GUIDANCE NOTES ON

STRUCTURAL DIRECT ANALYSIS FOR HIGH-SPEED CRAFT

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Foreword

These Guidance Notes are an extensive revision of and supersede the ABS *Guidance Notes on 'Dynamic Load Approach' and Direct Analysis for High Speed Craft* (February 2003). This revision is effective 1 April 2011.

These Guidance Notes provide information about the analysis procedure for Structural Direct Analysis, which is available to assess the strength of high-speed craft and high-speed naval craft. In addition, they provide 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 "these Guidance Notes".

Sections 1-1-3 and 1-2-2 of the ABS *Rules for Conditions of Classification – High-Speed Craft (Part 1)* contains descriptions of the various basic and optional classification notations available for high-speed craft. The requirements for Direct Analyses are specified in Section 3-1-3 of the ABS *Rules for Building and Classing High-Speed Craft (HSC Rules)*.

Sections 1-1-3 and 1-3-2 of the ABS *Rules for Conditions of Classification – High-Speed Craft (Part 1)* contains descriptions of the various basic and optional classification notations available for high-speed naval craft. The requirements for Direct Analyses are specified in Section 3-1-3 of the ABS *Guide for Building and Classing High-Speed Naval Craft (HSNC Guide)*.

Users of these Guidance Notes are welcomed to contact ABS with any questions or comments concerning these Guidance Notes. Users are advised to check periodically with ABS or by visiting the Rules and Guides section of the ABS website (www.eagle.org) that their version of these Guidance Notes is current.

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GUIDANCE NOTES ON

STRUCTURAL DIRECT ANALYSIS FOR HIGH-SPEED CRAFT

CONTENTS

SECTION 1 Introduction

1 Background

1.1 Types of High-Speed Craft

The size, speed, and installed power of high-speed craft and/or high-speed naval craft have steadily increased. Most of the craft built during the last decade may be categorized into the following three groups:

- Mono-hulls
- Catamarans
- Trimarans

A clear trend in the above types of high-speed craft is a continual increase in the length and complexity of craft that are being built. Most early high-speed craft were of the planing and semi-planing type, while the later and most recent builds have been shifting into the domain of the semi-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 high-speed craft.

Distinct from the design criteria used for planing or dynamically-supported craft, where hydrodynamic impact governs the structural loads, these changes have brought about a shift of emphasis in load types and combinations, with global hull girder 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 multi-hulls 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, however, are stipulated in the following documents:

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

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

1.5 Naval Requirements

ABS, with the assistance of the U.S. Navy, has developed the *HSNC Rules* for high-speed craft for a range of operations. Naval requirements specify that high-speed craft are to be designed to technical standards that will provide 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 Rules*, especially if initially designed or classed for restricted service. This safety evaluation will invariably require a structural assessment that involves direct analysis designed to identify the operational limits.

3 The Concept and Benefits of Structural Direct Analysis (SDA)

Direct analysis for high-speed craft provides enhanced structural evaluation capabilities to assess the adequacy of a structural design. In principle, a minimum requirement of direct analysis is that the preliminary design of the structure be in accordance with the *HSNC Rules* criteria. Should the direct analysis results indicate the need to increase basic scantlings, this increase is to be accomplished to meet the acceptance criteria of the direct analysis. If, however, these Guidance Notes are being used for alternative structural design in consultation with ABS and Naval Administration, scantling reductions justified by the results of the analysis may be considered.

The structural design portions of the *HSNC Rules* (i.e., especially Part 3, Chapter 2) are intended to provide the basis for a preliminary step-by-step design procedure of the structure of a high-speed craft. On the other hand, direct analysis is a process that emphasizes completeness and realism in both the extent of the structure modeled and the craft's loading conditions considered. The modeling and analysis process utilizes 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 this direct analysis method is the use of an advanced computational tool based upon linear and/or nonlinear seakeeping theory for calculating ship motions and wave-induced load effects in design wave conditions that best characterize the environmental and operating conditions of the craft.

The enhanced realism provided by the direct analysis approach has benefits that are of added value to the overall structural safety evaluation based on the attributes mentioned above. Additionally, the knowledge of structural behavior gained through this analysis is very useful in realistically evaluating and developing inspection and maintenance plans especially for aluminum and FRP hulls. Another potentially valuable benefit of direct 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 records or previous experience. This is discussed in detail in these Guidance Notes.

Global wave-induced load effects on high-speed craft are not significantly affected by elastic deformations in most cases because the rigid body motions are dominant. In this case, the external impact loads (generally called slamming loads), such as those due to bottom slamming, are determined through motion analysis. The slamming loads can then be applied to the structure to obtain the elastic hull girder responses, (generally called whipping responses).

For the enhanced structural assessments of modern high-speed craft, the slamming and whipping loads, in addition to the traditional wave-induced loads, are to be considered in the derivation of structural responses.

An addition to direct analysis would be to derive structural load effects from physically scaled model tests. Brief guidance on models used for this task is discussed in Subsection 14/7. Rigid models may be adequate for direct measurements of wave-induced ship motions and slamming pressures, which are not significantly affected by elastic deformations. For direct measurement of wave induced springing and whipping loads, where flexibility and dynamics of the hull structure are important, use of a flexible model, dynamically scaled to represent hull girder structural characteristics, is recommended. This can be realized using either a continuous elastic model or a segmented model with elastic backbones.

5.3 Fatigue

The main factors that contribute to general fatigue problems are material used for construction, welding methods, and connection details, along with the stress range and the number of stress cycles.

High-speed craft are usually designed for optimized structural weight, which results in increased flexibility of the hull. The combination of the increased hull flexibility and the higher encounter frequency due to high operational speed would tend to accelerate fatigue damage.

While fatigue analysis is not a condition for classing high-speed craft, a fatigue assessment is recommended, especially for craft with novel hull forms.

5.5 Vibration

Generally, vibration analysis is not a requirement for classing high-speed craft. However, in some high-speed craft designs subject to 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. The methods for dynamic response analysis developed for conventional vessels can be applied to vibration problems on high-speed craft. However, when applicable, the flexible stiffness and 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 high-speed craft fitted with water-jet propulsion.

5.7 Hydroelastic Considerations

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 operates 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 known to be of a hydroelastic nature. 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) 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 close to the natural period of the structure. 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 and cushioning effects will be significant, as they tend to lengthen the duration of impact.

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 impact rise time to the first natural period of vibration of the dry panel structure is greater than 2.0, the effect of hydroelasticity may be neglected. On the other hand, if the ratio is less than 2.0, the hydroelastic structural response of the panel is recommended to be taken into account in the calculation of impact loads on the panel.

7 Scope and Overview

Structural direct analysis is a strength assessment methodology based on first principles approach. In this regard, acceptance criteria are applied to verify 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 1-1-4/5.1 of the ABS *Rules for Conditions of Classification – High-Speed Craft (Part 1)*. The Guides also note that Supplementary Analyses may be required. The most likely such requirements are fatigue and vibration analyses. While outside the scope of these Guidance Notes, they are, nevertheless, discussed in general terms. However, these Guidance Notes do not provide specific guidance for assessing these failure modes.

Section 1, Figure 1 shows an overview of the SDA procedures for high-speed craft, wherein the strength analysis is highlighted and the supplementary analyses are shown shaded. In these Guidance Notes, special consideration is provided to include the slamming and whipping load effects in the strength analysis.

These Guidance Notes systematically introduce the analysis procedures in the load formulation, and the methodology underlying the analysis procedures used in applying direct analysis to high-speed craft. These include the following topics:

- Specification of the loading conditions and load cases
- Environmental and service conditions
- Formulation of equivalent design waves
- Calculation of nonlinear wave loads
- Structural finite element (FE) model development
- Strength analysis
- Application of the acceptance criteria

These topics are presented in the following Sections 2 through 14. Refer to Section 1, Figure 2 for a schematic representation of the steps involved in the direct structural analysis procedure.

A report detailing the analysis should be submitted for review and approval along with finite element models used in the analysis. As a minimum the report should include the following information:

i) Craft's loading conditions and weight distribution

ii) Craft's operational profile or Wave Scatter data for the area of operation

iii) A brief description of all software used in the analysis

iv) A detailed description of the analysis procedure and steps

v) All results of the hydrodynamic analysis and results of the Extreme Values analysis

vi) Model test data, with a comparison with analysis results (if applicable)

vii) Material properties and the allowable stresses applicable to the craft

viii) A brief description of the Finite Element model and the mesh size used

ix) Details of the Finite Element Analysis results

x) Graphs for all areas of non-compliance

xi) Detailed discussion of non-compliance areas and proposed fixes

xii) Description of the buckling analysis and a sample calculation

xiii) Any other available information related to the analysis

FIGURE 1
Overview of the Structural Direct Analysis for High-Speed Craft

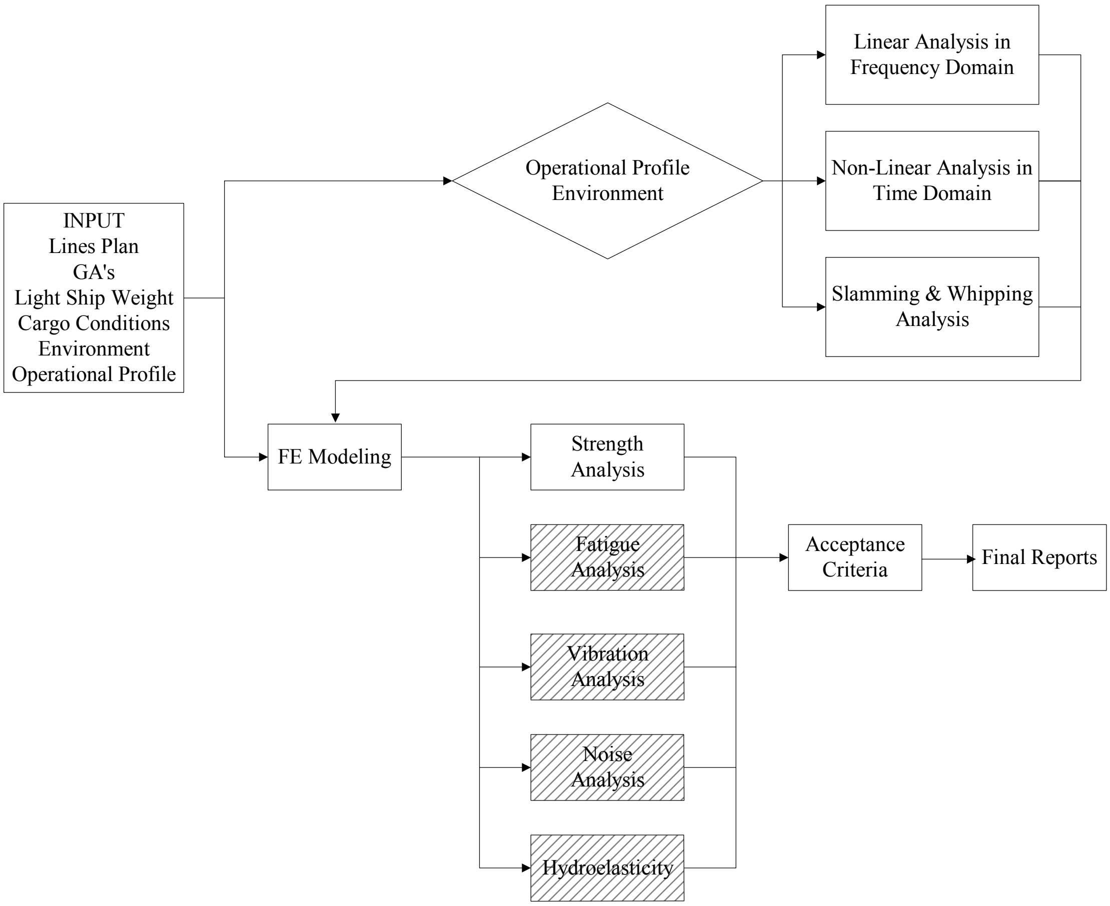
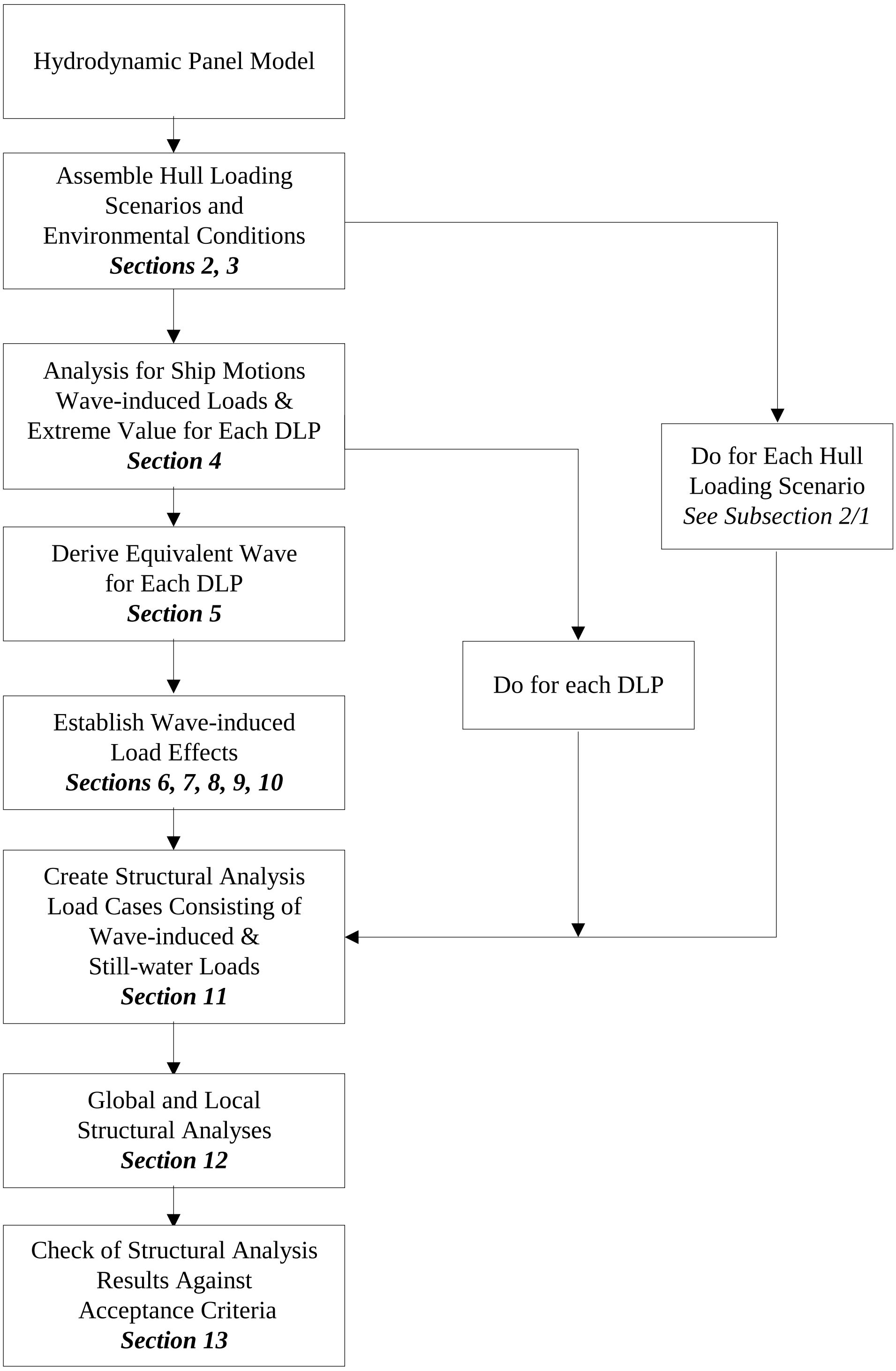


FIGURE 2
Schematic of the Structural Direct Analysis Procedure



SECTION 2 Loading Conditions and Load Cases

1 Loading Conditions

The design of a high-speed craft takes into account the most critical operational profile, the load capacity, and the structural arrangement. Hence, the loading conditions directly relate to the cargo and ballast loading patterns and craft's draft conditions. The following loading conditions are to be selected as representative conditions in the direct analysis:

i) Full Load Departure

ii) Minimum Operation Arrival

For special designs or operations, additional loading conditions will be required by ABS on a case-by-case basis.

3 Dominant Load Parameters (DLPs)

Dominant Load Parameter (DLP) refers to a ship motion or wave load effect (such as vertical acceleration or vertical bending moment in hull girder) that represents the extreme response of the craft. A proper selection of dynamic load parameters is required to effectively construct the load cases for FE structural analysis.

3.1 Mono-hull High-Speed Craft

For mono-hull high-speed craft, the dominant load parameters include:

i) Vertical bending moment amidships

ii) Vertical shear force at 0.25L and 0.75L from AP

iii) Vertical acceleration at bow

iv) Roll motion

v) Relative vertical velocity at bow

3.3 Multi-hull High-Speed Craft

For multi-hull high-speed craft, the dominant load parameters include:

i) Vertical bending moment amidships

ii) Vertical shear force at 0.25L and 0.75L from AP

iii) Vertical acceleration at bow

iv) Roll motion

v) Vertical and lateral shear at haunch

vi) Longitudinal shear along centerline of connecting structure

vii) Squeezing/prying moment

viii) Pitch torsion (connecting) moment

ix) Yaw splitting moment

x) Relative vertical velocity along centerline of wet deck

5 Load Cases

5.1 Basic Considerations

Structural direct 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 craft loading (see Subsection 2/1)
- Dominant load parameters (see Subsection 2/3)
- 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 of the craft. 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 FE 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 dynamic load established for a specific DLP (Subsection 2/3), and other loads accompanying the DLP (Subsection 2/7). A large number of load cases result from the hull loading conditions and the number of DLPs considered. They are to be screened and the most critical load cases are to be selected for the comprehensive global structural analyses outlined in Section 11.

The load cases considered possess the following attributes:

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

ii) They use equivalent design waves and/or design sea states that reflect the craft's extreme responses and wave environmental conditions

iii) Dominant load component and other accompanying 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 composed of combinations of a dominant load component and the other significant load components that are considered to accompany the dominant load component that is characterized by a DLP.

In general, the external pressure on the craft's hull combines with the hydrostatic pressure and wave-induced dynamic pressure. Hydrostatic pressure used in the analysis takes into account variations in immersion as the result of the combined effect of craft motions. Dynamic pressure combines the incident wave effects (Froude-Krylov), as well as the diffracted and radiation wave effects.

Typical DLPs that are recommended for structural direct 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 pressures, inertial loads from weights (including structural lightweight), weights of vehicles, and external forces from the actuation of control surfaces (such as those from canards, fins, rudders, etc.).

An equivalent design wave is determined through a process where each dominant load is analyzed to establish its *Response Amplitude Operator* (RAO) and extreme-value. The design wave defined by the amplitude, frequency and heading is considered equivalent in the sense that, when it is imposed on the structural model, it produces the long-term extreme value of the DLP. The process to perform this derivation is given in Sections 4 and 5.

As an alternative or additional approach to the equivalent design waves, the design sea states may be considered for direct analysis of high-speed naval craft. The design sea states are defined by the significant wave height and ship speed, as specified in 3-2-2/1.1 of the *HSNC Rules*. The design sea states for a specific high-speed naval craft are to be verified by Naval Administration (see 3-1-1/23 of the *HSNC Rules*).

The dominant and accompanying load components are to be directly calculated from linear or nonlinear seakeeping analysis to establish a load case. The process to perform the nonlinear seakeeping analysis is given in Section 6.

In these Guidance Notes, emphasis is given to the essential elements of load case creation using DLPs and the nonlinear seakeeping analysis to obtain the 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 ship motion, wave load analysis, and spectral analysis.

The other load components accompanying the dominant load component are to be directly calculated from the seakeeping analysis. The procedures to establish these load components accompanying the DLP are given in Sections 7, 8, and 9.

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 design regular waves or sea states. The calculation techniques to develop the accompanying load components are presented in later Sections as follows:

- Section 7 – External hydrodynamic pressures
- Section 10 – Internal pressures due to liquid fuel and cargo ballast tank wetted boundaries
- Section 11 – Motion-induced loads from the structural components and concentrated wheel loads from vehicles

9 Miscellaneous Loads

Other loads, such as those due to springing loads and fluid-structure interaction effects on local structures are only briefly discussed in this document (see Section 14). The loads resulting from these are to be treated using independent analysis or, if applicable, in accordance with the current *HSNC Rules* requirements.

Additional considerations that can be accommodated in 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

SECTION 3 Environmental Conditions

1 Basic Considerations

The environmental conditions required for direct analyses of high-speed craft are outlined in this Section. 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 ship motions and wave loads 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 direct analysis method of these Guidance Notes. The sources of the data, and the data's expected reliability should also be documented in the submitted report.

3.3 Special Wave Data Needs

Waves usually produce the dominant environmentally induced load effects. Therefore, 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, spectra developed for the specific route or regions are to be used. These environments 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 JONSWAP spectrum is to 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 a high-speed craft is to operate in a fully developed wave environment for unrestricted service, two-parameter spectra, such as the Bretschneider or P-M wave spectrum are to be used. 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, wave loads and their extreme values. 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 which will be used to determine the equivalent design wave in Section 5.

3 Still-water Loads

With the input of hull loading (see Subsection 2/1), the hull girder still-water shear force and bending moment are to be computed at a sufficient number of transverse sections along the hull length taking into account discontinuities in the weight distribution. A recognized hydrostatic analysis program is to be used to perform these calculations. The calculated displacement and longitudinal center of gravity (LCG) 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 calculation of RAOs for ship motions and wave loads, a recognized seakeeping analysis program is to be used. 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 ship motion and wave load RAOs are to be carried out through the application of linear seakeeping analysis codes utilizing three-dimensional potential flow based diffraction-radiation theory. As a minimum, all six degree-of-freedom rigid-body motions of the hull are to be considered. The effect of hull lift on motions is to be 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 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 the Rankine source panel method is recommended for solving the hydrodynamic boundary value problem. The Rankine sources have to be distributed not only on the hull surface but also on the free surface.

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 which take into account the coastal routes of operations and the relatively high forward speed of the craft. Considering the craft length and relatively high encounter frequencies, a frequency range between 0.3 rad/s and 1.5 rad/s in increments of 0.05 rad/s is to be used.

The worst frequency-heading (ω,β) combination is to be determined from an examination of the RAOs for each DLP. The heading, β_{max}, and the wave frequency, ω, at which the RAO of the DLP reaches the maximum, are to be used in the determination of equivalent design waves. In general, VBM and V_{acc} are at maximum in head and bow seas, while maximum L_{acc} and ϕ are realized in oblique seas. Precise headings at which these are at maximum are to be determined from the RAO output.

7 Extreme Values Analysis

Extreme value analysis is to be performed for each DLP to determine the equivalent design waves for use in the direct analysis. Preference is given to an extreme value method that follows the so-called long-term approach commonly used for strength assessment of craft structure. However, the use of a validated short-term extreme value approach, which corresponds to the craft type and route-specific environmental data, can also be considered.

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

SECTION 5 Equivalent Design Waves

1 General

An equivalent design wave is a sinusoidal wave characterized by its amplitude, frequency and heading. For each load case, an equivalent design wave is determined which simulates the magnitude and location of the extreme value of the dominant load component of the load case.

The procedure to be used to determine the equivalent wave parameters is given in this Section. Note that the equivalent design waves represent extreme wave conditions at a long-term probability level of 10^{-8}, which corresponds to the survival condition of high-speed naval craft. Therefore, unless otherwise specified, the craft speed is assumed to be 10 knots.

3 Equivalent Wave Amplitude

The 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:

$$a_{wj} = \frac{LTR_j}{\max RAO_j}$$

where

a_{wj} = wave amplitude, see Section 5, Figure 1

LTR_j = long-term 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 Dominant Load Parameter's RAO

5 Wave Frequency and Heading

The wave frequency and heading of the equivalent wave are determined from the peak RAO of each Dominant Load Parameter. When the RAO reaches its maximum, the corresponding peak frequency and heading are denoted by (ω,β). The wavelength of the equivalent wave system is calculated by:

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

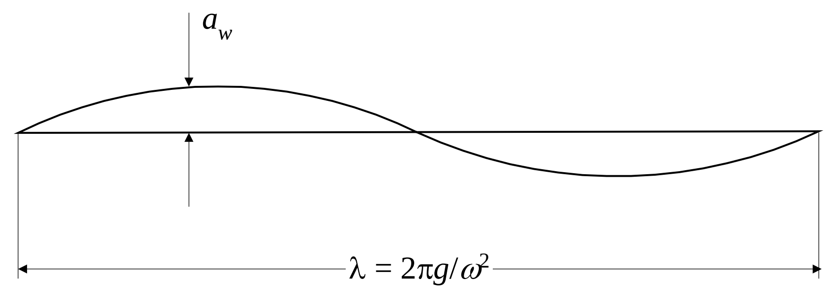
where

λ = wave length.

g = acceleration due to gravity.

ω = wave frequency of the equivalent wave

FIGURE 1
Equivalent Wave Amplitude



$$a_w = LTR_j / RAO_j^{\max}$$

SECTION 6 Nonlinear Seakeeping Analysis

1 General

For the equivalent design waves defined in Section 5, a nonlinear seakeeping analysis is to be performed to establish the instantaneous design loads at a specific time instant when each DLP reaches its maximum.

As an alternative approach, a nonlinear seakeeping analysis for design sea states is to be considered to supplement or substitute the equivalent design wave approach. The required design sea states for high-speed naval craft are defined in Part 3 of the *HSNC Rules*.

3 Nonlinear Seakeeping Analysis

Under the equivalent design waves and/or design sea states, the ship motions and wave loads are expected to be highly nonlinear, mainly due to the hydrodynamic interaction of incident waves with hull geometry above the mean waterline.

Hence, as a minimum requirement, a nonlinear seakeeping analysis needs to include the hull geometry above the mean waterline in consideration of:

i) Nonlinear hydrostatic force, and

ii) Nonlinear Froude-Krylov force

Calculation of hydrostatic and hydrodynamic pressures on the instantaneous wetted hull surface below the incident wave elevation are required.

A nonlinear seakeeping analysis in time domain is recommended to effectively account for the instantaneous nonlinear ship motions and wave loads. LAMP or equivalent computer programs may be used to perform these calculations.

5 Modeling Consideration

For a nonlinear seakeeping analysis, the 2D strip method or 3D panel method is to be used in time domain. In general, the 3D panel method can provide accurate modeling of the three-dimensional free surface flow effect around the hull.

5.1 Mathematical Model

For mathematical modeling using the 3D panel method based on potential flow theory, two alternative formulations may be considered: mixed-source formulation or Rankine source formulation. The mixed-source formulation requires a matching surface, which is the outer surface surrounding the hull surface and free surface. In the mixed-source formulation, the inner fluid domain inside the matching surface is formulated by a Rankine source, while the outer fluid domain outside the matching surface is formulated by a transient Green function. The velocity potentials of the inner and outer domains should be continuous at the matching surface.

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

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

5.3 Numerical Course-keeping Model

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

For the numerical course-keeping model, one of the following two models is to be used: a rudder-control system or a numerical soft-spring system. The rudder-control system, based on a simple proportional, integral and derivative (PID) control algorithm, may be used to control the rudder angle during the motion simulation. This system may be effective for a craft cruising at design speed in moderate sea states. However, for a craft operating in severe wave conditions at reduced speed, the rudder-control system is likely to get saturated causing a subsequent loss of control.

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

7 Nonlinear Instantaneous Load Components

From the nonlinear seakeeping analysis, the nonlinear instantaneous ship motions and wave loads are to be determined at the instant when each DLP under consideration reaches its maximum. The ship motions are to include all six degrees-of-freedom rigid-body motions.

The wave loads are the sectional loads acting on the hull along the craft length. The wave loads are obtained by integrating the nonlinear hydrostatic and hydrodynamic pressure acting on the instantaneous wetted hull surface as well as the inertial forces acting on the mass distribution of the cargo and lightship structure along the craft length.

To determine the nonlinear instantaneous load components accompanying the DLP, a specific instant of time is to be selected when the DLP under consideration reaches its maximum. For the regular wave simulation in equivalent design waves, simulation time is to be sufficiently long so that the response of the DLP reaches a steady state. General practice is that the simulation time is longer than twenty wave cycles and the first ten wave cycles may be ignored as a transient response. For the irregular wave simulation in design sea states, the simulation time may be longer than 10^3.

SECTION 7 External Pressure

1 General

For each Load Case defined by the DLP under consideration (see Subsection 2/7), the external pressure on the wetted hull surface is to be calculated using equivalent design waves or design sea states.

3 External Pressure Components

The external pressure is to include hydrostatic pressure, the pressure components due to waves, and the components due to craft motion. Components of the external pressure are to be calculated from the nonlinear seakeeping analysis.

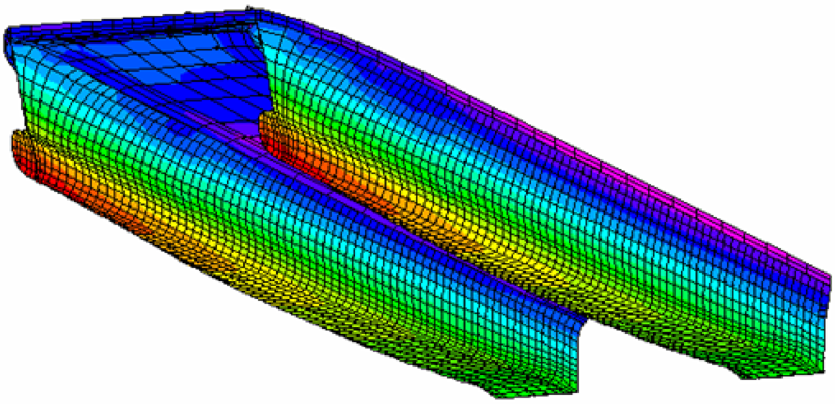
5 Pressures Accompanying the Dominant Load Component and Their Distribution

The simultaneously-acting external pressures accompanying the DLP are to be calculated at the specific time instant when the DLP reaches its maximum value. The instantaneous pressure distribution is to be calculated directly from the nonlinear seakeeping analysis (see Section 6).

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.

FIGURE 1
Instantaneous Pressure Distribution on FE Model of Multi-hull



SECTION 8 Slamming Loads

1 General

Loads due to slamming and wave impact can be significant, particularly for high-speed craft operating in severe seas. Special attention should be paid to the bottom and bowflare slamming on mono-hulls and wet-deck slamming on multi-hulls.

Slamming is a nonlinear impact load with very short duration acting on the craft, usually occurring in severe seas. A slamming analysis is to be performed using nonlinear seakeeping program or Computational Fluid Dynamics (CFD) method.

3 Slamming Analysis

Slamming events occur when a portion of the hull comes out of the water and then enters the water with a downward velocity. Slamming is a very complicated and challenging hydrodynamic problem involving fully-nonlinear three-dimensional free-surface flows. Other than scaled model testing, few numerical tools are available for slamming analysis. Most traditional numerical tools are two-dimensional slamming solvers based on potential flow theory without considering the 3D flow effects or air cushioning effects. Therefore, numerical tools for slamming are to be validated by comparing numerical results with existing recognized experimental and/or theoretical results.

As a traditional approach, slamming loads are often calculated on a series of 2D sections of the hull. Once the relative motion and velocity of each 2D section are given from a ship motion analysis, the slamming loads on the section can be calculated as a post process using a boundary-element method or simplified wedge approximation.

The generalized Wagner approach solves an initial-value boundary-value problem to calculate the slamming loads using the boundary-element method. This approach requires a significant computational effort. The wedge approximation is a simplified method of calculating slamming loads based on relative velocity and time rate change of added mass of each section. The added mass of the section may be approximated by a semi-empirical formula for a symmetrical wedge-shaped section.

As an alternative approach, a CFD method may to be considered for slamming analysis. A qualified CFD code can provide fully-nonlinear wave-body interaction solvers considering the three-dimensional slamming loads on the craft in design waves.

When a CFD method is used for a slamming analysis, the following criteria are to be considered:

i) Fully nonlinear free surface condition is to be satisfied on the actual free surface. No linearization of the free surface is allowed. Air flow is to be modeled as incompressible or compressible flow, as applicable. Viscous boundary layer flow may be ignored for the slamming analysis.

ii) All the geometries above the main deck including any foredeck, bulwark or superstructure are to be properly considered in the numerical model.

iii) All six degrees-of-freedom motions of the craft are to be considered. For head sea condition, only heave and pitch motions are to be considered.

iv) Mesh size and time step are to be fine enough to capture the spatial and temporal distribution of slamming impact loads.

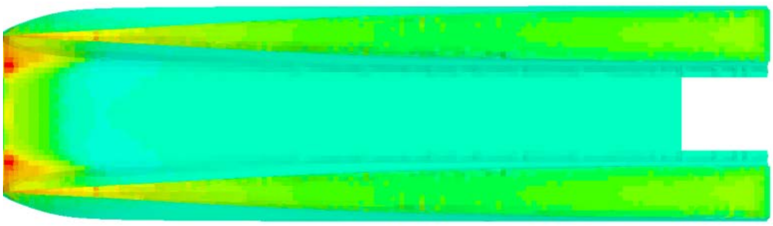
v) Global ship motions and local slamming pressures at any location are to be calculated. The instantaneous slamming pressure on the hull surface is to be mapped on the FE model.

CFD analysis is to be performed to calculate slamming pressure on the hull surface. Section 8, Figure 1 shows a typical example of the instantaneous slamming pressure distribution on a mono-hull, calculated from a CFD simulation when the slamming pressure at the bow bottom reaches its maximum. Section 8, Figure 2 shows the instantaneous slamming pressure distribution on a multi-hull when the wet-deck slamming pressure at the bow reaches its maximum.

The instantaneous slamming pressure distribution on the wetted hull surface is to be mapped on the FE model for the structural FE analysis. If the slamming impact duration is close to or shorter than the natural period of the hull girder structure, special attention is to be paid to the hydroelastic consideration, as given in 1/5.7. Otherwise, the instantaneous pressure distribution mapped on the FE model is to be assumed as a quasi-static pressure for the FE analysis.

FIGURE 1
Instantaneous Bottom Slamming Pressure on a High-Speed Mono-hull

FIGURE 2
Instantaneous Wet-Deck Slamming Pressure on a High-Speed Multi-hull



5 Whipping Analysis

Whipping is a transient hull girder vibratory response of the craft, mainly induced by slamming impact loads in severe seas. The whipping response is dominated by the two-node natural frequency of the hull girder, which is much higher than the wave excitation frequencies. Therefore, the influence of whipping response on the rigid-body motions and wave-induced loads are expected to be small, particularly for mono-hulls. In this regard, the whipping analysis is to be performed as a post process after the ship motion analysis is completed.

To calculate the hull girder whipping response of mono-hulls using a simple elastic beam model, the following equation is to be used:

$$f(x,t) = m(x)\frac{\partial^2}{\partial t^2} z(x,t) + \frac{\partial^2}{\partial x^2}\left[EI(x)\frac{\partial^2}{\partial x^2} z(x,t)\right]$$

where

$m(x)$ = sectional mass including added mass

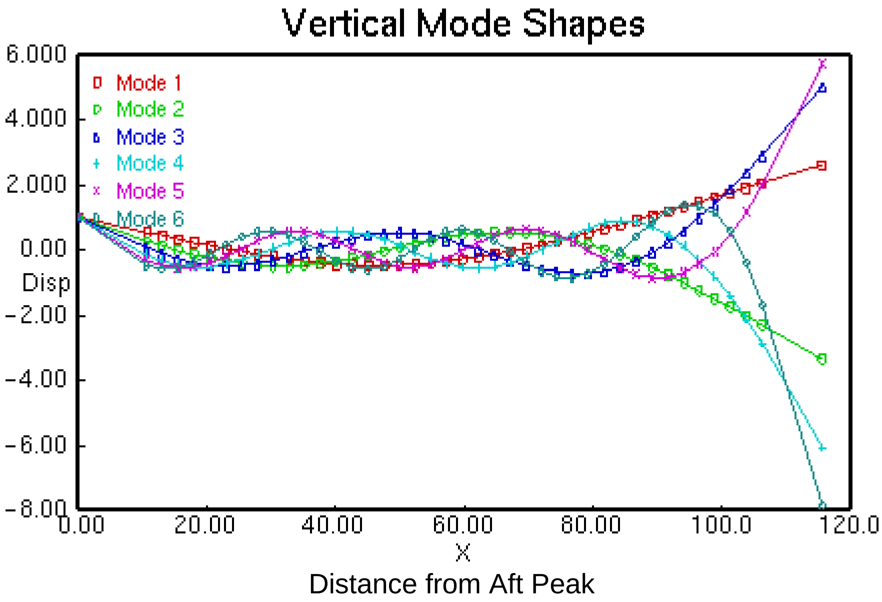
$I(x)$ = area moment of inertia

$f(x,t)$ = slam-induced sectional impact force

The mode shapes and corresponding natural frequencies need to be checked first to validate the sectional properties of the beam model under consideration. If possible, a free vibration analysis using a 3D FE model is to be performed to confirm the mode shapes and natural frequencies from the beam model. Section 8, Figure 3 shows typical mode shapes of a high-speed mono-hull in vertical mode.

For the whipping analysis of transient hull girder vibration, structural damping is to be considered. When structural damping of the craft is not available, typically 2-3% of critical damping may be used.

FIGURE 3
Sample Mode Shapes in Vertical Mode



SECTION 9 Internal Tank Pressure

1 General

The fluid pressure in cargo tanks is to be calculated and applied to the structural FEM model. 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 nonlinear seakeeping analysis discussed in Section 6.

The inertial component results from the instantaneous local accelerations of the tank content (liquid cargo or ballast) caused by the ship motions in six degrees of freedom. For this procedure, the vertical, transverse, and longitudinal accelerations due to ship motions are defined in the ship-fixed coordinate system. Therefore, transformation of the acceleration to the ship system due to roll and pitch inclinations is not needed.

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:

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

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_L, a_T, a_V	=	longitudinal, lateral, and vertical wave-induced accelerations relative to the craft's axis system at a point on a tank's boundary
g_L, g_T, g_V	=	longitudinal, lateral, and vertical components of gravitational accelerations relative to the craft's axis system at a tank boundary point
	=	$(-\sin\phi,\ g\sin\theta,\ g)$
θ	=	roll angle
ϕ	=	pitch angle

The influences of roll and pitch motions on the tank pressures are to be taken into account. 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.

5 Local Acceleration at the CG of Tank Content

The local acceleration of the tank contents, taken at the CG of the tank, due to ship motions is to be expressed by the following equation:

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

where

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

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

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

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

7 Simultaneously-acting Tank Pressure

For each DLP, the simultaneously-acting internal tank pressures are to be calculated on the tank boundaries due to the instantaneous motions and accelerations at the time instant when the DLP reaches its maximum value. These simultaneously-acting internal tank pressures are to be used in the structural FE analysis.

SECTION 10 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 is to be applied on hull structures. An evenly distributed load equivalent to the weight of the vehicles is to be used.

3 Local Acceleration

The local acceleration at a location of interest may be expressed by the following equation:

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

where

(a_L, a_T, a_V)	=	longitudinal, transverse, and vertical components of local acceleration
$\vec{a}$	=	surge, sway, and heave acceleration vector
$\vec{\Theta}$	=	roll, pitch, and yaw acceleration vector
$\vec{R}$	=	distance vector from the craft's center of gravity to the location of interest

5 Inertial Loads in the Structural FE Model

Static and dynamic components of the inertial loads are described in the following Paragraphs.

5.1 Static Load

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

$$F_S = mg$$

where

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

5.3 Dynamic Load

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

The inertial load is due to the instantaneous local acceleration on the lightship weight and equipment. For this procedure, the vertical, transverse, and longitudinal components of local accelerations are defined in the ship-fixed coordinate system.

The dynamic load components can be calculated from the following equations, which are expressed in combined formulae of the quasi-static and inertial components, as described below.

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

$$F_V = ma_V$$

where

a_V = local vertical acceleration

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

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

where

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

= $g \sin \theta$

a_T = local transverse acceleration

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

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

where

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

= $-g \sin \phi$

a_L = local longitudinal acceleration

7 Simultaneously-acting Loads on Lightship Structure and Equipment

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

SECTION 11 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 as described in Section 13. Each load case is to include the hydrostatic and still-water load components in accordance with Sections 7 to 11. These hydrostatic or still-water components are those caused, for example, by buoyancy or gravity, and are to be included in the FE analysis.

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

3 Equilibrium Check

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

The unbalanced forces in the model's global axis system for each load case are 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 the 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 include the entire hull. There should 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 direct structural analysis, the nonlinear seakeeping analysis method described in Sections 6 and 7 is deemed to be sufficient. However, the designer/analyst is encouraged to employ more advanced technology, especially to incorporate nonlinear slamming and whipping loads discussed in Sections 8 and 9 that are critical for high-speed craft. The adequacy of the selected software is to be demonstrated to the satisfaction of ABS.

The results of the 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 provide appropriate structural continuity and load transfer between the various levels of models.

SECTION 12 Analysis of the Hull Structure

1 General

The structural adequacy of the hull is to be examined by the finite element method (FEM) using three-dimensional (3-D) global and local models. The global model represents the entire hull girder structure and main supporting members. The local model consists of a number of fine mesh models for local structures. Results of nodal displacements obtained from the 3-D global 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 for the structural analysis of high-speed craft:

i) Deck plating, longitudinal stiffeners and girders

ii) Bottom and inner bottom plating, longitudinal stiffeners and girders

iii) Longitudinal bulkhead plating and stiffeners

iv) Transverse bulkhead plating, stiffeners and girders

iv) Side shell plating and longitudinal stiffeners

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 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 are also to be appropriately accounted for.

ii) Structural idealization should be based on the stiffness and expected 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) Typically, a one-longitudinal spacing mesh size is recommended for a global FE model. The 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 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 rod elements with axial stiffness only
- Bar or beam elements with axial, shear, and bending stiffness
- Plate elements, either triangular or quadrilateral

vi) The direct structural analysis uses a FE model based on the 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 the types, scantlings, and connectivity of elements 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 global model, indicated in Subsection 10/5, are also applicable to the development of the fine mesh local models. In addition, the following general rules concerning modeling techniques for the local models should also be closely observed:

i) The mesh size of the local FE 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 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 stress 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 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 topside 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 local 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 that the structures are being assessed against.

Boundary displacements obtained from the global analysis are to be used as boundary conditions in the fine mesh local 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
- FRP sandwich panels in the slamming areas
- Other areas of high stress indicated from the 3-D global analysis.

Additional analyses are required where the 3-D global analysis is not comprehensive enough to adequately determine the total stress in the longitudinal plating (e.g., deck and shell) and transverse bulkhead plating of the craft.

SECTION 13 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. These Guidance Notes provide the acceptance criteria for steel, aluminum, and FRP craft. The acceptance criteria for craft constructed of other materials will be specially considered.

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 2-5-A1/Table 2 of the ABS *Rules for Materials and Welding (Part 2) – Aluminum and Fiber Reinforced Plastics (FRP)*.

3 Yielding

For a plate element subjected to biaxial stress, a specific combination of stress components, typically, 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 the following design stress:

Steel:	$0.95\sigma_Y$
Aluminum:	$0.85\sigma_Y$
FRP	$0.33\sigma_U$

where σ_Y is the yield strength for steel or the yield strength for welded aluminum, and σ_U is the ultimate tensile or compressive strength of the laminate, whichever is less. Additionally, for global loads, component stresses (σ_x ,σ_y, τ_{xy}) are to be less than or equal to allowable design stress as obtained from section 14.5.

For local loads, component stresses (σ_x ,σ_y, τ_{xy}) are to be less than or equal to allowable local structure design stress.

5 Design Global Hull Girder Stresses

The design stresses are as follows:

- *Global Longitudinal Strength of All Hull Types*

σ_a = design longitudinal bending stress, f_p/CQ N/mm^2 (kgf/mm^2, psi)

τ_a = design shear stress, 110/Q N/mm^2 (1.122/Q tf/cm^2, 7.122/Q Ltf/in^2)

f_p = 17.5 kN/cm^2 (1.784 tf/cm^2, 11.33 Ltf/in^2)

C = 1.0 for steel craft

= 0.90 for aluminum craft

= 0.80 for fiber-reinforced plastic craft

Q for steel:

= 1.0 for ordinary strength steel

= 0.78 for grade H32 steel

= 0.72 for grade H36 steel

= 0.68 for grade H40 steel

Q for aluminum:

= 0.9 + q_5 but not less than Q_o

q_5 = 115/σ_y (12/σ_y, 17000/σ_y)

Q_o = 635/(σ_y + σ_u) [65/(σ_y + σ_u), 92000/(σ_y + σ_u)]

σ_Y = minimum yield strength of unwelded aluminum in N/mm^2 (kgf/mm^2, psi)

σ_u = minimum ultimate strength of welded aluminum in N/mm^2 (kgf/mm^2, psi)

Q for fiber reinforced plastic:

= 400/0.75σ_u (41/0.75σ_u, 58000/0.75σ_u)

σ_u = minimum ultimate tensile or compressive strength, whichever is less, verified by approved test results, in N/mm^2 (kgf/mm^2, psi). See Section 2-6-5 of the ABS *Rules for Materials and Welding (Part 2) – Aluminum and Fiber Reinforced Plastics (FRP)*. Strength properties in the longitudinal direction of the craft are to be used.

- *Global Transverse Strength of Multihulls*

σ_a = design transverse bending stress, 0.66σ_y for aluminum and steel craft and 0.33σ_u for FRP craft, in N/mm^2 (kgf/mm^2, psi)

σ_{ab} = design torsional or combined stress, 0.75σ_y for aluminum and steel craft and 0.367σ_u for FRP craft, in N/mm^2 (kgf/mm^2, psi)

τ_a = design transverse shear stress, 0.38σ_y for aluminum and steel craft and 0.40τ_u for FRP craft, in N/mm^2 (kgf/mm^2, psi)

σ_Y = minimum yield strength of the material, in N/mm^2 (kgf/mm^2, psi). For aluminum the yield strength is to be for the unwelded condition and not to be greater than 0.7σ_{uw}

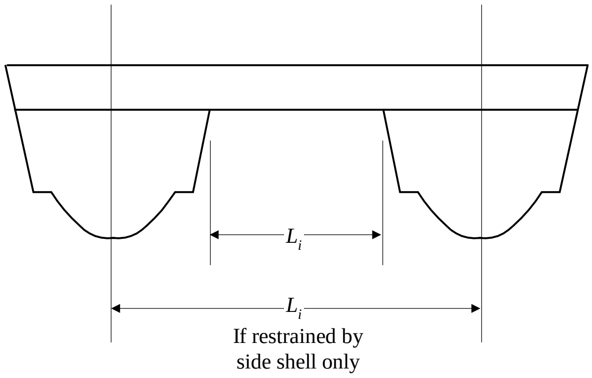
σ_u = minimum tensile or compressive strength, whichever is less, in N/mm^2 (kgf/mm^2, psi)

σ_{uw} = ultimate tensile strength of material in the welded condition, in N/mm^2 (kgf/mm^2, psi)

δ_m = maximum deflection for FRP craft, (σ_a/E)L_I, in m (in.)

τ_u = minimum ultimate through thickness shear strength, in N/mm^2 (kgf/mm^2, psi)

L_I = mean span of cross structure, in cm (in.), as indicated in the figure below:



E = tensile or compressive modulus of the FRP laminate, whichever is lesser, in N/mm^2 (kgf/mm^2, psi)

7 Buckling and Ultimate Strength

Plate panels, stiffened panels, and primary supporting members are to be checked against buckling and ultimate strength using the stresses obtained from FE analyses. Analytical or empirical formulas, such as described in 5C-1-5/5.3 and 5C-1-5/5.11 (SafeHull Criteria) of the ABS *Rules for Building and Classing Steel Vessels* are to be used for steel craft.

Structural instability can be treated at the ultimate strength level. The ultimate strength of plate panels and stiffened panels is to comply with the minimum requirements, while the buckled plates between stiffeners are to be replaced with a reduced effective width.

Combined loads in the buckling and ultimate strength analysis include, but are not limited to, bi-axial compression/tension, edge shear, in-plane loads, and lateral pressure.

Local stiffness and geometric proportions given in 5C-1-A2/11 of the *Steel Vessel Rules* are to be taken into account. The ABS *Guide for Buckling and Ultimate Strength Assessment for Offshore Structures* should be used for Aluminum structure.

SECTION 14 Additional Considerations

1 General Considerations

Loads due to slamming and whipping can be of particular importance to high-speed craft. In catamarans, wet deck slamming causing global whipping of the entire hull is common. While outside the scope of these Guidance Notes, additional consideration may be paid to the global springing response and local hydroelastic response of high-speed craft.

3 Global Springing Response

Springing response of the entire hull requires special consideration, particularly for high-speed craft operating in severe seas. The resulting dynamic stresses in the hull girder may be smaller than 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, springing response of the hull could have significant influence on the fatigue requirements.

For direct analysis, time-domain simulation involving short-term and long-term predictions are recommended. 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.

5 Local Hydroelastic Response

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 local 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 an over-conservative or under-conservative design depending on the rise and decay time of the peak slam pressures. To realistically assess the strength of these local structures, the impact needs to be hydroelastically modeled wherein the dynamics of the fluid and the elastic response of the plate and stiffeners are simultaneously modeled.

7 Scale Model Testing Using Segmented Flexible Model

A segmented model built to measure the longitudinal bending moment and shear force is recommended for mono-hulls. The hull may be composed of a minimum of four segments. These segments will be connected by a backbone frame, designed and fabricated to have the scaled hull girder stiffness of the craft. When the segments are connected to the frame and the mass distribution adjusted, the model will exhibit the correct dynamic characteristics. A backbone design and calibration report giving the properties of the frame, including 2-node natural frequency and structural damping, is to be submitted by the model test facility. The frame will be strain-gauged to measure the stresses at the segmentations. The stress readings will then be converted to derive the bending moment and the shear force. In the case of twin hulls, additional strain-gauged transverse frames will be required to measure the transverse load effects.