



**GUIDE FOR**

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# SPECTRAL-BASED FATIGUE ANALYSIS FOR VESSELS

**(FOR THE 'SFA (*years*)' CLASSIFICATION NOTATION)**

**JUNE 2016 (Updated October 2017 – see next page)**

**American Bureau of Shipping  
Incorporated by Act of Legislature of  
the State of New York 1862**

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## Updates

### **October 2017 consolidation includes:**

- February 2017 version plus Notice No. 2

### **February 2017 consolidation includes:**

- June 2016 version plus Notice No. 1 and Corrigenda/Editorials

## Foreword (1 October 2017)

This Guide provides information about the optional classification notations, ‘Spectral Fatigue Analysis’ – **SFA (years)** and **SFA (years, WWT)** – which are available to qualifying vessels as described in 1-1-3/21 of the *ABS Rules for Conditions of Classification (Part 1)*.

The source document for this Guide is the *Guidance Notes on Spectral-Based Fatigue Analysis for Vessels* (2004). Promoting the Guidance Notes to a Guide adheres to ABS standard practice as the source document was published more than ten years ago. Furthermore, classification notations are customarily provided by only Rules or Guides. Promotion to a Guide alleviates any confusion caused by deviation from standard practice.

The technical content in the Guide has not been significantly changed from that in the Guidance Notes. However, it has been significantly reorganized such that it more closely aligns with the procedure and steps commonly used to conduct spectral-based fatigue analyses for ship structures. Nomenclature has also been modified such that it is more consistent throughout the document. The organization of the Guide is detailed in Section 2. A flowchart depicting the spectral-based fatigue procedure is given by Section 2, Figure 1.

The table below shows how the existing Guidance Notes have been reorganized in the creation of this Guide.

<i>Section in SFA Guide</i>	<i>Section in SFA Guidance Notes</i>	<i>Remarks</i>
1 Introduction	1 Introduction	
2 Spectral-based Fatigue Analysis Procedure	1 Introduction	SFA procedure overview was expanded and moved to its own section.
3 Seakeeping Analysis	2 Establishing Fatigue Demand 4 Motion Analysis and Wave-induced Load Components 6 Loading for Global Finite Element Method (FEM) Structural Analysis Model	Seakeeping analysis was addressed in one section instead of across three sections. The content in the seakeeping analysis section is in agreement with the DLA/SFA System.
4 Structural Analysis	5 Wave-induced Load Components 6 Structural Modeling and Analysis	Structural analysis was addressed in one section instead of across two sections. The content in the structural analysis section is in agreement with the DLA/SFA System.
5 Spectral Analysis	9 Fatigue Life (Damage)	The discussion of spectral analysis was moved to its own section and expanded.
6 Fatigue Strength Assessment	8 Fatigue Strength 9 Fatigue Life (Damage)	The fatigue strength assessment section in the Guide contains most of the content in the fatigue strength and fatigue life sections from the Guidance Notes.

This Guide becomes effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website [www.eagle.org](http://www.eagle.org) to verify that this version of this Guide is the most current.

*We welcome your feedback. Comments or suggestions can be sent electronically by email to [rsd@eagle.org](mailto:rsd@eagle.org).*



**GUIDE FOR**

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## SECTION 1 Introduction

### 1 Purpose and Applicability (1 October 2017)

Part 5C of the ABS *Rules for Building and Classing Steel Vessels (Steel Vessel Rules)* includes the fatigue assessment criteria for the classification of various types of specialized vessels covered by the Rules. Part 5A and 5B of the ABS *Rules for Building and Classing Steel Vessels (Steel Vessel Rules)* contains fatigue assessment guidance for vessels subject to the “Common Structural Rules for Bulk Carriers and Oil Tankers”. A brief description of the background and objectives of these fatigue criteria is given in Subsection 1/3.

In addition to the simplified fatigue strength criteria required for classification by ABS, the Owner may wish to apply more extensive Spectral-based Fatigue Analysis (SFA) techniques to the vessel’s structural systems. It may be an added objective of these Spectral-based Fatigue Analyses to demonstrate a longer design fatigue life than that required for classification.

Spectral-based Fatigue Analysis techniques are used in addition to the SafeHull Fatigue Assessment technique, a Permissible Stress Range method (discussed in Subsection 1/3). The fatigue life of each critical location in the structural system is assessed for adequacy. The critical locations are to be selected using the results of the SafeHull Fatigue Assessment technique which is to be employed in the overall structural design and analysis effort.

The list of critical structural locations which are to be subjected to Spectral-based Fatigue Analysis is to be submitted to ABS for approval.

Provided that Spectral-based Fatigue Analysis is conducted in accordance with the procedures included in this Guide or equivalent, ABS will grant the optional classification notation, **SFA (years)** or **SFA (years, WWT)**. In either case, as a minimum, a vessel is to meet the fatigue strength criteria in the *Steel Vessel Rules* as described above. The **SFA (years)** notation is granted if the design fatigue life value is equal to 20 years or greater under the wave conditions of unrestricted service defined in Section 5, Table 1. The **SFA (years, WWT)** notation is granted if the design fatigue life value is equal to 40 years or greater under the wave conditions of worldwide trading service defined in Section 5, Table 2.

If a vessel is primarily operating in seas that exceed the worldwide trading pattern (i.e., a vessel operating half or more than half of its life in onerous seas including North Atlantic or North Pacific), **SFA (years, WWT)** is not applicable. It should be noted that the calculated fatigue lives for different design wave conditions may produce significantly different fatigue lives.

The value in parentheses is the design fatigue life in years specified by the applicant in 5-year increments starting at 20 for **SFA (years)** and 40 for **SFA (years, WWT)**. The structural system as a whole is analyzed to verify that the calculated fatigue life values for the entire system meet or exceed the design fatigue life. The actual service life of a vessel is dependent on many factors such as initial design, operational and maintenance schemes. The **SFA (years)** or **SFA (years, WWT)** notation denotes the design fatigue life of a vessel and is not a guarantee that the vessel or structure will achieve the design fatigue life.

In order to obtain the **SFA (years)** or **SFA (years, WWT)** notations, SFA methods must be applied to the entire vessel.

For vessels complying with Part 5A and 5B “Common Structural Rules for Bulk Carriers and Oil Tankers” of the *Steel Vessel Rules*, the design fatigue life for Spectral-based Fatigue Analysis is equal to 25 years or greater in 5-year increments.

### 3 Background (1 October 2017)

In the application of Part 5C of the *Steel Vessel Rules*, the SafeHull Fatigue Assessment technique is typically used to evaluate fatigue strength. The SafeHull Fatigue Assessment technique is a permissible stress range approach that is readily applied to large portions of a vessel's hull structure. The technique is required for certain vessels such as an oil tanker with a Rule length greater than 150 m for which the technique is detailed in Appendix 5C-1-A1 of the *Steel Vessel Rules*. The technique was derived considering unrestricted ocean service wave loads representing the North Atlantic and a design fatigue life of 20 years.

Part 5A and 5B “Common Structural Rules for Bulk Carriers and Oil Tankers” of the *Steel Vessel Rules* requires a design fatigue life of 25 years with wave loads representing the North Atlantic and multiple fatigue assessment techniques are employed. A simplified stress analysis method based on beam theory is presented in Part 5A, Pt 1, Ch 9, Sec 4 of the *Steel Vessel Rules*, a finite element stress analysis approach is described in Part 5A, Pt 1, Ch 9, Sec 5 of the *Steel Vessel Rules* and structural design following the detailed design standards is discussed in Part 5A, Pt 1, Ch 9, Sec 6 of the *Steel Vessel Rules*.

Supplementary to the SafeHull Fatigue Assessment technique or methods employed for vessels complying with Part 5C of the *Steel Vessel Rules*, ABS may require the use of additional or alternative techniques to demonstrate the fatigue strength adequacy of structural components. These techniques may include Spectral-based Fatigue Analysis methods. In many instances the structural details cannot be adequately analyzed via the permissible stress range fatigue assessment approach. An optional classification notation, **FL (years)**, may be requested in cases in which the owner or designer increases the target fatigue lives of some or all of the structural components above the 20 year minimum value. This notation is discussed in the *Steel Vessel Rules* and does not require the use of SFA methods.

### 5 Areas for Fatigue Strength Evaluation

The *Steel Vessel Rules* provide guidance on which locations should be included in the fatigue assessment. Various appendices provide guidance on which locations should be included in the fatigue assessment for different vessel types. For example, 5C-1-A1/3.3 of the *Steel Vessel Rules* provides guidance for location selection for oil tankers with a Rule length greater than or equal to 150 m and 5C-3-A1/3.3 of the *Steel Vessel Rules* provides guidance for location selection for bulk carriers with a Rule length greater than or equal to 150 m.

### 7 Methodology and Assumptions

Spectral-based Fatigue Analysis is a complex and numerically-intensive technique and there are multiple valid implementations of the method. ABS does not wish to eliminate the use of any valid approach by over-specifying the SFA technique. However, it is necessary to be clear about the basic assumptions that form the basis of a valid method and highlight key details that are to be incorporated in the method to produce acceptable results. The remainder of this Guide is devoted in large part to the presentation of these topics.

A typical spectral fatigue analysis for a structural location is to evaluate its fatigue strength by comparing its stress range distribution against its fatigue capacity. The following definitions are used in the context of this Guide:

- *Stress Range Distribution*: Stress range probability density functions calculated per this Guide.
- *Fatigue Capacity*: S-N data (S-N curves) representing the number of stress cycles at fatigue failure.
- *Fatigue Strength*: Fatigue life (or damage) calculated per this Guide.
- *Fatigue Demand*: Design fatigue life.



The main underlying assumptions of the Spectral-based Fatigue Analysis method are:

- i)* Ocean waves are the source of the fatigue stress range acting on the structural system.
- ii)* The load and structural analyses are assumed to be linear as required for the frequency domain formulation and the associated probabilistic analysis to be valid. As such, scaling and the superposition of stress transfer functions from unit amplitude waves are considered valid.
- iii)* Non-linearities due to non-linear roll motion and intermittent loads, such as wetting of the side shell in the splash zone, can be effectively accounted for using correction factors.
- iv)* Due to their insignificant contributions in typical load cases it is appropriate to disregard structural dynamic amplification, transient loads and effects such as springing. This allows for the use of quasi-static finite element analysis.

For the specific SFA method presented in Appendix 2, it is assumed that the short-term stress variation for a given sea-state is a random, narrow-banded, stationary process. Therefore a Rayleigh distribution can be used to represent the short-term stress range distribution.

The Spectral-based Fatigue Analysis method is applied to each of the selected structural locations by implementing the following process:

- Determine the stress range distributions.
- Determine fatigue capacity (S-N data).
- Calculate fatigue strength (fatigue life or damage).

Section 2 provides an overview of the spectral-based fatigue analysis procedure. A schematic representation of the SFA procedure can be found in Section 2, Figure 1.

An effort is made in this Guide to avoid the discussion of complicated formulae and instead to focus on the concepts being presented. It is necessary to present the complex formulae used in the calculation of fatigue damage resulting from the predicted stress range distributions, which are presented in Appendix 2. It should be noted that the contents of Appendix 2 are intended to serve as an example of a valid SFA method. It is not necessary that the process be followed exactly; however, any method used should adhere to the same principles.



## SECTION 2 Spectral-based Fatigue Analysis Procedure Overview

### 1 General

This Section provides an overview of the spectral-based fatigue analysis procedure for sea-going vessels. The section in which a detailed discussion of each step can be found is included in parentheses.

The spectral fatigue analysis for ocean-going vessels covers a wide scope of technical disciplines ranging from the analysis of ship's Response Amplitude Operators (RAOs) to the assessment of fatigue damages of structural details. Four main steps are typically involved:

- Seakeeping Analysis: to determine ship motion and wave pressure RAOs.
- Structural Analysis: to determine stress transfer functions.
- Spectral Analysis: to determine stress range distributions.
- Fatigue Strength Assessment: to determine fatigue life or damage.

The tasks that comprise each step are described below.

#### 1.1 Seakeeping Analysis (Section 3)

##### 1.1.1 Selection of Loading Conditions (Subsection 3/3)

Vessel loading conditions that a vessel is expected to experience during its service life are to be reviewed and selected. At least two loading conditions are to be analyzed – one representative of the most probable deepest draft and one representative of the most probable shallowest draft.

##### 1.1.2 Development of Hydrodynamic Models (Subsection 3/5)

A hydrodynamic model is to be created for each loading condition to be evaluated. This Guide is written with the assumption that the seakeeping analysis will be conducted using a three dimensional panel method. As such, all discussion of a seakeeping model in this Guide will be with respect to a three dimensional panel model.

##### 1.1.3 Determination of Ship Motion and Wave Pressure RAOs (Subsection 3/11)

The primary objective of seakeeping analysis is the determination of Response Amplitude Operators, which are mathematical representations of the vessel responses and load effects to unit amplitude sinusoidal waves. The ship motion and wave pressure RAOs are to be calculated for each vessel loading condition.

#### 1.3 Structural Analysis (Section 4)

##### 1.3.1 Development of Structural Models (Subsection 4/7)

A model representing the entire hull structure is to be created in order to determine the stress transfer functions. Typically, a three dimensional finite element model is used. However, a more simplified approach such as beam theory may be used instead. This Guide is written with the assumption that a finite element model will be created.

The global structural finite element model should adequately represent the stiffness and inertial properties of the vessel. In order to analyze fatigue critical details, the creation of fine mesh models is typically necessary.

**1.3.2 Determination of Tank and Inertial Load RAOs (Subsection 4/3)**

RAOs should be calculated for the following motion-induced load effects in addition to ship motions and wave pressures:

- Internal tank pressures and cargo hold loads due to fluid and cargo inclinations and accelerations,
- Inertial forces on the masses of structural components and, as applicable, significant equipment items.

**1.3.3 Determination of Stress Transfer Functions (Subsection 4/1)**

The stress transfer function for each location where the fatigue strength is to be evaluated should be determined via a suitable structural analysis approach. Finite element analysis (FEA) is a commonly used approach.

The stress transfer functions are required in order to derive the stress range distributions. Therefore, structural analysis is a fundamental task of spectral-based fatigue analysis.

**1.5 Spectral Analysis (Section 5)**

**1.5.1 Selection of Wave Spectra and Wave Scatter Diagrams (Subsection 5/3)**

Wave spectra and wave scatter diagrams (wave scatter data) are environmental data and need to be decided prior to performing Spectral-based Fatigue Analysis. They are to be used in conjunction with the stress transfer functions to determine the stress spectra.

**1.5.2 Determination of Stress Range Probability Density Functions (Subsection 5/5)**

The stress spectra and spectral moments are calculated according to the selected wave spectra and scatter diagram. It is customary to apply a wave spreading function to the spectral moment to account for the fact that most fatigue damage is due to low or moderate seas which tend to be short-crested and result in kinetic energy spread. The stress zero up-crossing frequencies, bandwidth parameters and stress range probability density functions are calculated using the stress spectral moments.

**1.7 Fatigue Strength Assessment (Section 6)**

**1.7.1 Selection of S-N Data (Subsection 6/3)**

The capacity of a location to resist fatigue damage is characterized by the application of S-N data. The selection of S-N data depends on the structural details and stresses used.

**1.7.2 Calculation of Fatigue Damage and Life (Subsections 6/5 and 6/7)**

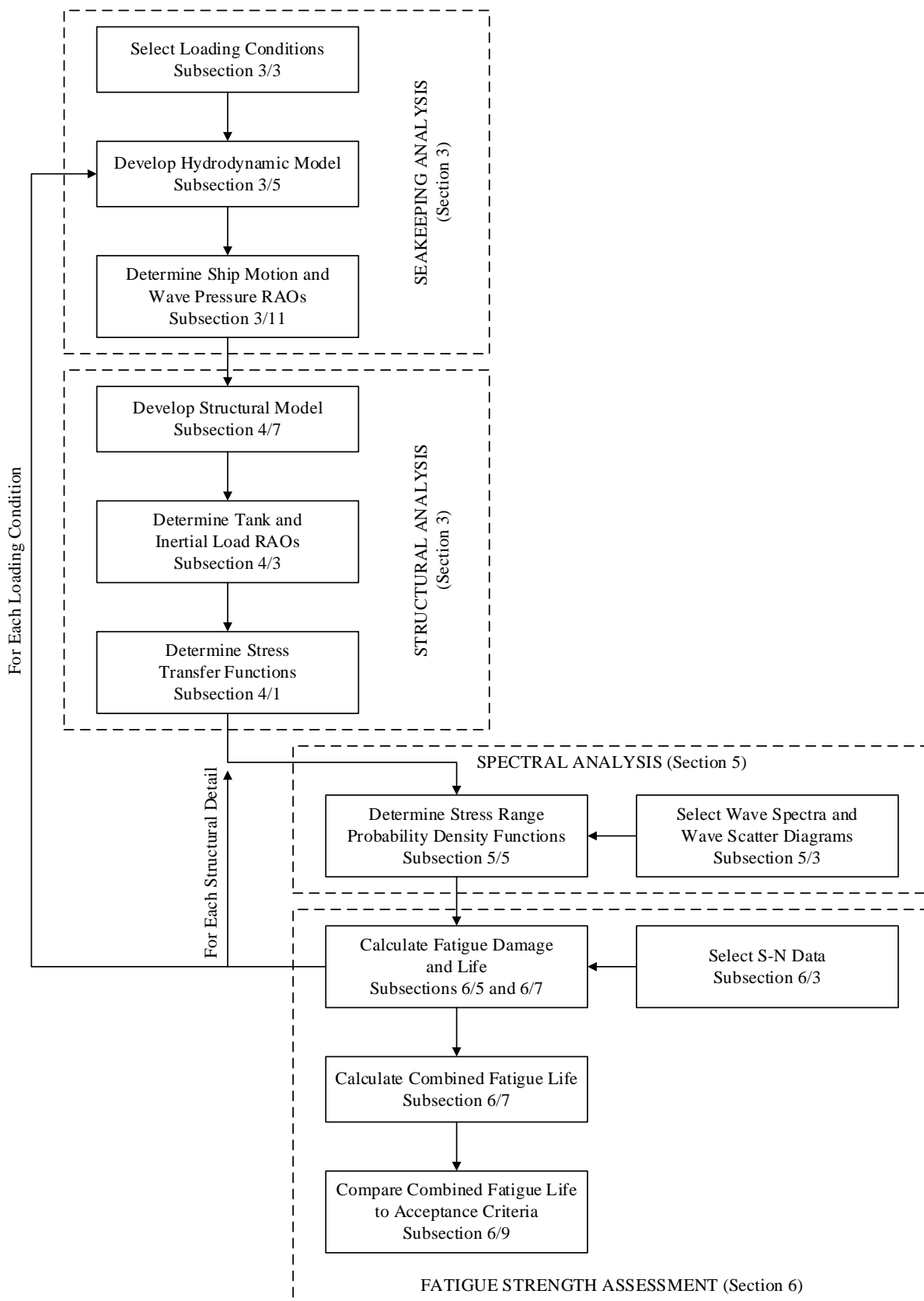
For a given time span, the short term fatigue damage corresponding to each individual sea state can be calculated from the stress range distributions, the selected S-N data and the probability of the sea state. The long term fatigue damage can be calculated by applying a linear damage summation technique such as Miner's Rule to the short term fatigue damages.

In order to determine the suitability of the structure for a design fatigue life, it is necessary to calculate the total long term fatigue damage for the design fatigue life. One can use the total fatigue damage and the design fatigue life to calculate the fatigue life of a detail.

**1.7.3 Acceptance Criteria (Subsection 6/9) (1 October 2017)**

To meet the requirements of the **SFA (years)** or **SFA (years, WWT)** notations, the calculated fatigue life is to be equal to or greater than the design fatigue life.

**FIGURE 1**  
**Schematic Spectral-based Fatigue Analysis Procedure**





## SECTION 3 Seakeeping Analysis

### 1 Scope of Seakeeping Analysis

Response Amplitude Operators (RAOs) are mathematical representations of the vessel responses and load effects to unit amplitude sinusoidal waves. A seakeeping analysis is to be conducted primarily to determine the ship motion and wave pressure RAOs. This section is referring to motion and load RAOs when discussing wave induced motions and load components.

A seakeeping analysis is to be performed at 75% of the vessel's design speed for each wave frequency, vessel heading angle and selected loading condition to be used in the spectral analysis. Normally, the frequency range to be used is 0.1 rad/sec to 1.80 rad/sec in increments not larger than 0.1 rad/sec. However, depending on the characteristics of the response, it may be necessary to consider a different frequency range. The wave heading range is to be 0 to 360 degrees in increments not larger than 30 degrees.

### 3 Vessel Loading Conditions

The loading conditions defined in the loading manual relate to the probable variations in loading that the vessel will experience during its service life. Prior to conducting a seakeeping analysis, appropriate vessel cargo loading conditions need to be selected. The main parameters for selecting loading conditions are tank or hold loading and ballast arrangements, draft and trim. These parameters have a direct influence on the static stress components of the hull's response, and they also affect the wave-induced variable stress range experienced at a structural location.

Because of the variability of the loading conditions and their impact on fatigue strength predictions, it is necessary to consider more than one loading condition in the fatigue analysis. At a minimum, two cases, the most probable deepest and shallowest drafts that the vessel is expected to experience during its service life, should be represented and used in the Spectral-based Fatigue Analysis process.

### 5 Hydrodynamic Models

Boundary element methods generally require that the wetted surface of the vessel be discretized into many three dimensional panels. The panel mesh should be fine enough to resolve the radiation and diffraction waves with reasonable accuracy. A general rule is that there are at least four panels within the shortest wave length being analyzed. The plots of the RAOs versus frequency should be reviewed for any abrupt changes; they are indicative of an insufficient number of panels to fully capture the wave characteristics.

The hull offset data can be used to facilitate the generation of the panel model. For each loading condition, the draft at the forward and aft perpendiculars, the location of the center of gravity, the radii of gyration and the sectional mass distribution along the ship length are to be in accordance with the Loading Manual.

In addition, there should be sufficient compatibility between the hydrodynamic and structural models such that the mapping of fluid pressures onto the structural model can be done appropriately.

## 7 Initial Balance Check

The seakeeping analysis should be performed on the hydrodynamic model with respect to static initial conditions representing the vessel geometry and loading conditions (see Subsection 3/3). The still-water bending moment (SWBM) and still water shear force (SWSF) distributions should be calculated at a sufficient number of transverse sections along the hull length such that weight distribution discontinuities are accounted for accurately. A recognized hydrostatic analysis program should be used to perform these calculations. The convergence of the displacement, Longitudinal Center of Buoyancy (LCB) and trim of the hydrodynamic model should be checked to meet the following tolerances:

- Displacement:  $\pm 1\%$
- Trim:  $\pm 0.5$  degrees
- Draft:
  - Forward  $\pm 1$  cm
  - Mean  $\pm 1$  cm
  - Aft  $\pm 1$  cm
- LCB:  $\pm 0.1\%$  of length
- SWBM:  $\pm 5\%$

Additionally, the longitudinal locations of the maximum and the minimum SWBMs and SWSFs and, if appropriate, those of zero SWBM and zero SWSF should be checked to ensure proper distribution of the SWBM along the vessel's length.

## 9 Seakeeping Analysis Methods

Computations of the wave-induced motions and loads should be carried out using appropriate, proven methods. Preference should be given to the application of seakeeping analysis codes utilizing three-dimensional, potential flow-based diffraction-radiation theory. These codes, based on linear wave and motion assumptions, make use of boundary element methods with constant or higher order sink-source panels over the entire wetted surface of the hull on which the hydrodynamic pressures are computed. The analysis should account for rigid body motions in all six degrees-of-freedom.

For the load component types and structural responses of primary interest, analysis software formulations derived from linear idealizations are deemed to be sufficient.

## 11 Effects of Ship Motions and Wave Pressures

### 11.1 Inertial and Gravitational Loads due to Ship Motions

Wave-induced loads on a buoyant structure are complex. In addition to direct forces (e.g., wave pressures on the external surface of the hull), there are indirect force components produced by the rigid body motions of the vessel. The motions result in both inertial forces and gravitational loads due to the vessel's inclinations (the rotational components of motion). The inclination induced gravitational loads are in addition to the pure static (still water) gravitational loads on the hull structure and are referred to as quasi-static loads in this Guide. Therefore, the total loads in general are composed of static and dynamic components, and the dynamic component can be further decomposed into quasi-static and inertial components. These load components are discussed in detail in Section 4.

### 11.3 Real and Imaginary Parts

The treatment of ship motions and various loads is typically done through the use of their real and imaginary parts which are employed separately in structural analyses. In a physical sense, the real and imaginary parts correspond to two wave systems that are 90 degrees out of phase.

### 11.5 Pressure Mapping

The wave pressures on a hydrodynamic panel model need to be mapped to its corresponding structural model for structural analysis. The mesh densities of the hydrodynamic panel model and the structural model are typically different. Consequently, it is usually necessary to interpolate the pressure distribution (via three dimensional linear interpolation) when transferring it from the coarser hydrodynamic model to the finer structural model.

### 11.7 Intermittent Wetting

Seakeeping analysis based on linear theory will not predict the non-linear effects due to intermittent wetting near the mean waterline. In actual service, this phenomenon is manifested by a reduction in the number of fatigue cracks at side shell plating stiffeners located near the mean waterline compared to those about four or five bays below. To take into account the pressure reduction near the mean waterline due to this non-linearity, the following reduction factor can be applied to the pressure RAOs:

$$RF = 0.5[1.0 + \tanh(0.35d)]$$

where  $d$  is depth, in meters, of the field point below the still-water line.

In order to correctly account for the intermittent wetting effects, it is recommended that the vertical height of the panels near the waterline be no greater than two times the longitudinal spacing. If the panels are too large, the pressure reduction factor can be applied to the structural model after the wave pressures are mapped from the hydrodynamic model.

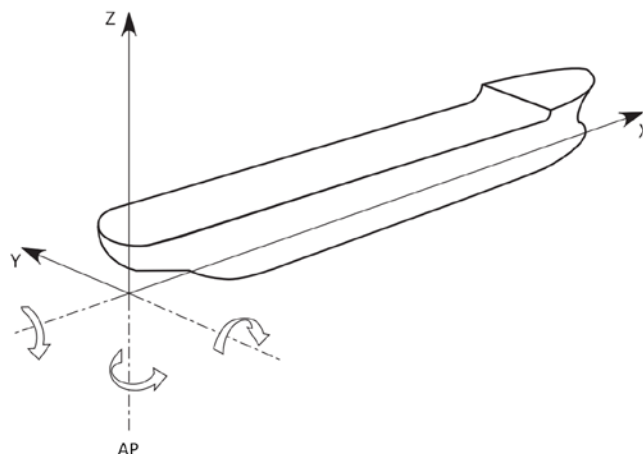
## SECTION 4 Structural Analysis

### 1 General (1 October 2017)

The structural analysis procedure described in this Section is based on the assumption that the structural analysis is performed through a typical finite element analysis. Subsections 4/3 and 4/5 address the loading of the structural analysis finite element model. Finite element modeling guidance is provided in Subsection 4/7.

Motion and load components are presented in ship fixed coordinate system in this section. The origin is located at the intersection of the aft perpendicular, centerline and baseline. The positive sign convention is longitudinal forward, transverse port and vertical upwards (See Section 4, Figure 1).

**FIGURE 1  
Ship Coordinate System**



A structural analysis is to be conducted to calculate the stress transfer functions necessary for spectral-based fatigue analysis. The stress transfer functions are used in the spectral response analysis to calculate the stress range distributions as discussed in Section 5.

The wave induced motion and load components described in this Section are RAOs, and the stress responses are stress transfer functions. The following loads are to be calculated via a structural analysis: liquid tank pressures (4/3.1), dry bulk cargo loads (4/3.3) and container loads (4/3.5). In each Paragraph, the static, quasi-static, and inertial loads are discussed. In addition, the inertial loads of discrete masses, which are applicable to significant items of equipment, are discussed (4/3.7).

The effect of sloshing loads due to fluid in partially filled tanks is not within the scope of the **SFA (years)** or **SFA (years, WWT)** classification notations. However, the designer is encouraged to perform and submit such calculations, if deemed important.

There may be situations where partial models of the structural system are used. In such instances, hull girder shear and axial forces, and bending and torsional moments should be determined to appropriately represent the boundary conditions at the ends of the partial model.

The general approach used in the calculation methods described below is to calculate the total stress response considering both static and dynamic loads. Subsequently, the static stress is deducted from the total, leaving the pure wave-induced stress response. Alternative methods and formulations that directly produce the dynamic stress response may also be used.



### 3 Internal Load

The procedures to calculate liquid tank pressure, bulk cargo pressure, container loads, and loads on discrete masses are presented in this subsection. Each of these loads is composed of static and dynamic components. The static load component results from gravity. The dynamic load component can be further decomposed into quasi-static and inertial components. The quasi-static load component results from gravity, considering the roll and pitch inclinations of the vessel. The direction of gravitational forces in the ship-fixed coordinate system varies with roll and pitch motions, resulting in the quasi-static loads. The inertial load component results from the local accelerations caused by the ship motions in six degrees-of-freedom. It is assumed that the ship motions are calculated in the ship-fixed coordinate system. Therefore, coordinate transformations are not needed for the local accelerations.

The following definitions are used in this Subsection:

$\theta$	=	roll angle, positive starboard down
$\phi$	=	pitch angle, positive bow down
$g_V$	=	acceleration of gravity. It can be considered as the vertical component of gravitational acceleration relative to the ship-fixed coordinate system to the accuracy of the first order.
$g_V$	$\approx$	$g$
$g_T, g_L$	=	transverse and longitudinal components of gravitational acceleration relative to the ship-fixed coordinate system due to roll and pitch inclinations
	=	$(-g \sin \phi, g \sin \theta)$
$a_V, a_T, a_L$	=	vertical, transverse and longitudinal components of local accelerations caused by ship motions relative to the ship-fixed coordinate system at a calculation point
	=	$\vec{A} + \vec{\Theta} \times \vec{R}$
$\vec{A}$	=	surge, sway and heave acceleration vector at vessel's center of gravity
$\vec{\Theta}$	=	roll, pitch and yaw acceleration vector
$\vec{R}$	=	distance vector from the vessel's center of gravity to the calculation point

#### 3.1 Liquid Tank Pressures

As appropriate, the liquid pressure on liquid tank (or liquid cargo hold) boundaries should be considered in the analysis. The pressures acting on the internal surfaces of liquid tanks are to be calculated and applied to the structural model. Static and dynamic pressures on completely filled and/or partially filled tanks are to be considered in the analysis. Tank sloshing loads are not included in the analysis. These sloshing loads are to be treated in accordance with the current Rule requirements.

The liquid tank pressure for each of the tank boundary points can be calculated from the following equation, which is expressed as a combination of the static and dynamic pressure components:

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

where

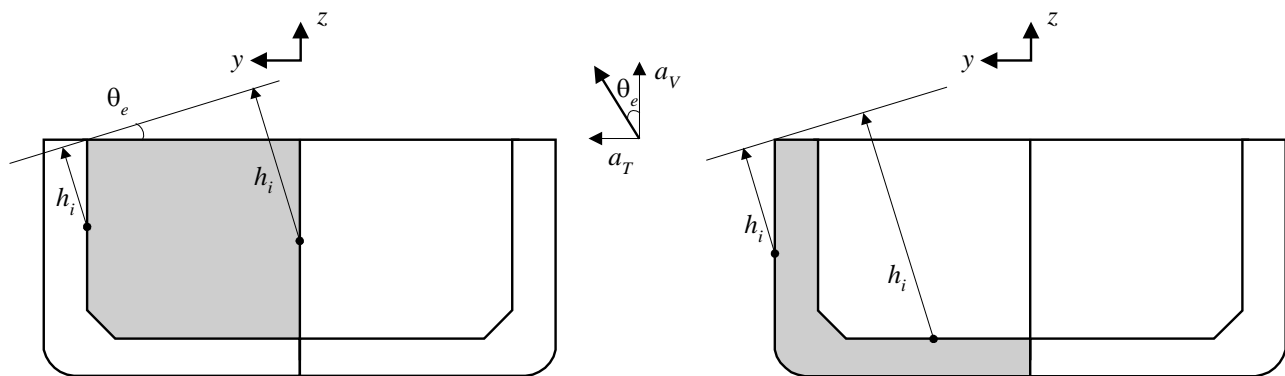
$p$	=	liquid tank pressure at a tank boundary point
$p_o$	=	the vapor pressure or the pressure setting on the pressure/vacuum relief valve
$\rho$	=	density of tank liquid

$h_i$  = internal pressure head defined by the height of projected liquid column in the direction of a resultant acceleration vector. For a completely filled tank, the pressure head is to be measured from the highest point of the tank to the load point (see Section 4, Figure 2). For a partially filled tank, the pressure head is to be measured from the free surface level to the load point (see Section 4, Figure 3). The free surface is defined as the liquid surface normal to the resultant acceleration vector. In the aforementioned figures, only vertical and transverse accelerations are indicated.

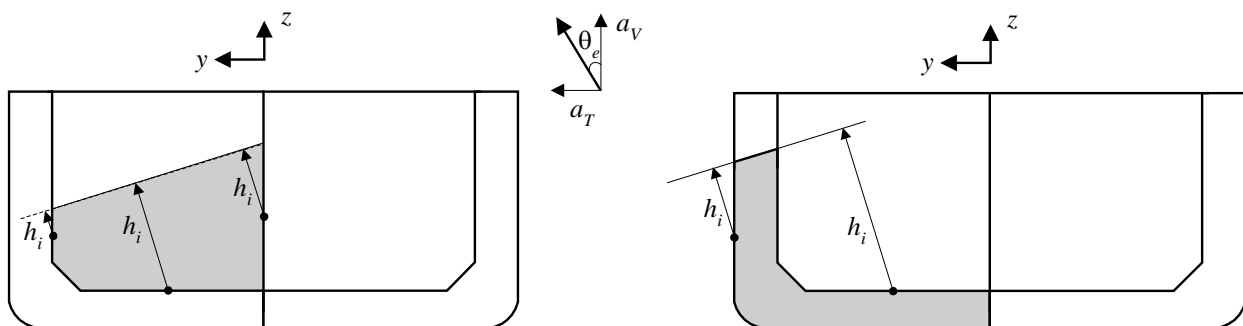
$a_V, a_T, a_L$  = local accelerations at the center of gravity (CG) of tank contents

The liquid tank pressure  $p$  in the above formula becomes the static pressure if  $a_V, a_T, a_L, g_T$  and  $g_L$  are all set to zero, and  $h_i$  is calculated in the direction of  $g$ .

**FIGURE 2**  
Liquid Pressure on a Completely Filled Tank



**FIGURE 3**  
Liquid Pressure on a Partially Filled Tank



### 3.3 Bulk Cargo Pressure

A loaded bulk cargo hold can be partially or completely filled. For light bulk cargo, the bulk cargo may be loaded up to the top of the hatch coaming. For heavy bulk cargo, unless otherwise specified, the top surface of bulk cargo may be considered to have a slope equal to half the angle of repose at sides and have a flat surface with half the cargo hold beam width.

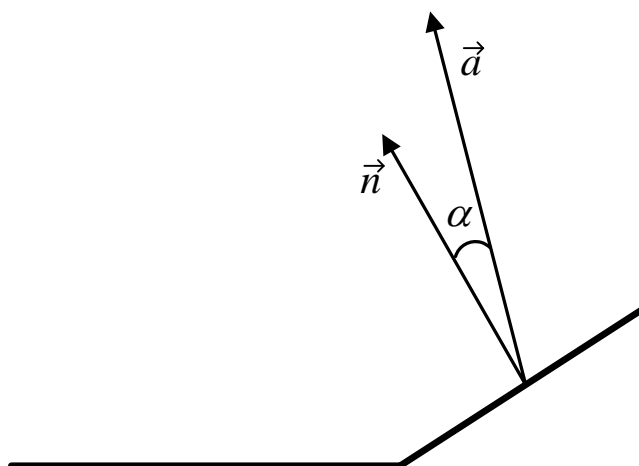
The bulk cargo pressures acting on the internal surfaces of cargo holds are to be calculated and applied to the structural model for analysis. Static and dynamic bulk cargo pressures should be included in the analysis assuming there is no relative motion between the cargo hold and contained bulk cargo.

The following definitions are used in the formulas for the static and dynamic load calculations in this Paragraph.

- $\alpha_o$  = angle of repose for the bulk cargo considered
- = 30 deg. in general, 35 deg. for iron ore, 25 deg. for cement
- $\rho$  = density of the bulk cargo
- $a_V, a_T, a_L$  = local accelerations at the CG of cargo contents
- $\vec{n}$  = surface unit normal vector in the ship coordinate system, towards the inside of the cargo hold
- =  $n_x \vec{i} + n_y \vec{j} + n_z \vec{k}$
- $\vec{a}$  =  $(a_L + g_L) \vec{i} + (a_T + g_T) \vec{j} + (a_V + g) \vec{k}$
- $a$  = magnitude of  $\vec{a}$
- =  $|\vec{a}|$
- $\alpha$  = the angle between the surface unit normal vector,  $\vec{n}$ , and the acceleration vector,  $\vec{a}$  (see Section 4, Figure 4)
- =  $\cos^{-1} \left( \frac{\vec{a} \cdot \vec{n}}{|\vec{a}| |\vec{n}|} \right)$

Both static and dynamic bulk cargo pressures can be decomposed into normal and tangential components relative to the surface of cargo hold. The positive normal component is defined in the opposite direction of  $\vec{n}$ , and the positive tangential component is defined in the direction of  $\vec{n} \times (\vec{n} \times \vec{a})$ .

**FIGURE 4**  
**Depiction of Surface Normal Vector,  $\vec{n}$ , Acceleration Vector,  $\vec{a}$ , and  $\alpha$**



The normal and tangential components of bulk cargo pressure can be calculated using the following equations, each of which is expressed as a combination of the static and dynamic pressure components:

$$\begin{aligned}
 p_n &= \rho h_T a \{ \cos^2 \alpha + (1 - \sin \alpha_o) \sin^2 \alpha \} & 0^\circ \leq \alpha \leq 90^\circ \\
 p_n &= 0 & \text{otherwise} \\
 p_t &= \rho h_T a \{ \sin \alpha_o \sin \alpha \cos \alpha \} & 0^\circ \leq \alpha \leq 90^\circ \\
 p_t &= 0 & \text{otherwise}
 \end{aligned}$$

where

- $p_n$  = pressure component normal to the hold surface
- $p_t$  = pressure component tangential to the hold surface
- $h_T$  = bulk cargo pressure head defined by the height of projected bulk cargo column in the direction of the acceleration vector. The pressure head is to be measured from the top of the cargo surface to the load point.

The total pressure components  $p_n$  and  $p_t$  in the above formulae become the static pressure components if  $a_v, a_T, a_L, g_T$  and  $g_L$  are all set to zero, and  $h_T$  is calculated in the direction of  $g$ .

### 3.5 Container Loads

The container loads acting on the cargo holds and deck are to be calculated and applied to the structural model for analysis. Static and dynamic container loads should be included in the analysis assuming that there is no relative motion between the hull and the containers.

#### 3.5.1 Static Load

The static container load due to gravity acting on the cargo hold bottom or on deck can be expressed as:

$$F_S = mg$$

where

- $m$  = mass of the container.

The static load due to a stack of containers may be summed and applied to appropriate nodes on the cargo hold bottom plate. Total vertical load due to the containers on the deck may be applied to the appropriate nodes on the hatch coaming top plates.

#### 3.5.2 Dynamic Load

The vertical component (see Section 4, Figure 5) of dynamic container load can be calculated using the following equation:

$$F_V = m a_v$$

where

- $m$  = mass of the container.
- $a_v$  = local vertical acceleration at the CG of a container.

The transverse component (see Section 4, Figure 5) of dynamic container load can be calculated using the following equation which is expressed as a combination of the quasi-static and inertial load components:

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

where

- $a_T$  = local transverse acceleration at the CG of a container.

The transverse load due to containers may be distributed to appropriate nodes on the bulkhead structure via the container cell guide. The total transverse load due to the containers on deck may be applied to the appropriate nodes on the hatch coaming top plates via the container lashing system.

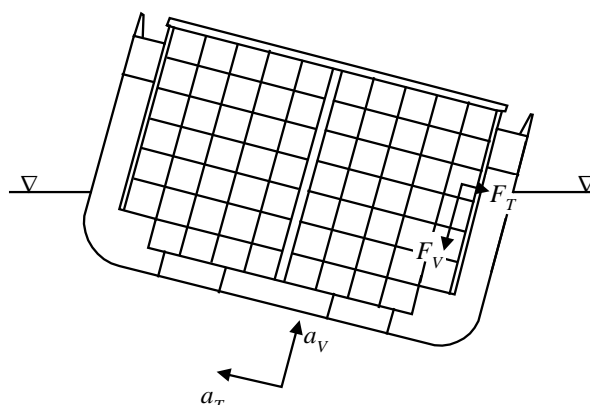
The longitudinal component of dynamic container load can be calculated using the following equation which is expressed as a combination of the quasi-static and inertial load components:

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

where

- $a_L$  = local longitudinal acceleration at the CG of a container.

**FIGURE 5**  
**Vertical and Transverse Container Load Components**



### 3.7 Loads on Lightship Structure and Equipment

The static and dynamic loads acting on the lightship structure and equipment are to be calculated and applied to the structural model for the structural analysis.

The static load acting on a node of the lightship structure and equipment can be expressed as:

$$F_S = mg$$

where

$$m = \text{point mass of the structural member or equipment}$$

The dynamic components of the load acting on the node in vertical, transverse and longitudinal directions can be calculated from the following equations:

$$F_V = m a_V$$

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

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

where

$$a_V, a_T, a_L = \text{local accelerations at the mass point}$$

The formulas for  $F_T$  and  $F_L$  above represent a combination of the quasi-static and inertial load components.

## 5 Load Cases and Model Equilibrium

### 5.1 Number of Load Cases

A load case in the spectral-based fatigue analysis corresponds to a combination of a loading condition, a vessel heading angle, a wave frequency, and the real or imaginary component of the wave. The structural analysis is to be carried out at each wave frequency and vessel heading angle for each considered loading condition.

The stress transfer function for each location of fatigue strength evaluation needs to be calculated for each load case. It is likely that the number of analysis load cases will be very large. The recommended parameters for a spectral-based fatigue analysis for each considered loading condition are 18 wave frequencies (0.1 to 1.80 rad/s in increments of 0.10 rad/s), 12 wave headings (0 to 360 degrees in 30 degree increments) and the real and imaginary wave components. In the case of a standard analysis, the total number of load cases per loading condition will be  $(18 \cdot 12 \cdot 2) = 432$ . In addition, a static load case may be needed. Provided that the shape of each RAO and its local maxima are adequately captured, larger frequency steps may be used to reduce the number of analysis load cases.

### 5.3 Equilibrium Check

The applied hydrodynamic external pressure should be in equilibrium with the other applied loads on a full length ship structural model. For each load case, the forces and moments in each global direction should be summed to calculate the force and moment imbalances. A suitable load balancing scheme should be applied to the structural model to balance the unbalanced forces and moments prior to conducting the structural analysis.

## 7 Structural Modeling and Analysis

A three dimensional (3-D) global FE model representing the entire hull structure is to be created in order to determine the stress transfer functions. While the global FE model analysis may produce results of sufficient accuracy, it is typically necessary to perform fine mesh FE analyses of local areas. The FE models to be used for the local fine mesh analyses can be created either by refining a region of the global FE model or by creating a separate fine mesh FE model of the local area and applying boundary conditions determined from the global FE analysis. The load cases discussed in Subsection 4/5 are to be used for both global and fine mesh FE analysis.

Reference should be made to additional ABS guidance on modeling and analysis techniques for vessel structure (e.g., the *ABS Guidance Notes on SafeHull Finite Element Analysis for Hull Structures*). While the partial hull model used for a SafeHull analysis is different from the full ship model used for an SFA analysis, the modeling practices and considerations presented are applicable. Detailed modeling guidance relating to items such as element types, mesh sizes, dependence between local and global models, etc., are also presented in the *ABS Guidance Notes on SafeHull Finite Element Analysis for Hull Structures*.

### 7.1 3-D Global Analysis Modeling

The global structural finite element model should be as detailed and complete as practicable. Gross scantlings are ordinarily used for the Spectral-based Fatigue Analysis of a new-build vessel.

While creating the model, a sufficient number of nodes, elements and degrees of freedom are to be used to adequately represent the stiffness and inertial properties of the vessel.

Three types of elements are typically used to approximate the geometry, configuration, and stiffness of the vessel structure:

- i) Truss or rod elements with axial stiffness only.
- ii) Beam elements with axial, shear and bending stiffness.
- iii) Membrane and bending plate elements, either triangular or quadrilateral.

### 7.3 Analyses of Local Structure

Fine mesh finite element models should be created in order to obtain more refined stress distributions of local structure. When creating the fine mesh models, care is to be taken to ensure that the geometry and stiffness of the structure is accurately represented. If a separate model is created, displacements extracted from the global 3-D FE analysis are to be used as boundary conditions. In addition to the boundary constraints, all pertinent local loads should be applied to the fine mesh models.

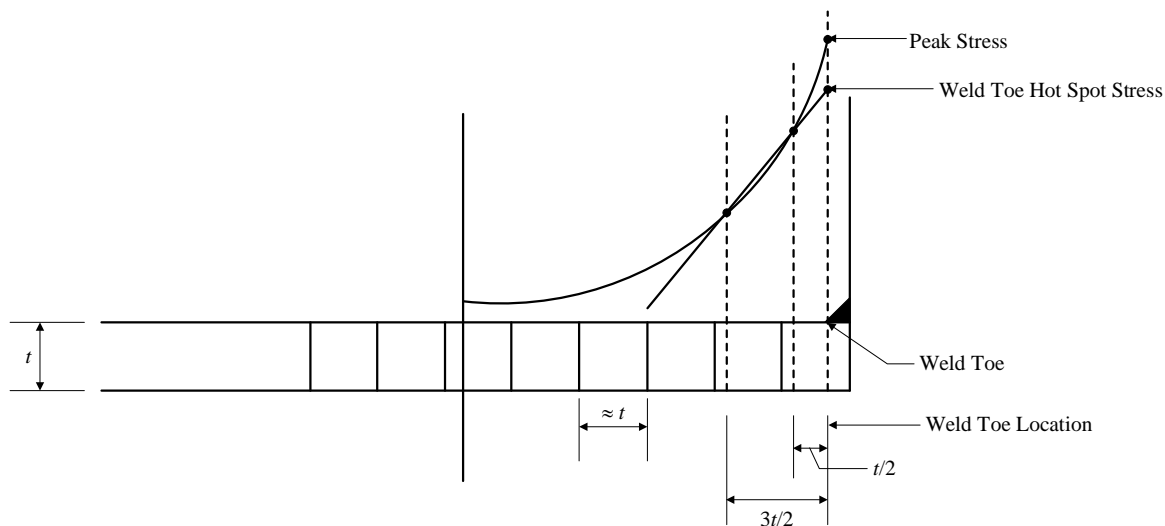
### 7.5 Hot Spot Stress Concentration

The Hot Spot Stress Approach, which is often used to characterize the fatigue strength of details such as the toe of a fillet weld, requires the use of a regimented procedure. The two major parts of the procedure are:

- The selection of an S-N data class (see Subsection 6/3 and Appendix 1) that applies for each instance.
- Creating the fine mesh FEM adjacent to the detail and calculating the stress at the hot spot location via extrapolation of the stress distribution.

Section 4, Figure 6 depicts an acceptable method that can be used to calculate the hot spot stress for a weld toe. Element sizes near the detail of interest are to be approximately equal to the plating thickness. The hot spot stress is found via linear extrapolation of the calculated stress results at distances of  $t/2$  and  $3t/2$  from the detail. For stresses obtained using this approach, the use of E class S-N data (see Appendix 1) is considered to be most appropriate. The surface stresses (considering a “bending plate” element type) should be used to determine the hot spot stress. A detailed description of the numerical extrapolation procedure can be found in 5C-1-A1/13.7 of the *Steel Vessel Rules*.

**FIGURE 6**  
**Definition of Hot Spot Stress**





## SECTION 5 Spectral Analysis

### 1 General

The spectral analysis is used to calculate the stress range distributions using the stress transfer functions calculated via structural analysis and the selected wave spectra and a wave scatter diagram. Mathematically, Spectral-based Fatigue Analysis begins after the determination of the stress transfer functions. A detailed presentation of an example method is presented in Appendix 2.

### 3 Wave Spectra and Wave Scatter Diagram (1 October 2017)

Wave data are represented in terms of wave energy spectra and wave scatter diagrams.

The Bretschneider or two parameter Pierson-Moskowitz wave spectrum is recommended for the North Atlantic, described by the following expression:

$$S(\omega) = \frac{H_s^2}{4\pi} \left( \frac{2\pi}{T_z} \right)^4 \omega^{-5} \exp \left[ -\frac{1}{\pi} \left( \frac{2\pi}{T_z} \right)^4 \omega^{-4} \right]$$

where

- $H_s$  = significant wave height, in m
- $\omega$  = wave frequency, in rad/s
- $T_z$  = average zero up-crossing wave period, in seconds

Spectral-based fatigue analysis typically uses environmental data for ocean waves that are given in a wave scatter diagram format. A wave scatter diagram consists of cells, or sea-states, which are short-term descriptions of the sea in terms of joint probability of occurrence of a significant wave height,  $H_s$ , and a characteristic period. Each cell contains three data items:

- i) The significant wave height,  $H_s$ , (typically in meters),
- ii) The characteristic wave period (in seconds),
- iii) The number of occurrences for the sea state.

Section 5, Tables 1 and 2 present the wave scatter diagram data that is to be used in the spectral-based fatigue analysis of a vessel classed for unrestricted service and for world-wide trading service, respectively. It can be assumed that there is an equal probability of each vessel heading relative to the direction of the waves.

### 5 Stress Range Distributions

The calculation of the stress transfer functions is done via a structural analysis as presented in Section 4. The stress amplitude can be determined by selecting two points on the sinusoidal stress time series of frequency  $\omega$  with a 90-degree phase shift.

Once the stress transfer functions are obtained via a structural analysis and the wave spectra are selected for each of the cells in the wave scatter diagram, the stress spectra and spectral moments can be calculated. With the available stress spectra, the Rayleigh probability density function (pdf) describing the short term stress-range distribution, the zero up-crossing frequency of the stress response, and the stress bandwidth parameter used in calculating rainflow correction can be calculated for each sea state in the wave scatter diagram. The aforementioned terms are defined in Appendix 2 which presents a detailed example of a closed form spectral-based fatigue analysis procedure. The stress range is considered to be twice the stress amplitude.



**TABLE 1**  
**ABS Wave Scatter Diagram for Unrestricted Service Classification**  
**(Representing the North Atlantic)**

\* Wave heights taken as significant values,  $H_s$

\*\* Wave periods taken as zero crossing values,  $T_z$

		Wave Period (sec)**										Sum Over All Periods	
		3.50	4.50	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50		13.50
Wave Height (m)*	0.5	8	260	1344	2149	1349	413	76	10	1			5610
	1.5		55	1223	5349	7569	4788	1698	397	69	9	1	21158
	2.5		9	406	3245	7844	7977	4305	1458	351	65	10	25670
	3.5		2	113	1332	4599	6488	4716	2092	642	149	28	20161
	4.5			30	469	2101	3779	3439	1876	696	192	43	12625
	5.5			8	156	858	1867	2030	1307	564	180	46	7016
	6.5			2	52	336	856	1077	795	390	140	40	3688
	7.5			1	18	132	383	545	452	247	98	30	1906
	8.5				6	53	172	272	250	150	65	22	990
	9.5				2	22	78	136	137	90	42	15	522
	10.5				1	9	37	70	76	53	26	10	282
	11.5					4	18	36	42	32	17	7	156
	12.5					2	9	19	24	19	11	4	88
	13.5					1	4	10	14	12	7	3	51
>14.5					1	5	13	19	19	13	7	77	
Sum over All Heights		8	326	3127	12779	24880	26874	18442	8949	3335	1014	266	100000

**TABLE 2**  
**ABS Wave Scatter Diagram for World-Wide Trading Service**  
**Classification (1 October 2017)**

\* Wave heights taken as significant values,  $H_s$

\*\* Wave periods taken as zero crossing values,  $T_z$

		Wave Period (sec)**										Sum Over All Periods	
		3.50	4.50	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50		13.50
Wave Height (m)*	0.5	1888	5417	5836	3392	1260	313	55	8	1			18170
	1.5	493	3739	8374	9339	6517	2985	940	219	41	6	1	32654
	2.5	96	1128	3682	5934	6159	4216	1930	629	158	33	6	23971
	3.5	18	294	1217	2439	3269	2959	1769	734	229	57	12	12997
	4.5	4	79	388	893	1417	1568	1142	568	208	60	15	6342
	5.5	1	23	130	328	581	745	631	361	150	49	13	3012
	6.5		8	47	126	239	341	325	208	96	34	10	1434
	7.5		2	18	51	101	156	163	115	58	22	7	693
	8.5		1	7	21	44	72	82	63	34	14	5	343
	9.5			3	10	20	34	42	34	20	9	3	175
	10.5			1	5	10	17	22	19	11	5	2	92
	11.5			1	2	5	9	12	10	7	3	1	50
	12.5				1	3	5	6	6	4	2	1	28
	13.5				1	1	2	3	4	3	1	1	16
>14.5				1	2	3	5	5	4	2	1	23	
Sum over All Heights		2500	10691	19704	22543	19628	13425	7127	2983	1024	297	78	100000



## SECTION 6 Fatigue Strength Assessment

### 1 General

Section 4 of this Guide addressed calculating the stress transfer functions for locations in the structure for which the adequacy of fatigue strength is to be evaluated. Appendix 2 presents a spectral-based analysis procedure that may be used for the calculation of the stress range distributions. The capacity of a location to resist fatigue damage is characterized by the use of S-N Data, which are described below. Refer to Appendix 1 of this Guide and Part 5C of the *Steel Vessel Rules* concerning the S-N Data recommended by ABS.

S-N data is typically used in two ways. In the first, the *nominal stress approach*, it is assumed that the acting variable stress range can be adequately determined from the nominal stress distribution (which may include geometric stress concentration effects) in the area surrounding the location for which the fatigue life is to be evaluated. The second method, the *hot spot approach* (see 4/7.3), is used for locations in which complicated geometry or relatively steep local stress gradients invalidate the use of the nominal stress approach.

Reference should be made to Part 5C of the *Steel Vessel Rules* for further explanation and application of these two approaches and for guidance on the categorization of structural details into the various S-N data classes.

### 3 S-N Data (15 February 2017)

To provide a ready reference, the S-N Data recommended by ABS are given in Appendix 1 of this Guide. (Note: source United Kingdom's Dept of Energy (HSE) Guidance Notes, 4<sup>th</sup> Edition.)

It may be necessary to make adjustments to the S-N data to reduce the fatigue capacity of the detail in some instances. Conversely, if the detail has characteristics beneficial to fatigue performance, the S-N data may be adjusted to increase its fatigue capacity.

A reduction in fatigue capacity may be required to account for factors such as the absence of corrosion protection (coating) for structural steel or relatively large plate thickness. The reduction is to be done in accordance with standard ABS practice. The fatigue capacity of a detail may be increased to account for conditions such as compressive mean stress effects – a high compressive portion of the acting variable stress range – or the use of weld improvement techniques.

The use of a weld improvement technique such as weld toe grinding or peening to relieve ambient residual stress can be effective in increasing fatigue life. However, such effects should not be considered in the design of the structure. Typically, an increase in fatigue capacity through weld improvement techniques will be considered only for situations arising during construction, operation or future reconditioning of the structure. If the design fatigue life cannot be obtained using preferred design measures such as layout refinement, geometric changes, scantling adjustment or weld profile modification to reduce fatigue damage, an exception may be granted.

**Weld improvement techniques such as weld toe grinding or ultrasonic peening may be used to improve fatigue life only if the calculated fatigue life is sufficient when the weld improvement techniques are not considered. The required calculated fatigue life without considering weld improvements for various design fatigue lives are listed in the table below:**

<i>Design Fatigue Life</i>	<i>Calculated Fatigue Life without Considering Weld Improvements</i>
20 years	15 years
25 years	17 years
Greater than 25 years	Greater than 2/3 design fatigue life

Where an improvement technique is applied, full details of the technique are to be submitted for review along with supporting calculations indicating the proposed fatigue life improvement factor. If grinding is used, the full details of the grinding standard, including the extents, profile smoothness particulars, final weld profile, improved workmanship technique and quality acceptance criteria are to be clearly indicated on the applicable drawings.

Grinding is to produce a smooth concave profile at the weld toe with a penetration depth of at least 0.5 mm into the plate surface below the bottom of any visible undercut. It is preferable that a rotary burr be used and that the grinding extend below the plate surface in order to remove toe defects. The ground area is to have effective corrosion protection. The groove depth is to be minimized and generally should not exceed 1 mm. In no circumstances may the grinding depth exceed the lesser of 2 mm or 7% of the plate gross thickness. The grinding area is to extend well beyond the high stress region.

A weld surface treated using ultrasonic peening should have a smooth finished shape and all traces of the weld toe are to be removed. The minimum peening depth is to be 0.2 mm below the original surface. Generally, the maximum peening depth is 0.5 mm.

A maximum fatigue life improvement of 2 times may be granted provided the above recommendations are followed.

## 5 Fatigue Strength

An appropriate method is to be employed to calculate the fatigue damage resulting from each considered sea state. The damage resulting from individual sea states is referred to as short-term. The total fatigue damage resulting from combining the damage from each of the short-term conditions can be calculated using a weighted linear summation technique (e.g., Miner's Rule).

Appendix 2 contains a detailed description of the steps involved in a suggested Spectral-based Fatigue Analysis method that follows the basic elements mentioned above. ABS should be provided with background and verification information that demonstrates the suitability of the analytical method employed.

## 7 Combined Fatigue Life from Multiple Loading Conditions

To calculate combined fatigue life from multiple loading conditions, exposure time factors need to be specified for each individual loading condition. In addition, for conventional trading vessels a factor of 0.85 is to be applied to account for non-sailing time for operations such as loading and unloading, repairs, etc. For vessels engaged in a service with less sailing time, special consideration may be given to accepting a lower factor subject to Owner agreement.

The fatigue life for each loading condition is to be calculated separately. If the exposure time ratios have been considered in the fatigue life calculations for each loading condition, the combined fatigue life is given by:

$$L_C = \frac{1}{\alpha_s \left[ \frac{1}{L_1} + \frac{1}{L_2} + \dots + \frac{1}{L_n} \right]}$$

where

$L_C$  = combined fatigue life

$\alpha_s$  = factor of 0.85 to account for non-sailing time

$L_i$  = fatigue life for the  $i^{\text{th}}$  loading condition ( $i = 1$  to  $n$ ) prior to accounting for non-sailing time

$n$  = number of loading conditions.

If the exposure time ratios have not been considered in the fatigue life calculations for each loading condition, the combined fatigue life is given by:

$$L_C = \frac{1}{\alpha_s \left[ \frac{p_1}{L_1} + \frac{p_2}{L_2} + \dots + \frac{p_n}{L_n} \right]}$$

where

$p_i$  = exposure time ratio of the  $i^{\text{th}}$  loading condition ( $i = 1$  to  $n$ ) satisfying:

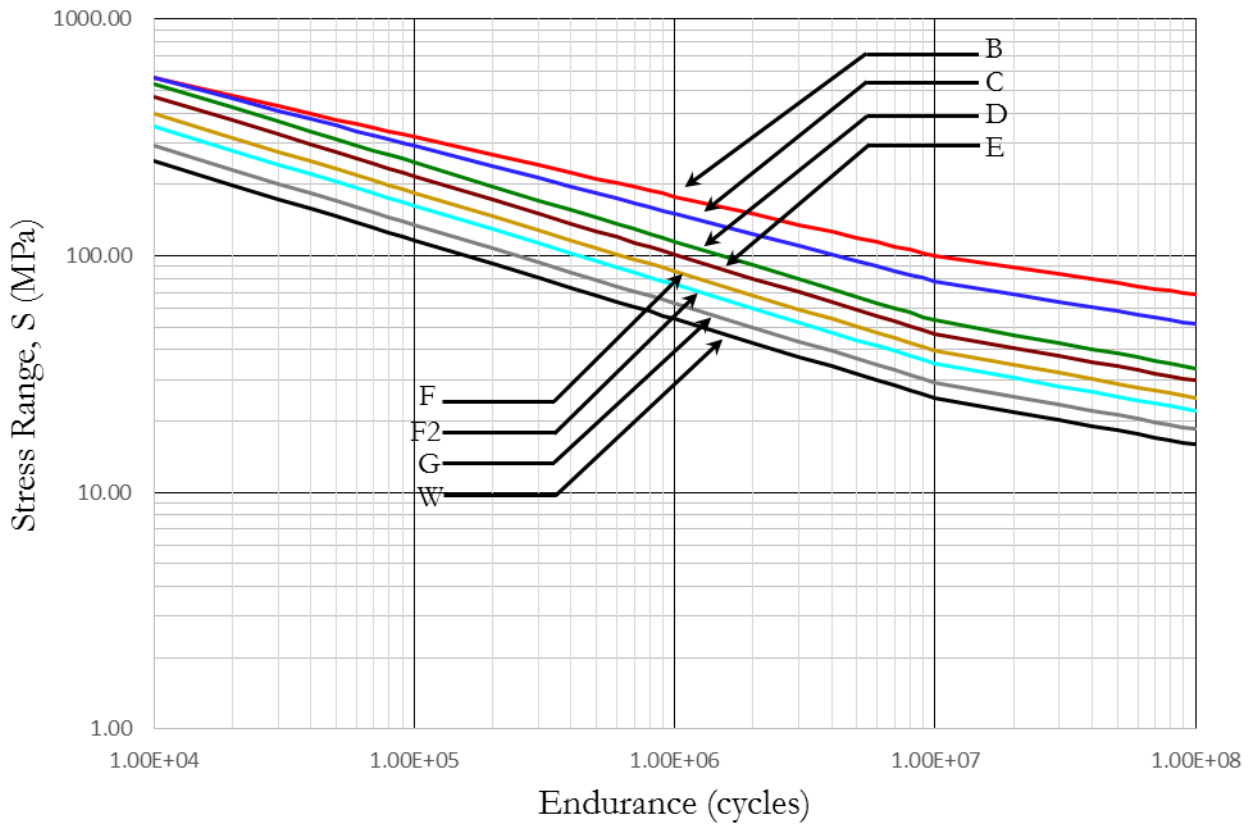
$$\sum_{i=1}^n p_i = 1.0$$

## 9 Acceptance Criteria (1 October 2017)

The minimum required fatigue life for a spectral-based approach is customarily stated as either a damage ratio (D) or a design fatigue life (L). The latter is employed in this Guide. To meet the requirements of the **SFA (years)** or **SFA (years, WWT)** notations, the calculated fatigue life is to be equal to or greater than the design fatigue life.

APPENDIX 1 Basic Design S-N Curves

**FIGURE 1  
S-N Curves**



The S-N Curves are represented by the following equation:

$$S^m N = A$$

where

$S$  = stress range

$N$  = number of cycles to failure

$A, m$  = parameters representing the intercept and inverse slope of the upper (left) portion of the S-N Curve. These change at  $N = 10^7$  cycles to  $C$  and  $r$ , respectively. Values of these parameters are given in the following table.

**TABLE 1**  
**Parameters for Basic S-N Design Curves**

Class	$N \leq 10^7$		$N > 10^7$	
	A (For MPa units)	$m$	C (For MPa units)	$r$
B	$1.013 \times 10^{15}$	4	$1.020 \times 10^{19}$	6
C	$4.227 \times 10^{13}$	3.5	$2.584 \times 10^{17}$	5.5
D	$1.519 \times 10^{12}$	3	$4.239 \times 10^{15}$	5
E	$1.035 \times 10^{12}$	3	$2.300 \times 10^{15}$	5
F	$6.315 \times 10^{11}$	3	$9.975 \times 10^{14}$	5
F2	$4.307 \times 10^{11}$	3	$5.278 \times 10^{14}$	5
G	$2.477 \times 10^{11}$	3	$2.138 \times 10^{14}$	5
W	$1.574 \times 10^{11}$	3	$1.016 \times 10^{14}$	5

Refer to Part 5C of the *Steel Vessel Rules* for guidance on the categorization of structural details into the indicated classes.

*Notes for Application of Classes:*

Class B: Parent material with automatic flame-cut edges ground to remove flame cutting drag line.

Class C: Parent material with automatic flame-cut edges and full penetration butt welds ground flush in way of hatch corners in container carriers or similar deck areas in other vessel types.

Class D: Full penetration butt welds in way of hatch corners in container carriers or similar deck areas in other vessel types.



## APPENDIX 2 Outline of a Closed Form Spectral-based Fatigue Analysis Procedure

Notes:

- (1) (1 October 2017) This Appendix is referred to in Section 6. It is provided to describe the formulations comprising a Spectral-based Fatigue Analysis approach, which can be employed to satisfy the criteria to obtain the **SFA (years)** or **SFA (years, WW7)** Classification notations. However, it is at this formulation level that there are multiple valid methods that may be selected. For that reason, it is emphasized that the contents of this Appendix are provided primarily to illustrate principle rather than to give mandatory steps for the Spectral-based Fatigue method.
- (2) The procedure described below considers the use of a wave scatter diagram (e.g., Section 5, Table 1). Where a different base period for the wave scatter diagram is employed, the procedure must be suitably modified.

### 1 General

In the “short-term closed form” approach described below, the stress range is normally expressed in terms of probability density functions for different short-term intervals corresponding to the individual cells or bins of the wave scatter diagram. These short-term probability density functions are derived by a spectral approach based on the Rayleigh distribution method, whereby, it is assumed that the variation of stress is a narrow-banded random Gaussian process. To take into account effects of swell, which are not accounted for when the wave environment is represented by the scatter diagram, Wirsching’s “rainflow correction” factor is applied in the calculation of short-term fatigue damage. Having calculated the short-term damage, the total fatigue damage is calculated through their weighted linear summation (using Miner’s rule). Mathematical representations of the steps of the Spectral-based Fatigue Analysis approach just described are given next.

### 3 Key Steps in Closed Form Damage Calculation

1. Determine the complex stress transfer function,  $H_\sigma(\omega|\theta)$ , at a structural location of interest for a particular loading condition. This is done in a direct manner where structural analyses are performed for the specified ranges of wave frequencies and headings, and the resulting stresses are used to explicitly generate the stress transfer function.
2. Generate a stress energy spectrum,  $S_\sigma(\omega|H_s, T_z, \theta)$ , by scaling the wave energy spectrum  $S_\eta(\omega|H_s, T_z)$  in the following manner:

$$S_\sigma(\omega|H_s, T_z, \theta) = |H_\sigma(\omega|\theta)|^2 S_\eta(\omega|H_s, T_z) \dots\dots\dots (1)$$

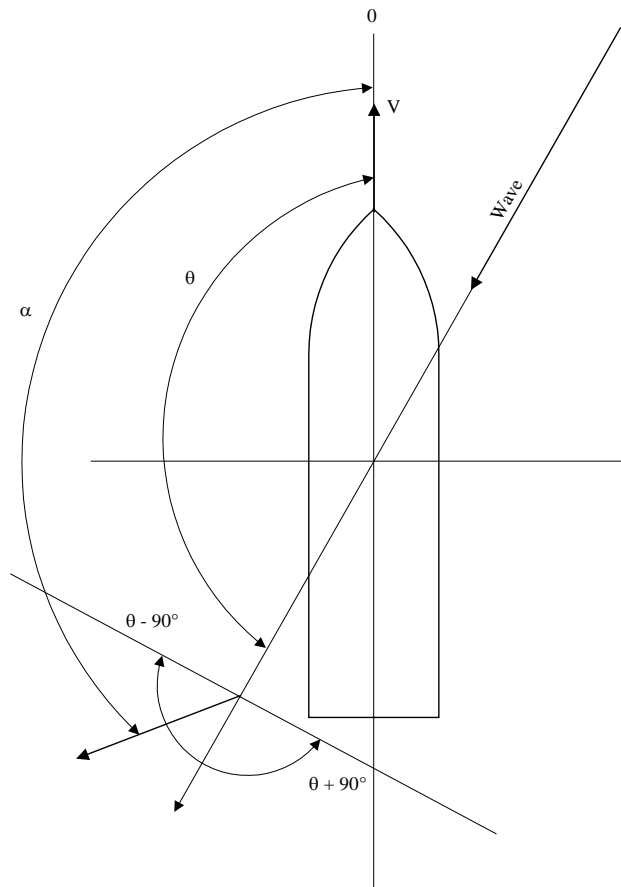
3. Calculate the spectral moments at the same ship forward speed,  $V$ , used in the seakeeping analysis. The  $n^{\text{th}}$  spectral moment,  $m_n$ , is calculated as follows:

$$m_n = \int_0^\infty (\omega - V\omega^2 \cos\theta / g)^n S_\sigma(\omega | H_s, T_z, \theta) d\omega \dots\dots\dots (2)$$

Most fatigue damage is associated with low or moderate seas, hence, confused short-crested sea conditions must be allowed. Confused short-crested seas result in a kinetic energy spread, which is modeled using the cosine-squared approach,  $(2/\pi) \cos^2\theta$ . Generally, cosine-squared spreading is assumed from +90 to -90 degrees on either side of the selected wave heading (refer to Appendix 2, Figure 1). Applying the wave spreading function modifies the spectral moment as follows:

$$m_n = \int_{\theta-90}^{\theta+90} \left(\frac{2}{\pi}\right) \cos^2(\alpha - \theta) \cdot \left( \int_0^\infty (\omega - V\omega^2 \cos\alpha / g)^n S_\sigma(\omega | H_s, T_z, \alpha) d\omega \right) d\alpha \dots\dots\dots (3)$$

**FIGURE 1**  
**Spreading Angles Definition**



- Using the spectral moments, the Rayleigh probability density function (pdf) describing the short term stress-range distribution, the zero up-crossing frequency of the stress response and the bandwidth parameter used in calculating Wirsching’s “rainflow correction” are calculated as follows:

Rayleigh pdf:

$$g(s) = \frac{s}{4\sigma^2} \exp\left[-\left(\frac{s}{2\sqrt{2}\sigma}\right)^2\right] \dots\dots\dots(4)$$

Zero-up crossing frequency, in Hz:

$$f = \frac{1}{2\pi} \sqrt{\frac{m_2}{m_0}} \dots\dots\dots(5)$$

Bandwidth Parameter:

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \dots\dots\dots(6)$$

where

- $s$  = stress range (twice the stress amplitude)
- $\sigma$  =  $\sqrt{m_0}$
- $m_0, m_2, m_4$  = spectral moments



5. Calculate cumulative fatigue damage based on Palmgren-Miner’s rule, which assumes that the cumulative fatigue damage ( $D$ ) inflicted by a group of variable amplitude stress cycles is the sum of the damage inflicted by each stress range ( $d_i$ ), independent of the sequence in which the stress cycles occur:

$$D = \sum_{i=1}^J d_i = \sum_{i=1}^J \frac{n_i}{N_i} \dots\dots\dots (7)$$

where

- $n_i$  = number of stress cycles of a particular stress range
- $N_i$  = average number of loading cycles to failure under constant amplitude loading at that stress range according to the relevant S-N curve
- $J$  = number of considered stress range intervals

Failure is predicted to occur when the cumulative damage ( $D$ ) over  $J$  exceeds a critical value equal to unity.

The short term damage incurred in the  $i$ -th sea-state, assuming an S-N curve of the form  $N = AS^{-m}$ , is given by:

$$D_i = \left(\frac{T}{A}\right) \int_0^\infty (k_t k_{ms} k_h s)^m f_{0i} p_i g(s)_i ds \dots\dots\dots (8)$$

where

- $D_i$  = damage incurred in the  $i$ -th sea-state
- $k_h$  = a factor for high tensile steel, applicable to parent material only
  - = 1.000 for mild steel or welded connections
  - = 0.926 for H32 steel
  - = 0.885 for H36 steel
  - = 0.870 for H40 steel
- $k_t$  = a factor for thickness effect, which is not applicable to longitudinal stiffeners which are flat bars or bulb flats
  - =  $\left(\frac{t}{22}\right)^n$  for  $t \geq 22$  mm
  - = 1.0 for  $t < 22$  mm
- $n$  = 0.25 for cruciform joints, transverse T joints and plates with transverse attachments
  - = 0.20 for transverse butt welds
  - = 0.10 for butt welds ground flush, base metal, longitudinal welds or attachments

If it can be conclusively established that the detail under consideration is always subject to a mean stress of  $\sigma_{ms}$ ,  $D$  is to be adjusted by a factor  $k_{ms}$ .

- $k_{ms}$  = a factor for mean stress effect, which is
  - = 1.0 for  $\sigma_{ms} > s_4/2$
  - =  $0.85 + 0.3 \sigma_{ms}/s_4$  for  $-s_4/2 \leq \sigma_{ms} \leq s_4/2$
  - = 0.7 for  $\sigma_{ms} < -s_4/2$

- $\sigma_{ms}$  = mean stress
- $s_d$  = long-term stress range corresponding to the representative probability level of  $10^{-4}$
- $m, A$  = physical parameters describing the S-N curve
- $T$  = design fatigue life, in seconds
- $f_{0i}$  = zero-up-crossing frequency of the stress response, Hz
- $p_i$  = joint probability of  $H_s$  and  $T_z$
- $g_i$  = probability density function governing  $s$  in the  $i$ -th sea state
- $s$  = specific value of stress range

Summing  $D_i$  over all of the sea-states in the wave scatter diagram leads to the total cumulative damage,  $D$ . Therefore:

$$D = (k_h k_t k_{ms})^m \left( \frac{f_0 T}{A} \right) \int_0^\infty s^m \left[ \sum_{i=1}^M f_{0i} p_i g_i / f_0 \right] ds \dots\dots\dots(9)$$

where

- $D$  = total cumulative damage
- $f_0$  = “average” frequency of  $s$  over the design fatigue life
- =  $\sum_i p_i f_{0i}$  (where the summation is done from  $i = 1$  to  $M$ , the number of considered sea-states)

Introducing long-term probability density function,  $g(s)$  of the stress range as:

$$g(s) = \frac{\sum_i f_{0i} p_i g_i}{\sum_i f_{0i} p_i} \dots\dots\dots(10)$$

and

$$N_T = \text{total number of cycles in design fatigue life} = f_0 T$$

the expression for total cumulative damage,  $D$ , can be rewritten as:

$$D = (k_h k_t k_{ms})^m \frac{N_T}{A} \int_0^\infty s^m g(s) ds \dots\dots\dots(11)$$

6. If the total number of cycles,  $N_T$ , corresponds to a required minimum design fatigue life of 20 years, the calculated fatigue life would then be equal to  $20/D$ . Increasing the design fatigue life to higher values can be done accordingly. The fatigue safety check is to be done in accordance with the applicable Rules where factors of safety (or Fatigue Design Factors) are specified.

## 5 Closed Form Damage Expression

The closed form expression of damage can be obtained using equation 11 and assuming an analytical distribution for the long term probability density function of the stress range  $g(s)$  (e.g., Weibull probability density function). For all one-segment linear S-N curves, the closed form expression of damage,  $D$ , as given by equation 9, is as follows:

$$D = \frac{T}{A} (2\sqrt{2})^m \Gamma(m/2 + 1) \sum_{i=1}^M \lambda(m, \varepsilon_i) f_{0i} p_i (k_h k_t k_{ms} \sigma_i)^m \dots\dots\dots(12)$$

where

$$\begin{aligned} \Gamma &= \text{complete gamma function with the argument } (m/2 + 1) \\ \sigma_i &= \sqrt{m_0} \text{ for the } i\text{-th considered sea state} \\ \lambda &= \text{rainflow factor of Wirsching and is defined as:} \\ &\lambda(m, \varepsilon_i) = a(m) + [1 - a(m)][1 - \varepsilon_i]^{b(m)} \dots\dots\dots (13) \end{aligned}$$

where

$$\begin{aligned} a(m) &= 0.926 - 0.033m \\ b(m) &= 1.587m - 2.323 \\ \varepsilon_i &= \text{Spectral Bandwidth (equation 6)} \end{aligned}$$

For bi-linear S-N curves (see Appendix 1) where the negative slope changes at point  $Q = (N_Q, S_Q)$  from  $m$  to  $r = m + \Delta m$  ( $\Delta m > 0$ ) and the constant  $A$  changes to  $C$ , the expression for damage, as given in equation 12, is as follows:

$$D = \frac{T}{A} (2\sqrt{2})^m \Gamma(m/2 + 1) \sum_{i=1}^M \lambda(m, \varepsilon_i) \mu_i f_{0i} p_i (k_h k_t k_{ms} \sigma_i)^m \dots\dots\dots (14)$$

where  $\mu_i$  is the endurance factor having its value between 0 and 1 and measuring the contribution of the lower branch to the damage. It is defined as:

$$\mu_i = 1 - \frac{\int_0^{S_Q} s^m g_i ds - \left(\frac{A}{C}\right) \left[(k_h k_t k_{ms})^{\Delta m}\right] \int_0^{S_Q} s^{m+\Delta m} g_i ds}{\int_0^{\infty} s^m g_i ds} \dots\dots\dots (15)$$

If  $g(s)$  is a Rayleigh distribution, then  $\mu_i$  is:

$$\mu_i = 1 - \frac{\Gamma_0(m/2 + 1, v_i) - (1/v_i)^{\Delta m/2} \left[(k_h k_t k_{ms})^{\Delta m}\right] \Gamma_0(r/2 + 1, v_i)}{\Gamma(m/2 + 1)} \dots\dots\dots (16)$$

where

$$\begin{aligned} v_i &= \left(\frac{S_Q}{2\sqrt{2}\sigma_i}\right)^2 \\ \Gamma_0 &= \text{incomplete gamma function and is} \\ &\Gamma_0(a, x) = \int_0^x u^{a-1} \exp(-u) du \end{aligned}$$

See steps 2-6 above, regarding the fatigue safety check.