequate to represent the overall stiffness of the considered local structure as a whole such that smooth stress distributions in the structure can be obtained. Too fine an overall mesh is considered unnecessary. The 2-D fine-mesh analysis is for the purpose of determining local stresses in the local structure, not for determining stress concentrations in cutouts or at the discontinuities of detail connections in the local structure.

iv) It is often desirable to use finer meshes in the probable high stressed areas in order to obtain better and more accurate stress distributions for these areas. As such, the use of a uniform mesh with smooth transition and with avoidance of abrupt changes in mesh sizes is recommended. Using a varying mesh size in 2-D models is usually more flexible and can be easily accomplished.

v) In laying out the mesh, the shapes of membrane elements created should be as regular as possible. Shapes that are too irregular can often result in distorted stresses in the elements. As a general rule, it is preferable to keep the aspect ratios of plate elements within 2:1. Using elements with an aspect ratio higher than 5:1 is usually not advisable, however they may be used for convenience of modeling in way of low stress areas, or areas of low interest.

vi) The grid line spacing and element sizes for the transverse section can generally be determined by the spacing of the longitudinals on the bottom shell, inner bottom, and top side tank. The grid lines can either be in line with the longitudinals, or for a finer mesh, an additional one division can be added between the longitudinal spacing. This is usually an adequate mesh size to create the appropriate mesh for the transverses.

vii) Cutout openings for longitudinals need not be considered in the 2-D models. (To consider cutouts, much finer meshes are required.) Access holes can also be ignored because it is difficult to model them properly with the mesh size used. This is also true for all lightening holes or other small openings in the webs.

viii) In local hull structures, there are numerous stiffeners, panel breakers, and ribs to prevent local buckling. The majority of these stiffening members do not significantly affect the stress distribution in the structure, since many of them are normal to the principal direction of stress. However, if the stiffeners are parallel to the principal direction of stress, e.g. parallel to the flange of a bracket, they contribute significantly in reduction of stresses, and should be accounted for. More importantly, the stiffening members and their associated panel definition should be modeled accurately, since buckling is one of the failure modes the structures are being assessed against.

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 model.

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

A number of transverse web frames;

Centerline longitudinal girder;

Bottom, side and deck longitudinals;

Horizontal stringers of watertight transverse bulkhead;

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

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 craft, 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

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. Although the acceptance criteria apply only to craft of steel and aluminum, similar criteria are expected to be valid, in principle, for craft built of other materials, but not mentioned in this Guide.

The choice of a suitable aluminum alloy for any structural component should take into account a combination of factors including strength, corrosion resistance, formability, weldability, and resistance to brittle fracture. The 5000 series alloy sheets and plates are widely used in shipbuilding due to their industrial availability and the good compromise among these factors. The welded yield strength is the most critical mechanical property for welded aluminum alloys. A welded member is normally weaker than an extruded member because of the likely softening in the heat-affected zone. The minimum requirements for the yield strength of welded aluminum plates are specified in the *HSC Guide* Table 2/E.1 or the *HSNC Guide* 2-5-A1/Table 2.

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 total equivalent stress is to be based on the Hencky von-Mises criterion as the following equation:

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

where

σ_X = normal stress in the X coordinate direction of the element

σ_Y = normal stress in the Y coordinate direction of the element

τ_{XY} = in-plane shearing stress

The total equivalent stress (von-Mises stress) is to be less than or equal to 95% the material's yielding strength for steel and 85% for aluminum. The reduced yield strength of welded aluminum should be based on the *HSC Guide* Table 2/E.1, or the *HSNC Guide* 2-5-A1/Table 2.

5 Buckling and Ultimate Strength

Plate panels, stiffened panels and primary supporting members are to be checked against buckling and ultimate strength using stresses obtained from FEM analyses. For this purpose, established analytical or empirical formulas suitable to the hull structure, such as 5-1-5/5.3 and 5-1-5/5.11 of the ABS *Steel Vessel Rules* (SafeHull Criteria) are to be used.

The problem of structural instability can be treated at the classical, bifurcation-type level or the ultimate strength level. Plate buckling between stiffeners in the elastic range is considered acceptable because elastic buckling is not a catastrophic phenomenon. The ultimate strength of plate panels and stiffened panels, a more rational measure of structural strength, is to comply with the minimum requirements, while the buckled plates between stiffeners may be replaced with a reduced effective width.

Plate panels and stiffened panels are generally subjected to loads due to hull girder bending and shear and water pressure. Combined loads include bi-axial compression/tension, edge shear and compression/tension, in-plane loads and lateral pressure. The effects of combined load components should be accounted for, and the interaction formulae for combined loads should be applied.

Proper modifications to the buckling and ultimate strength criteria should be made, taking into account the differences in gross scantling in DLA. 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.

SECTION 12 Additional Considerations

1 Slamming Loads – General Considerations

Loads due to slamming and wave impact on craft hulls are of particular significance to high-speed craft. As for the case of conventional vessels, these loads can be categorized into two: global slamming effects and local slam-induced structural response.

3 Global Slamming Effects

Slamming loads cause whipping response of the entire hull particularly for high-speed craft operating in severe seas. The resulting dynamic stresses in the hull girder can be of the same order of magnitude as those induced by quasi-static wave bending moments. But their frequencies are much higher than those generated by wave and motion-induced loads, closer to the lowest natural frequency of the hull girder. Therefore, slam-induced whipping response of the hull could also have significant influence on the strength requirements.

Simplified formulae given in ABS Rules may be used to account for global slamming effects in the preliminary design stage. These are typically expressed as an equivalent quasi-static increment over the wave-induced sagging moment as a function of the size and speed of the craft. The total moment is then super-imposed on the still-water sagging moment.

For detailed analysis, direct time-domain simulation involving short-term predictions are recommended as a minimum requirement for strength assessment for monohulls. In most cases involving high speeds, the absolute motions or relative motions will be of such large amplitude that nonlinear calculations will need to be employed. For fatigue life prediction, cycle counting methods must be applied at least in certain stages of the analysis. In catamarans, wet deck slamming causing global whipping of the entire hull is common. This involves coupling of symmetric and anti-symmetric modes of responses, the calculations of which will also require time-domain analysis methods.

5 Local Impact Loads

Panel structures with horizontal flat or nearly flat surfaces such as a wet deck of a multi-hull craft are subject to slamming pressures that are significantly influenced by elastic deformation. The peak slam pressures experienced are not good measures of the resulting peak structural responses. A common procedure followed by designers is to estimate slamming pressure and apply it statically to calculate the response of the local structure. This can lead to very conservative designs, if semi-empirical or measured slamming pressures are used. To realistically assess the strength of these structures, the impacts need to be hydroelastically modeled, wherein the dynamics of the fluid and the elastic response of the plate and stiffeners are simultaneously modeled.