Guidance Notes on

Fracture Analysis for Marine and Offshore Structures

ABS

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GUIDANCE NOTES ON

FRACTURE ANALYSIS FOR MARINE AND OFFSHORE STRUCTURES
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Foreword

Fatigue and fracture are significant failure modes for marine and offshore structures which are subject to wave, vibration, and other loads throughout their service lives. In general, stress concentrations and residual stress exist at weldments and heat affected zones (HAZ) and at other critical areas with irregularities in the geometry where fatigue and fracture may occur. Marine and offshore structures are usually designed for a service life using detailed structural analysis considering dynamic loads and predetermined material fatigue properties. Under cyclic loading, fatigue damage may occur, and a macro crack may initiate, propagate from an existing defect, a discontinuity, or a stress riser, and eventually lead to fracture. These Guidance Notes provide a general procedure for crack propagation analysis and structural integrity assessment for marine and offshore structures with a defect, a discontinuity, or a stress riser.

These Guidance Notes provide guidelines for determining the long-term stress range distribution in the form of a stress range histogram at a critical location on a marine or offshore structure under wave-induced loads, vibration-induced loads, or combined loads. The stress range histogram is employed for the crack propagation analysis for a flawed structure based on fracture mechanics theory. Additionally, the fracture mechanics method is introduced, including stress intensity factors for various flaw configurations and crack propagation analysis following Paris' law. Based on the failure assessment diagram (FAD), the structural integrity assessment can be performed for a structure with a known defect, flaw, or discontinuity. In marine and offshore applications, crack propagation analysis also can be conducted to predict the remaining life of a defective structure in service.

The objective of this document is to provide guidance for the fracture analysis not covered by the ABS Rules and Guides and supplement the design and analysis requirements issued for the Classification of specific types of marine and offshore structures.

The effective date of these Guidance Notes is the first day of the month of publication.

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GUIDANCE NOTES ON

FRACTURE ANALYSIS FOR MARINE AND OFFSHORE STRUCTURES

CONTENTS

SECTION 1
Introduction

1 General

Fatigue and fracture are significant failure modes for marine and offshore structures under wave-induced loads and other loads such as vibration-induced loads during service. Many failures on marine and offshore structures surprise engineers because of the unexpected crack initiation and propagation at welded connections under cyclic loads. A crack at a critical area in a structure can initiate and propagate until the final failure occurs under static or dynamic loads.

ABS Rules and Guides for the classification of ship and offshore structures require fatigue assessment in the design, which also specifies material toughness requirements and detailed analysis methods. These methods for evaluating the fatigue life are intended for determining design requirements as well as in-service assessment.

After a ship or offshore structure is in service for a certain period, flaws may occur at critical locations due to dynamic loads such as wave-induced loads, vibration-induced loads, etc. Flaws also may occur due to undetected construction issues such as weld inclusions and structural misalignments. The types of flaws refer to Subsection 5/1.2. Flaws and defects observed on a structure are usually required to be repaired according to established procedures and the applicable ABS Rules. However, it could happen that flaws are unable to be repaired immediately.

The presence of a flaw in a ship, offshore structure, or equipment could have an impact on structural integrity and present safety concerns. In such cases, the fracture mechanics method can be applied to analyze crack propagation and to evaluate the probable influence on structural integrity under service loads. Note that any damages and repairs on ABS Classed vessels/units are to be communicated to ABS in accordance with the Section 1-1-8 of the ABS *Rules for Conditions of Classification (Part 1)* or Section 1-1-8 of the ABS *Rules for Conditions of Classification – Offshore Units and Structures (Part 1)*.

2 Marine and Offshore Applications

Fracture mechanics theory has been well established and widely applied in many industries, such as the aerospace industry, where flaws found within materials subjected to high cycle fatigue loads are evaluated. Marine and offshore structures usually experience not only wave-induced dynamic loads in environmental conditions but also other loads during operation, such as vibration-induced loads and low cycle loads due to cargo loading/offloading. Once a flaw initiates, the structure is more prone to fracture-related failures and thus fracture analysis can be applied for structural safety assessment. These Guidance Notes provide the recommended practices for assessing flaws or crack-like defects found in marine and offshore structures and the fracture mechanics method for the verification of structural integrity.

The Guidance Notes address three major types of loads: wave-induced loads, vibration-induced loads, and cyclic loads due to loading/offloading. The stress analysis method is provided for determining the long-term stress range distribution. An introduction of the types of fractures, possible countermeasures, crack drivers, and fracture assessment methods, are briefly outlined.

In the current context, the primary use of fracture mechanics is for evaluating the impact of a defect on structural integrity during the service life. The ABS *Guide for Nondestructive Inspection* can be referred to for the applicable requirements for nondestructive testing. Another application of fracture mechanics approach is the prediction of remaining life of a structure containing a defect, in conjunction with a risk-based inspection plan. The ABS *Guide forRisk-Based Inspection for Floating Offshore Installations* describes the use of fracture mechanics analysis in the risk-based inspection program.

It is noted that fracture mechanics is not intended to be used for design purposes. However, there are some structures that require fracture analysis as part of the design process (e.g., Tendons on a Tension-Leg Platform (TLP)). Three major elements to the fracture mechanics assessment, including applied loads, materials fracture properties, and crack growth and fracture assessment, are described in these Guidance Notes.

3 Abbreviations and References

3.1 Abbreviations

CFD	Computational Fluid Dynamics
CDF	Crack Driving Force
CT	Compact Tension
ECA	Engineering Critical Assessment
FAD	Failure Assessment Diagram
FAL	Failure Assessment Line
FCGR	Fatigue Crack Growth Rate
FE	Finite Element
FPI	Floating Production Installations
HAZ	Heat Affected Zone
IMO	International Maritime Organization
LC	Load Case
LEFM	Linear Elastic Fracture Mechanics
LGC	Liquefied Gas Carriers
MARPOL	International Convention for the Prevention of Pollution
MVR	Marine Vessel Rule
RAO	Response Amplitude Operator
SCF	Stress Concentration Factor
SIF	Stress Intensity Factor
SOLAS	International Convention for the Safety of Life at Sea
TLP	Tension-Leg Platform
VIV	Vortex-Induced Vibration

3.2 References

References to specific sections of industry standards are based on the versions listed below.

i) ABS *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)*

ii) ABS *Rules for Materials and Welding (Part 2)*

iii) ABS *Rules for Building and Classing Floating Production Installations (FPI Rules)*

iv) ABS *Guide for Spectral-Based Fatigue Analysis for Vessels*

v) ABS *Guide for Fatigue Assessment of Offshore Structures*

vi) ABS *Guidance Notes on SafeHull Finite Element Analysis of Hull Structures*

vii) A. Almar-Næss: Fatigue Handbook – Offshore Steel Structures, TAPIR publishers, 1985

viii) BS EN 1999-1-3: Eurocode 9 – Design of Aluminum Structures – Structures Susceptible to Fatigue

ix) BS 7608:2014: Guide to Fatigue Design and Assessment of Steel Products., 2014.

x) BS 7910:2910: Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures, 2019

xi) API 579-1/ASME FFS-1:2016: Fitness-For-Service, 2016

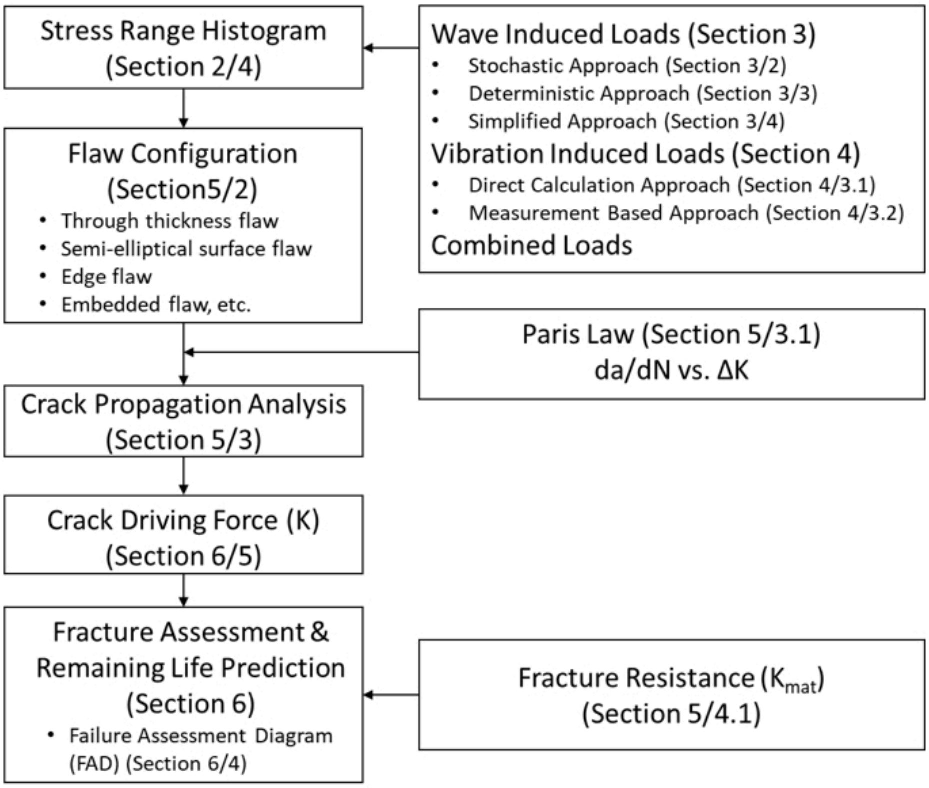
4 Overview of Fracture Analysis Procedure

The general procedure for fracture analysis is given in Section 1, Figure 1. The common stress analysis methods are employed for marine and offshore structures subjected to wave-induced loads and vibration induced loads. The stress analysis results are applied for the crack propagation analysis and fracture assessment based on fracture mechanics theory.

For marine and offshore structures, the most dominant source of fluctuating loads are waves. However, in some particular cases, other sources, such as slamming-induced vibration, engine and propeller induced vibrations, vortex-induced vibration (VIV), wind, and operational loads, may be significant and need to be included in the analysis. Two stress analysis methods for wave-induced loads and vibration-induced loads can be used to obtain the long-term stress range distribution for marine and offshore structures. For wave-induced loads, common analysis approaches including stochastic approach, deterministic approach, and simplified approach are used to generate the long-term stress range distributions to determine the stress range histogram. For vibration-induced loads, common analysis approaches including direct calculation approach and measurement-based approach are introduced to generate the long-term stress range distributions to determine the stress range histogram. In most cases, the structure is simultaneously subjected to the combined wave- and vibration-induced loads, indicating that the total long-term stress range histogram is the sum of the effect caused by these two types of loads.

In Fracture Mechanics (FM) based Engineering Critical Assessment (ECA), when the orientation and position of a flaw are known, with given structural configuration and material fracture properties, the stress range histogram can be applied to calculate the crack propagation under dynamic loads using Paris' law for a defected structure. At each cycle of crack extension, the crack driving force, such as the stress intensity factor, can be calculated and then employed together with material fracture resistance properties to check whether the flaw has reached a critical length, which may cause the final failure of the structure due to unstable growth. The Failure Assessment Diagram (FAD) is employed and provides an estimated remaining fatigue life. Thus, fracture analysis of a flaw or flaws can be applied to predict the remaining life of a structure by evaluating the number of cycles expected for an existing flaw to develop to an extent that will cause the final rupture of a structure, structural member, or component. This information also can be used to evaluate the need to take mitigating actions such as repair or reduced operating load conditions.

FIGURE 1
Fracture Analysis Procedures



SECTION 2

Applied Loads and Stress Range Distribution

1 General

The stress range distribution caused by dynamic loads is the key crack driving force for crack propagation analysis. Dynamic loads on marine and offshore structures can be subdivided into three major categories according to the loading frequency or cycle:

- *Wave-induced Loads:* Wave-induced pressure due to vessel motions in the seaway generates cyclic stresses with relatively low frequency in the order of 0.1 Hz, or periods around 10s. For an operational lifetime of 25 years, the total number of wave load cycles a vessel experiences can be between 10^7 and 10^8.
- *Vibration-induced Loads:* Higher-frequency loads caused by engines, propellers, and other rotating machinery result in forced vibrations with a high number of load cycles, typically 10^{10} or more in their operating lifetime. In addition, wave impacts (slamming), as well as small regular waves, may excite hull girder vibrations (whipping and springing) on ships and ship-shaped floating production installations (FPIs) on the order of 1 Hz.
- *Loads Due to Loading/Offloading:* Changes in cargo loading/offloading conditions and associated drafts generally cause loads to fluctuate in rather low frequencies. For instance, the cargo loading may vary between hours for ferries and weeks for long distance ships, thus resulting in loading/offloading cycles depending on the service and type of vessel during operation lifetime.

When individual or combined dynamic loads on the structure susceptible to crack initiation and propagation are identified, stress analyses using the finite element (FE) method can be performed to calculate the stress and time history of the structure. Subsection 2/2 discusses recommended practices when carrying out stress analysis by FE analysis. To capture the high stress concentration, a refined mesh arrangement is needed for the local FE model of critical locations such as the weld toe. Weld hot spot stress should be evaluated in accordance with the deterministic procedure described in 2/2.2.

Stress range can be expressed using a time history or in a statistical format. When a stress range time history is obtained from a stress analysis, the rainflow counting approach introduced in Subsection 2/3 may be used to obtain the stress range histogram. If a statistical method such as the simplified approach is conducted, the long-term stress range distribution may be assumed to follow the Weibull distribution, which is introduced in Subsection 2/4.

2 Stress Analysis

Structural analysis should be performed under wave-induced loads, vibration-induced loads, or loading/offloading induced loads. In structural analysis, the stress can be calculated using either simplified Rule-based equations or numerical simulations. For structures with the geometric complexity of marine vessels and offshore structure, the FE analysis is usually conducted to determine the stress distribution at critical locations. The calculated hot spot stress at the weld toe capturing the stress concentration is then employed for the fracture assessment.

2.1 FE Modeling for Marine and Offshore Structures

Evaluating localized stresses for marine and offshore structures can be challenging. When building FE models for stress analysis, three types of elements are typically used to discretize the geometry of the 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

Mesh size is one of the important FE modeling considerations for discretizing the geometry of the structure. Typically, a one-longitudinal spacing mesh size is recommended for a global FE model. More information and guidance on global mesh discretization can be found in 2/9.3 of the ABS *Guidance Notes on Safehull Finite Element Analysis of Hull Structures.*

For a local FE model, those structural details which are simplified or ignored in the global model are reinstated to obtain more detailed stress distributions. A finer mesh size of "$t \times t$" of shell elements should be applied immediately adjacent to those hot spot locations, where t represents the member thickness. The performance of elements degrades as they become more skewed. If the mesh is graded, rather than uniform, the grading should be applied in a way that minimizes the difference in size between adjacent elements.A refined local stress distribution can be obtained from a fine-meshed FE analysis. Reference can be made to the ABS *Guidance Notes on SafeHull Finite Element Analysis of Hull Structures*. Section 2, Figure 1 shows an example for a global FE model of three tanks in a ship and Section 2, Figure 2 gives an example showing a local FE model at a critical location.

Generally, weld toes are critical points particularly in need of stress checks, and the hot spot stress approach has been widely implemented to assess the stresses at those critical locations via a linear extrapolation manipulation on the calculated FE stress results. Introduction of the hot spot stress approach is given in 2/2.2.

If the IACS Common Structural Rules (CSR) are applied for bulk carriers and oil tankers, the calculation of hot spot stress refers to Section 5A-9-5 of the *Marine Vessel Rules*.

FIGURE 1
Global FE Mesh Model

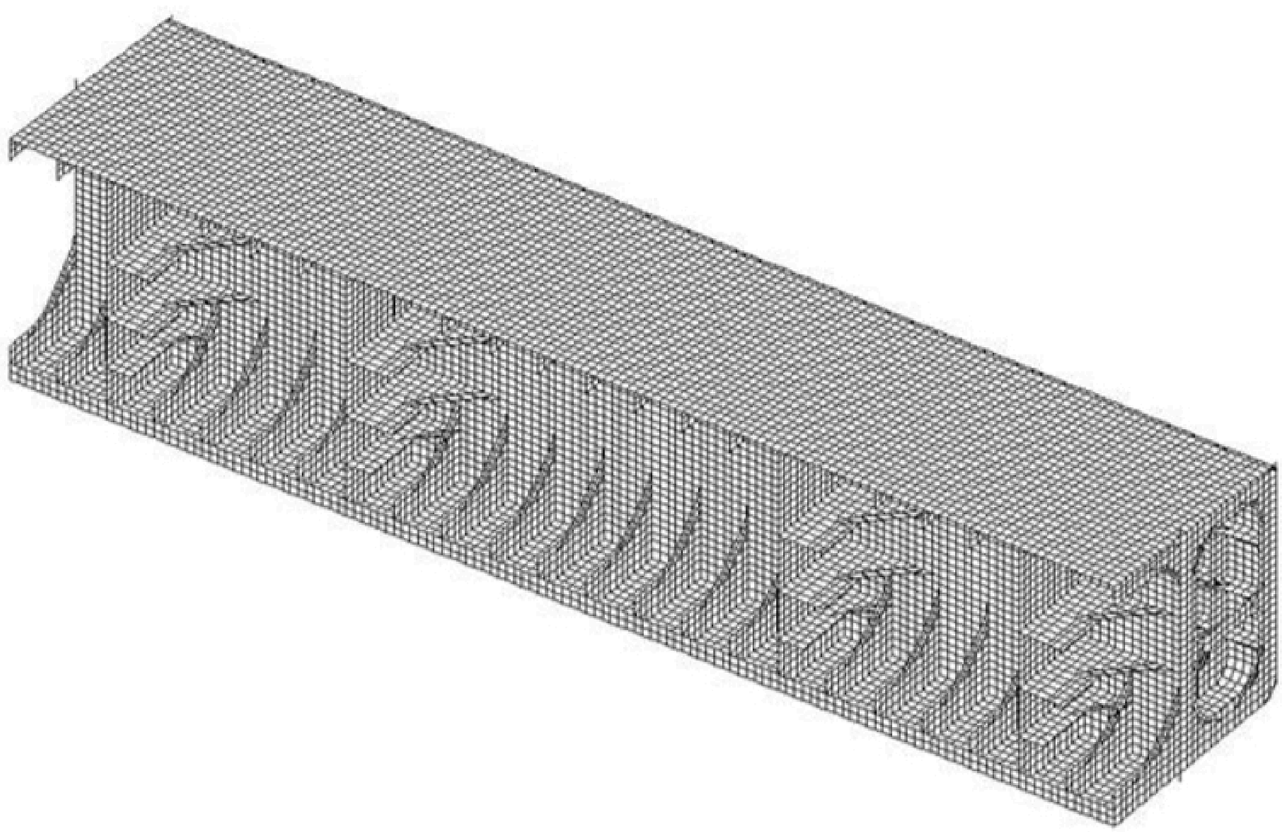
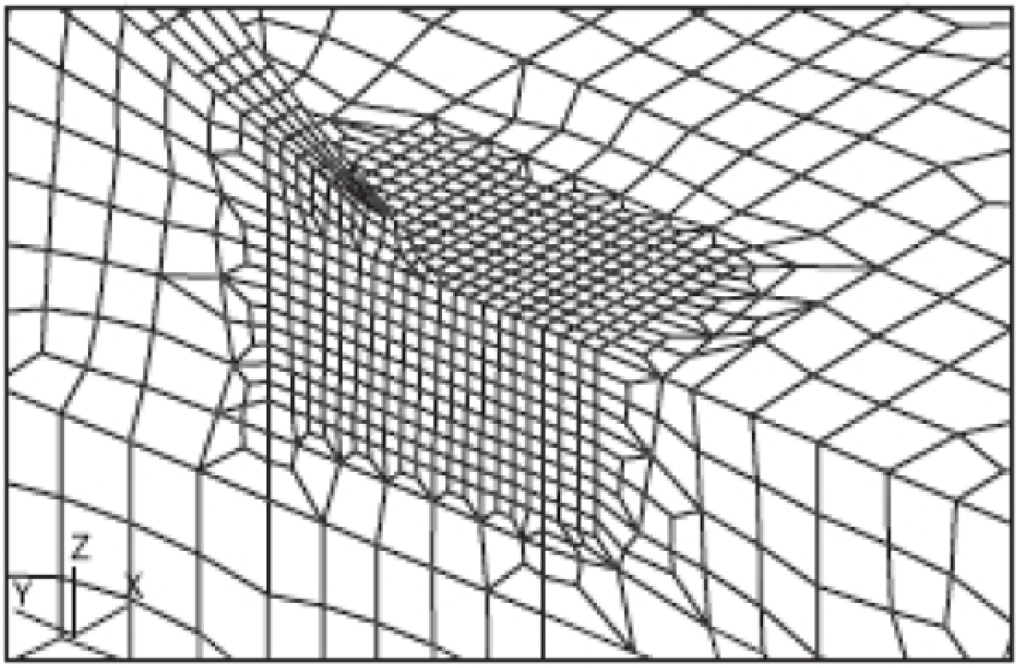


FIGURE 2
Local FE Mesh Model with Refined Elements



2.2 Hot Spot Stress Approach for Weld Toe

A hot-spot stress is defined at one particular hot spot in a structural detail where fatigue cracking is expected to initiate. The hot-spot stress includes stress risers due to structural discontinuities and the presence of attachments but excludes the effects of welds. To determine hot-spot stresses, the mesh size needs to be finer than 1/10 of longitudinal spacing (e.g., plate thickness size).

The hot spot stress approach for ship structures, as shown in Section 2, Figure 3 and Figure 4, extracts and interprets the stresses of elements "near weld toe" and obtains a stress at the weld toe. The principal stresses at the hot spot are then calculated based on the extrapolated stresses and used for fatigue crack propagation analysis. Assuming that the applicable surface component stresses, S_i, at P_i have been determined from FEM analysis, the corresponding stresses at "hot spot" can be determined by the following procedure:

i) Select two points, L and R, such that points L and R are situated at distances $t/2$ and $3t/2$ from the weld toe, i.e.:

$$X_L = t/2, \qquad X_R = 3t/2$$

ii) Let X = XL and compute the values of four coefficients, as follows:

$$C_1 = [(X - X_2)(X - X_3)(X - X_4)]/[(X_1 - X_2)(X_1 - X_3)(X_1 - X_4)]$$
$$C_2 = [(X - X_1)(X - X_3)(X - X_4)]/[(X_2 - X_1)(X_2 - X_3)(X_2 - X_4)]$$
$$C_3 = [(X - X_1)(X - X_2)(X - X_4)]/[(X_3 - X_1)(X_3 - X_2)(X_3 - X_4)]$$
$$C_4 = [(X - X_1)(X - X_2)(X - X_3)]/[(X_4 - X_1)(X_4 - X_2)(X_4 - X_3)]$$

The corresponding stress at Point L can be obtained by interpolation as:

$$S_L = C_1S_1 + C_2S_2 + C_3S_3 + C_4S_4$$

iii) Let $X = X_R$ and repeat the step of ii to determine four new coefficients. The stress at Point R can be interpolated likewise, i.e.:

$$S_R = C_1S_1 + C_2S_2 + C_3S_3 + C_4S_4$$

iv) The corresponding stress at hot spot, S_0, is given by:

$$S_0 = (3S_L - S_R)/2$$

FIGURE 3
Extrapolation of Dynamic Stress Range at Weld Toe

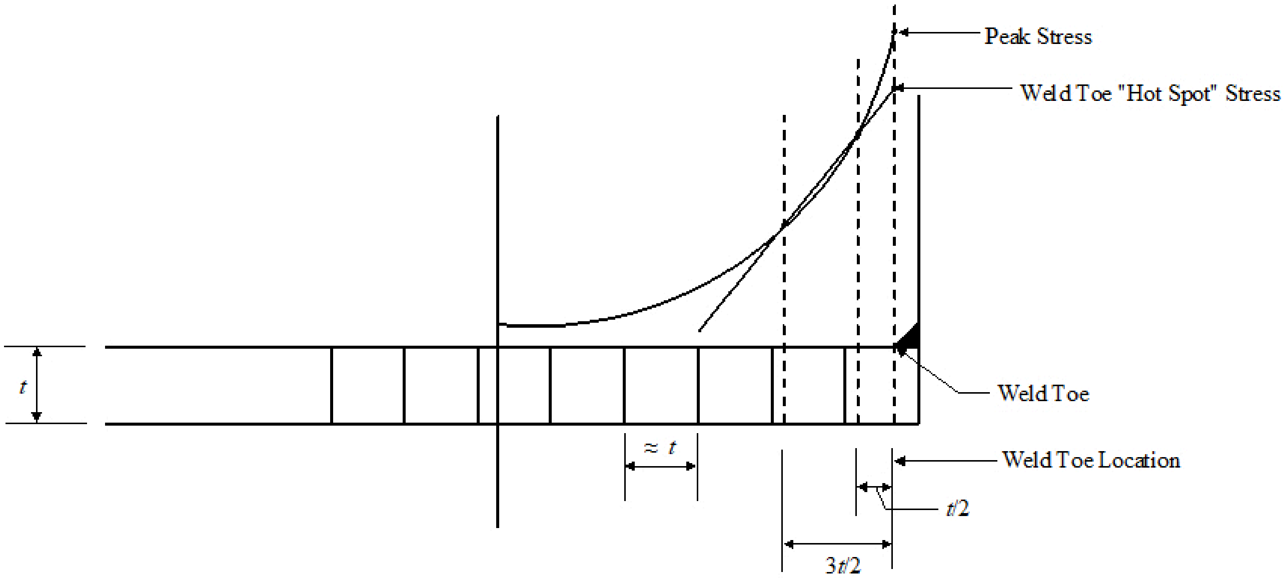
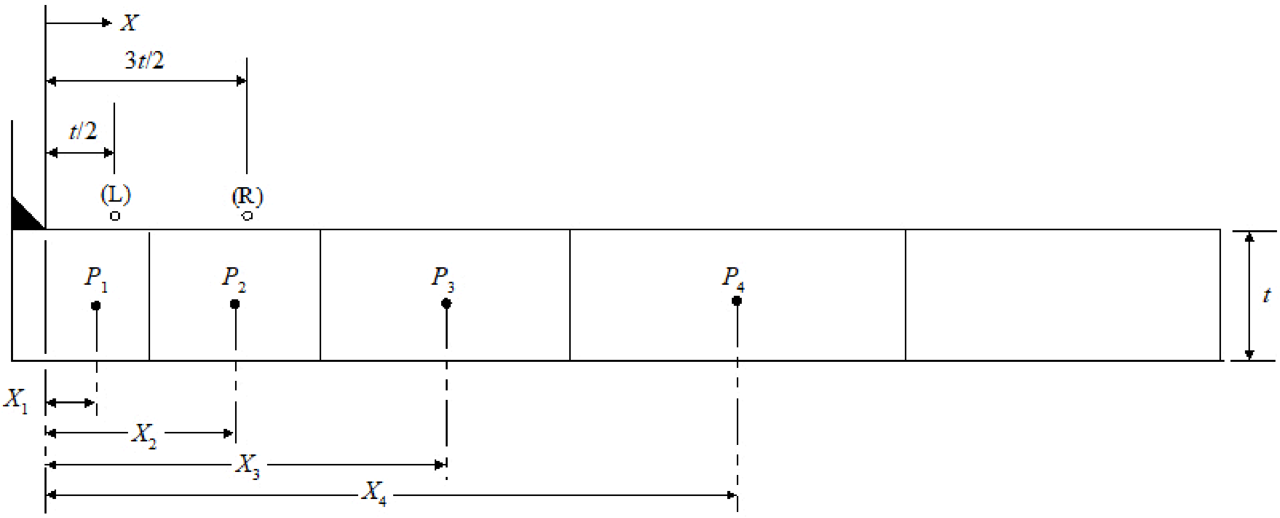


FIGURE 4
Determination of Hot Spot Stress at Weld Toe



When CSR criteria is chosen to apply on oil tankers or bulk carriers, an alternative hot spot stress approach and requirements are given for both welded and non-welded hot sports. The hot spot stress, σ_{HS}, is determined as:

$$\sigma_{HS} = 1.12 \cdot \sigma$$

where σ is the extrapolated finite element stress at the point with distance of an half mesh size from the hot spot.

The hot spot stress approach to determine σ for welded details, except web-stiffened cruciform joints, is provided in 5A-9-5/3.1 of the *Marine Vessel Rules*, non-weld base materials in 5A-9-5/3.2 of the *Marine Vessel Rules*, and web-stiffened cruciform joints in 5A-9-5/4 of the *Marine Vessel Rules*.

The hot spot stress approach for offshore structures refers to Subsection 2/5 of the *Guide for Fatigue Assessment of Offshore Structures*.

3 Rainflow Counting Approach

When a time series of stress results is available, the rainflow counting approach can be applied to determine the stress range histogram for further fracture mechanics-based crack propagation analysis. The rainflow counting approach is used to extract closed loading reversals or cycles. The "rainflow" was named from a comparison of this method to the rain flow falling on a pagoda and running down the edges of the roof. The algorithm of the rainflow cycle counting, as shown in Section 2, Figure 5, is summarized as follows:

1) Rotate the loading history 90° such that the time axis is vertically downward, and the load time history resembles a pagoda roof.

2) Draw a flow of rain starting at each successive extremum point.

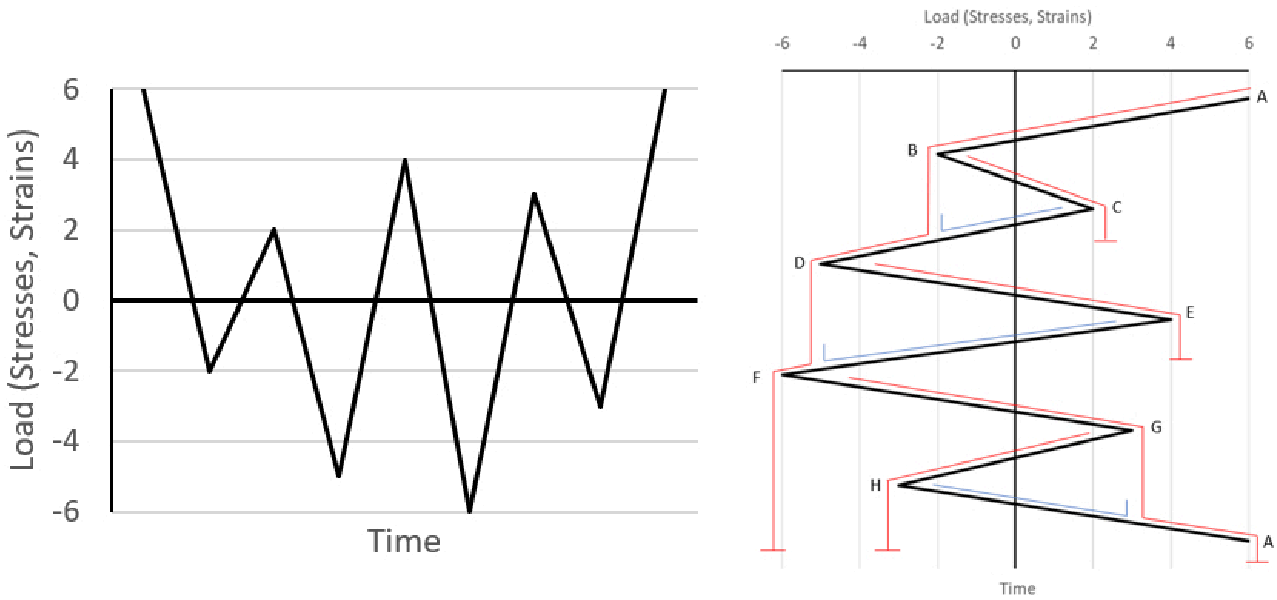
3) Define a loading reversal (half-cycle) by allowing each rainflow to continue to drip down these roofs until:

- ***a)*** It falls opposite a larger maximum (or smaller minimum) point (e.g., red lines: B-C, D-E, and G-H).
- ***b)*** It meets a previous flow falling from above (e.g., all blue lines).
- ***c)*** It falls below the roof (e.g., red lines: A-B-D-F and F-G-A).

4) Identify each hysteresis loop (cycle) by pairing up the same counted reversals.

5) Finally the stress range histogram can be constructed.

FIGURE 5
Rainflow Counting Algorithm



4 Long-Term Stress Range Distribution

In the simplified approach, the reference stress range for a structure is calculated corresponding to a specified probability of exceedance. The Weibull distribution is usually employed to describe the long-term distribution of stress range for marine and offshore structures subjected to wave-induced loads. In the Weibull probability density function, the long-term distribution of stress ranges is governed by the shape parameter, γ, and the scale parameter, δ. The Weibull probability density function of the stress range, $f(s)$, is defined as:

$$f(s) = \frac{\gamma}{\delta} \cdot \left(\frac{s}{\delta}\right)^{\gamma - 1} exp\left[-\left(\frac{s}{\delta}\right)^{\gamma}\right]$$

where

s = stress range

γ = Weibull's shape parameter

δ = Weibull's scale parameter

= $\frac{S_R}{(ln \quad N_R)^{1/\gamma}}$

S_R = reference stress range with probability of exceedance of $1/N_R$

N_R = number of cycles corresponding to the probability of exceedance of $1/N_R$

The cumulative probability function is:

$$P(s) = 1 - exp\left[-\left(\frac{s}{\delta}\right)^{\gamma}\right]$$

The probability value for the stress range not greater than S_R is:

$$P(s) = 1 - \frac{1}{N_R} = 1 - exp\left[-\left(\frac{S}{\delta}\right)^{\gamma}\right]$$

Thus, the stress range histogram can be derived that a series number of occurrence cycles, N_i, is calculated with respect to the given stress range interval, ΔS_i, in a duration containing a total occurrence cycle N_T.

$$N_i = P(\Delta S_i)N_T$$

where

$$\Delta S_i = S_{i+1} - S_i$$

$$P(\Delta S_i) = exp\left[-\left(\frac{S_i}{\delta}\right)^{\gamma}\right] - exp\left[-\left(\frac{S_i + \Delta S_i}{\delta}\right)^{\gamma}\right]$$

SECTION 3
Wave-Induced Loads and Stress Range Distribution

1 General

Marine and offshore structures are subjected to different types of loads during their service lives in which environmental loads (e.g., wave-induced loads) and vibration-induced loads are the most dominant loads causing fatigue and fracture damage. This Section provides guidance on the calculation of wave-induced loads and the resulting cyclic stresses that cause the crack propagation.

In general, hydrodynamic loads can be calculated through hydrodynamic analysis (e.g., seakeeping analysis) and then applied for structural analysis (e.g., FE analysis) to determine stress distributions. For large-volume bodies, the wave forces on the structure in the diffraction regime are usually calculated based on the potential flow theory. For small-volume bodies, the hydrodynamic forces on the structure in drag and inertia regimes can be calculated using the Morison's equation.

This Section presents the procedure and methodology to determine the long-term distribution of stress ranges due to wave-induced loads. The following three common approaches are introduced in these Guidance Notes.

- Stochastic Approach
- Deterministic Approach
- Simplified Approach

1.1 Stochastic Approach

The stochastic approach is suitable for marine and offshore structures and this approach considers the most detailed and complete load information that a structure could experience in its service life. The deterministic approach is applicable for offshore structures when the structural behavior is dominated by a limited number of discrete sea states. The simplified approach is also suitable for marine and offshore structures and this approach assumes that the long-term stress range distribution of a structure follows the Weibull distribution. The procedure for each approach is briefly outlined as follows.

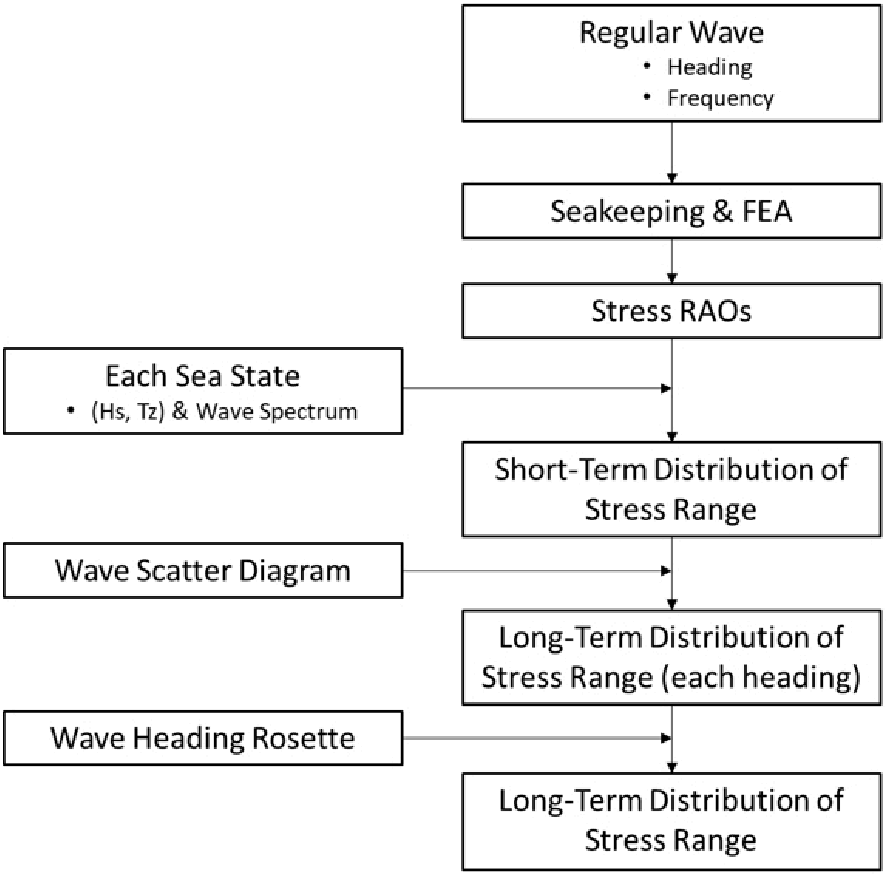
The stochastic approach is introduced in Subsection 3/2. Section 3/FIGURE 1 provides a flowchart describing:

i) For each heading and each regular wave frequency, seakeeping and FE analyses are carried out to determine stress RAOs,

ii) For each sea state, the stress RAOs are combined with wave spectrum to obtain the short-term stress range distribution, and

iii) For all headings and sea states, the long-term stress range distribution is determined based on wave data scatter diagram and wave heading rosette.

FIGURE 1
Stochastic Approach Flowchart



1.2 Deterministic Approach

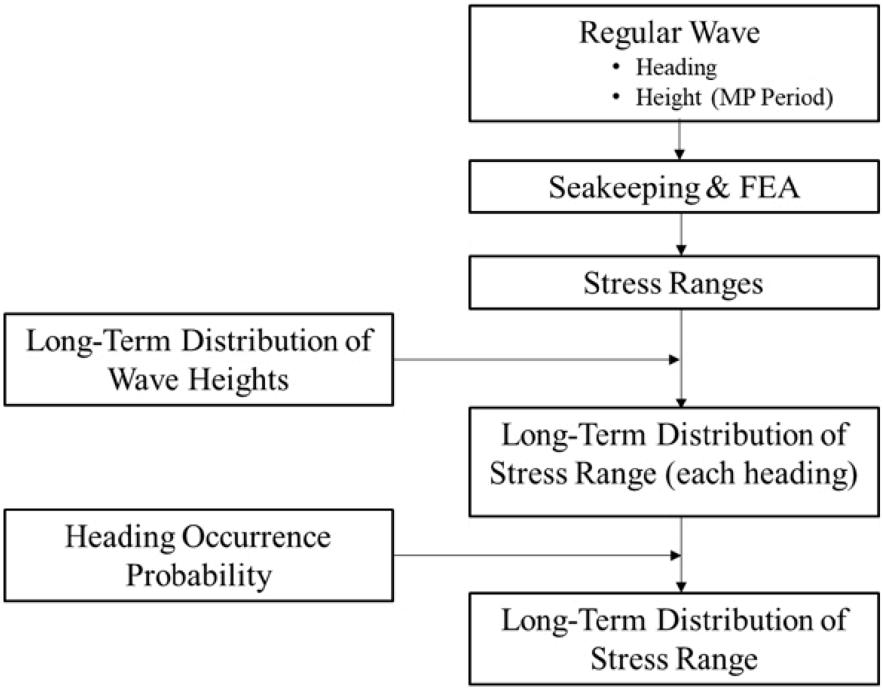
The deterministic approach is introduced in Subsection 3/3. Section 3/FIGURE 2 gives the flowchart of this approach describing:

i) For each selected heading and regular wave condition (wave height and its corresponding most probable period), the stress range is calculated by seakeeping and FE analyses. The deterministic approach does not use wave spectra or transfer functions, but instead performs a relatively few discrete wave analyses to determine stress range values. Alternatively, Rule-based equations, which are provided in the *Marine Vessel Rules* or the *FPI Rules*, can be employed to directly calculate stress range values.

ii) For each selected heading, the long-term stress range distribution is obtained according to the long-term wave height distribution, and

iii) For all headings, the long-term stress range distribution is determined based on heading occurrence probabilities.

FIGURE 2
Deterministic Approach Flowchart



1.3 Simplified Approach

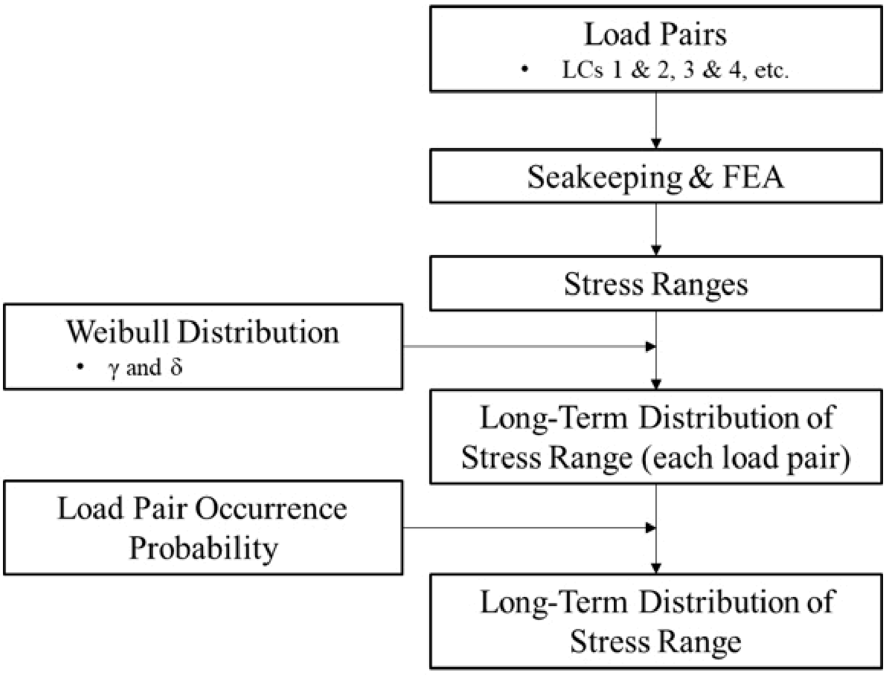
The simplified approach is introduced in Subsection 3/4. Section 3/FIGURE 3 gives the flowchart of this approach describing:

i) For each defined load pair with load cases (LCs), the reference stress range is calculated using seakeeping and FE analyses,

ii) For each load pair, the long-term stress range distribution is determined following a Weibull distribution, and

iii) For all load pairs, the long-term stress range distribution is determined based on load pair occurrence probabilities.

FIGURE 3
Simplified Approach Flowchart



Finally, the stress range histogram, which is further derived from the long-term stress range distribution, will be employed for crack propagation analysis based on fracture mechanics theory.

2 Stochastic Approach

The stochastic approach is a spectral-based approach for determining long-term stress range distributions for both marine and offshore structures. This approach includes the use of pre-calculated stress transfer functions, individual wave spectrum, and wave direction and the long-term stress range distribution considering all headings and sea states. Section 3/FIGURE 4 illustrates the concept and procedure of the spectral analysis for determining the long-term stress range distribution.

A stochastic analysis requires a complex description of environmental data and loads. The general procedure is summarized as follows:

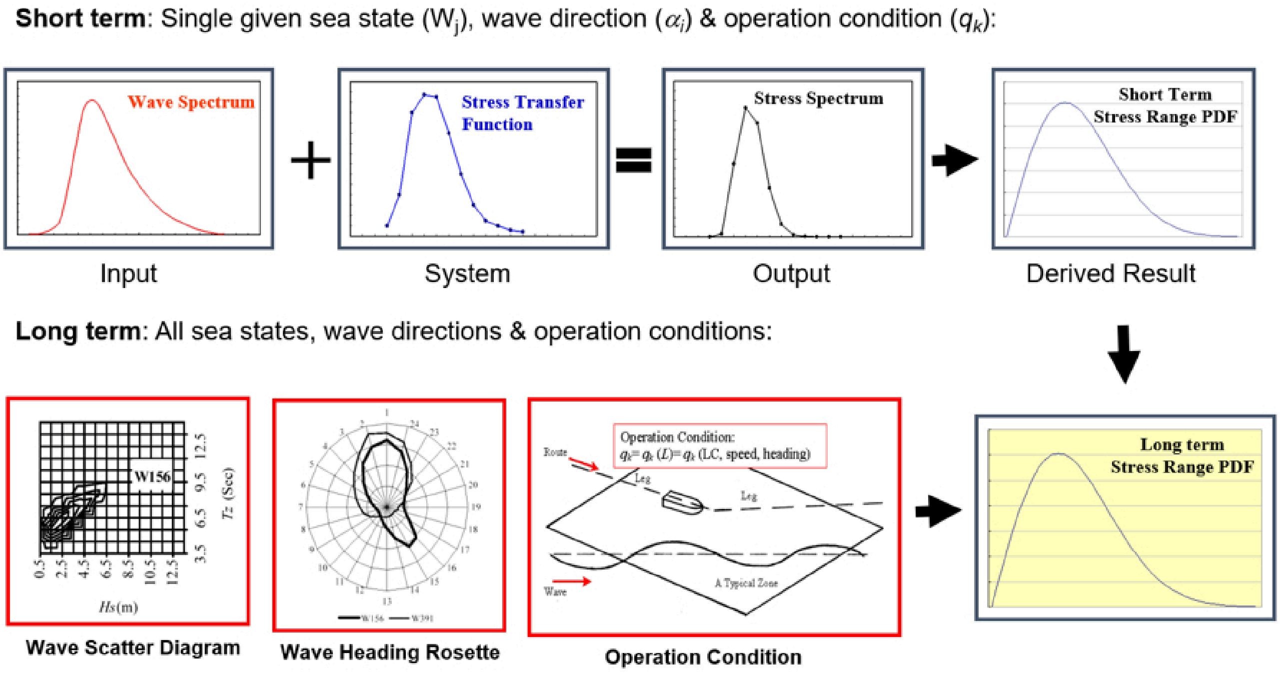
Step 1: For each heading, the stress transfer functions, also called stress Response Amplitude Operators (RAOs), for a given range of frequencies are determined via seakeeping analysis and structural analysis.

Step 2: For each heading, the stress spectrum for each sea state is determined through combining the stress RAOs with a wave spectrum.

Step 3: For each heading, the short-term distribution of stress range is determined with the Rayleigh probability density function.

Step 4: For all headings and sea states, the long-term distribution of stress ranges is determined based on a wave scatter diagram and a wave heading rosette.

FIGURE 4
Stochastic Approach Concept



2.1 Seakeeping Analysis and FE Analysis

Stochastic analysis involves the use of a stress transfer function, which defines the relationship between the stress at a particular location in a structure and the load due to a unit amplitude wave with a frequency (ω) and a heading (θ). The stress transfer function can be derived using seakeeping analysis and FE analysis. In seakeeping analysis, at least two loading conditions should be analyzed, including the most probable deepest draft and the most probable shallowest draft for a marine vessel. Seakeeping analysis is performed to determine vessel motion and wave pressure RAOs under unit amplitude sinusoidal waves.

At each heading and wave frequency for each considered loading condition, structural analysis using FE method is performed to calculate the stress transfer functions.

2.2 Wave Scatter Diagram (H_s, T_z) and Wave Heading Rosette (θ)

A wave scatter diagram consists of a table of the probabilities of occurrence of various "sea states". Each cell in the table contains information on three data items, namely (1) the significant wave height, H_S, (2) the characteristic wave period, T_Z, and (3) the fraction of the total time or probability of occurrence for the sea state defined by spectrum with parameters H_S and T_Z. A wave heading rosette (also called long-term wave directionality) describes the probability of each heading angle (the main wave direction) at a site. If the wave rosette is not available, it is reasonable to assume equal probability of all heading angles in open ocean conditions. However, for a moored offshore structure, the waves may have strong directional characteristics that should be accounted for.

2.3 Wave Spectrum

The shape of a spectrum supplies useful information about the characteristics of the ocean wave system to which it corresponds. There are many wave spectral formulations (e.g., Bretschneider spectrum, Pierson-Moskowitz spectrum, ISSC spectrum, ITTC spectrum, JONSWAP spectrum, Ochi-Hubble 6-parameter spectrum, etc.). Each wave spectral formulation is developed for a specific sea environment and care should be taken when selecting a wave spectrum to apply to a structure. The Bretschneider spectrum is discussed in these Guidance Notes. Other wave spectra can be found in 3/3.3 of the ABS *Guidefor Spectral-Based Fatigue Analysis for Floating Production, Storage and Offloading (FPSO) Installations.*

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

$$S_\eta(\omega) = \frac{5H_S^2\omega_p^4}{16\omega^5} \quad \exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]$$

or

$$S_\eta(\omega) = \frac{H_S^2}{4\pi\omega^5}\left(\frac{2\pi}{T_z}\right)^4 \quad \exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4\omega^{-4}\right]$$

where

ω_p	=	modal (peak) frequency corresponding to the highest peak of the spectrum, in rad/s
ω	=	circular frequency of the wave, in rad/s
H_s	=	significant wave height, in m
	=	$4\sqrt{\int_0^\infty S_\eta(\omega)d\omega}$
T_z	=	average zero up-crossing period of the wave, in seconds

2.4 Stress Transfer Function

For each wave frequency and wave heading, seakeeping analysis should be conducted to determine the vessel motion and wave pressure RAOs for a loading condition and vessel speed, if applicable. Consequently, a structural analysis should be carried out to determine the stress transfer functions. The frequency range to be used is usually 0.1 rad/sec to 1.80 rad/sec in increments up to 0.1 rad/sec. The wave heading range should be 0 to 360 degrees in increments of up to 30 degrees.

2.5 Stress Spectrum and Stress Range Distribution

The short-term stress spectrum can be calculated by means of the design wave spectrum, S_η, and associated stress RAOs of a desired location at a time. The short-term stress spectrum, S_σ, has a form as follows:

$$S_\sigma\left(\omega \mid H_s, T_z, \theta\right) = \left|H_\sigma\left(\omega \middle| \theta\right)\right|^2 S_\eta\left(\omega \mid H_s, T_z\right)$$

where

ω	=	wave frequency, in rad/sec
H_S	=	wave significant height, in m
θ	=	heading angle, in rad
T_z	=	up-crossing wave period, in sec
H_σ	=	stress RAO

Thus, the short-term stress range distribution in a specific heading direction, $g(s\,|\,\theta)$, can be represented by a form of Rayleigh probability density function, as follows:

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

where

s	=	stress range
σ	=	the scale parameter of Rayleigh probability density function
	=	$\sqrt{m_0}\, of \quad S_\sigma\left(\omega \middle| H_s, T_z, \theta\right)$
$\sqrt{m_0}$	=	0-th spectrum moment, and
		$m_n = \int_0^\infty \omega^n S_\sigma\left(\omega \mid H_s, T_z, \theta\right) d\omega$

The long-term stress range distribution is formed by considering the short-term stress range distribution with its occurrence probability for each sea state:

$$g(s) = \frac{\sum_{i=1}^{k} f_{0i} p_i g_i(s)}{\sum_{i=1}^{k} f_{0i} p_i}$$

where

i	=	i-th sea-state
k	=	total number of sea states in the wave scatter diagram
f_{oi}	=	zero-up-crossing frequency of the stress response
p_i	=	joint probability of H_s and T_z
g_i	=	probability density function governing stress range, s

For offshore structures, "wave scatter diagram" and "wave heading rosette" at a specified site are required when performing the long-term statistical analysis of structural response.

3 Deterministic Approach

The deterministic approach developed for offshore structure analysis is a simplified method compared to the stochastic method in Subsection 3/2. This approach is suitable for dynamically insensitive structures and for situations in which all dynamic waves are of sufficiently long wave periods. Compared to the stochastic method using a great number of sea states in a wave scatter diagram, the deterministic method uses relatively fewer discrete waves in which each wave is characterized by a deterministic wave height and period. In other words, the natural random waves approaching to the structure are represented by a few representative and regular waves while the stochastic characteristics of the sea waves is not directly modeled.

Deterministic analysis does not use wave spectra or transfer functions; instead, it implements discrete wave analyses to determine immediate stress range values so that a relationship between wave characteristics and resulting stress ranges can be established. An appropriate number of waves with heights and periods must be selected to determine their individual stress ranges, and the occurrence of each wave is taken into account to calculate the long-term distribution of stress ranges at hot spots of interest. The detailed approach includes:

i) Several major wave directions (e.g., 4-8 directions) are selected for deterministic analysis. The total number of waves is distributed among these selected major wave directions. Major wave propagation directions, as well as the directions causing high stresses in major structural elements, should be selected. If the structure is symmetric, identical waves propagating in opposite directions may cause equal stress ranges.

ii) For each given wave direction, the long-term distribution of wave heights, which is represented by an appropriate number of regular waves, should be established, and the total number of waves reaching the structure during the time under consideration should be the sum of the waves from the directions considered. Each regular wave includes two parameters, wave height and wave period, which should be the most probable period corresponding to the given wave height. For North Sea, there is a relation between the wave height and the most probable wave period, T, as follows:

$$T = 0.7 + 4.2H^{0.4}$$

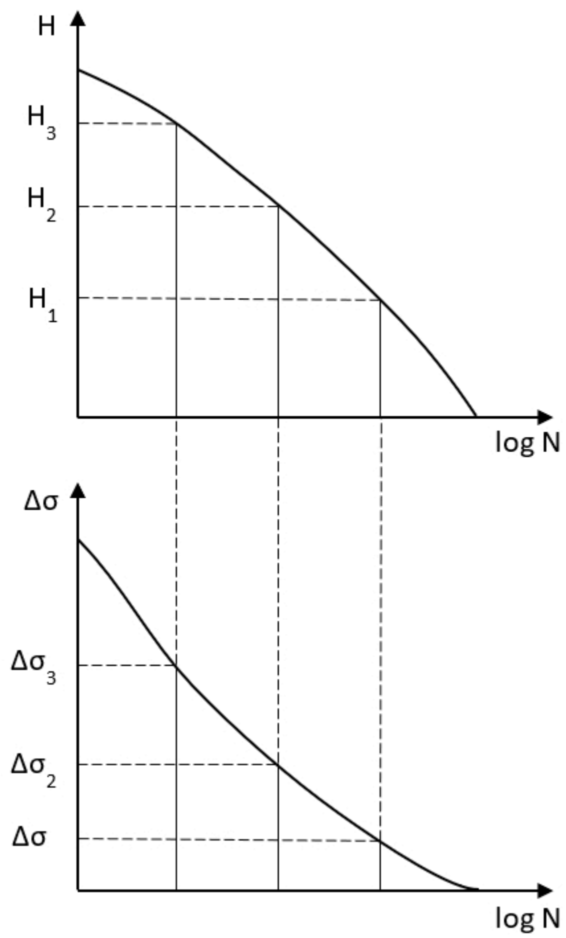
iii) For each wave in a given direction, the stress range is calculated using the applicable method, which depends on the nature of the relationship between wave height and response, as the structure is subjected to a regular wave with the wave height and the wave period.

iv) For each wave direction, the long-term stress range distribution is established, as shown in Section 3/FIGURE 5. The wave height and the number of occurrences are plotted, giving a wave height exceedance diagram. Thus, the stress range induced by the wave height in a given wave direction is plotted in a stress range exceedance diagram.

v) The long-term distribution of stress ranges is the sum of all those from selected major directions with occurrence probabilities.

It is noted that the deterministic analysis results may be sensitive to the selection of waves and the corresponding periods, since the analysis is performed based on a limited number of waves.

FIGURE 5
Long-Term Wave Height and Stress Range Distributions



4 Simplified Approach

A simplified approach is used to determine stress range distributions for marine and offshore structures under wave-induced loads. In this approach, the long-term stress range distributions are assumed to follow a two-parameter Weibull distribution. In the Weibull distribution, a reference stress range S_R needs to be calculated which characterizes the largest stress range anticipated to occur once within a reference number of stress cycles, N_R. To determine the reference stress range, fatigue load pairs should be defined under wave conditions. All loads in each load case, which include hull girder loads, pressure, inertia loads, etc., can be calculated following relevant Rules. Then, structural analysis is conducted so that hot spot stresses at critical location are calculated following the method discussed in Subsection 2/2.

4.1 Ship Structures

The total stress range at critical locations can be calculated through either Rule-based equations or detailed FE analysis. In Rule-based equations, the stress range is determined by hull girder bending stresses due to wave-induced loads in hogging and sagging conditions, referring to the *Marine Vessel Rules*. In FE analysis, a required number of fluctuating loading pairs should be used to account for both global and local dynamic effects. It is noted that the use of the loading pairs varies with the type of ship and assessment zones which consist of the structural details undergoing fracture assessment in accordance with the *Marine Vessel Rules*.

The general procedure for determination of stress range distribution is as follows.

4.1.1 Wave-induced Loads – Load Components

The wave-inducing load components to be considered are those induced by the seaway and divided into the following three groups:

- Hull girder wave-induced bending moments and shear force (both vertical and horizontal)
- External hydrodynamic pressures
- Internal tank loads (inertial liquid loads and added static head due to ship motion)

4.1.2 Combinations of Load Cases

The stress ranges of a ship should be calculated in accordance with the specific combinations of load cases referenced in 3/4.1.1. Loading conditions (i.e., full load or normal ballast) and zone areas (i.e., Zone A, Zone B, or Transitional Zone) of the structural details to be assessed will determine the values of load components.

The list below gives examples of loading pairs for typical load cases. The exact load pairs and the associated constants used to determine the load values should follow corresponding ABS Rules or Guides (e.g., *Marine Vessel Rules*, ABS *Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks (LGC Guide)*) for the stress range calculation.

- Load pair 1: Load Cases 1 and 2 for maximum vertical bending moment range
- Load pair 2: Load Cases 3 and 4 for maximum local pressure range
- Load pair 3: Load Cases 5 and 6 for maximum transverse acceleration range
- Load pair 4: Load Cases 7 and 8 for maximum horizontal bending moment range

The dominant fatigue load parameter for each dynamic sea load case corresponds to a probability of exceedance of 10^{-4}.

As an example, containerships and bulk carriers can use different combinations of load cases, depending on the location of the structural detail in a specific zone, to determine an appropriate stress range.

If the IACS Common Structural Rules (CSR) are applied for bulk carriers and oil tankers, the determination of load pairs refers to 5A-9-1/7 of the *Marine Vessel Rules*.

4.1.3 Stress Range Calculation

For each load pair defined for a specific vessel in 3/4.1.2, the reference stress range can be calculated by either Rule-based equations mentioned below or FE analysis. For Rule-based equation calculations, the stress range can be assessed by hull girder stress due to vertical hogging and sagging bending moments for gross scantlings. The hull girder stress varies with ship type and is specified in individual Appendix "Longitudinal Strength Requirements" in Part 5C of the *Marine Vessel Rules* or other applicable ABS Guide, such as the ABS *Guide for Application of Higher-Strength Hull Structural Thick Steel Plates in Container Carriers*.

For example, the hull girder stresses defined in the above Rule due to hogging and sagging conditions are:

$$\sigma_{w-Hog} = k_1 M_{w-Hog}(z - z_{NA})/I_Y$$

$$\sigma_{w-Sag} = k_1 M_{w-Sag}(z - z_{NA})/I_Y$$

where

k_1	=	10 (10, 2240)
M_{w-Hog}	=	vertical wave-induced hogging bending moments, in kN-m (tf-m, Ltf-ft), in accordance with 5C-5-3/5.1 of the *Marine Vessel Rules*
M_{w-Sag}	=	vertical wave-induced sagging bending moments, in kN-m (tf-m, Ltf-ft), in accordance with 5C-5-3/5.1 of the *Marine Vessel Rules*
I_Y	=	moment of inertia of cross section for net scantlings with respect to horizontal neutral axis, z_{NA}, in cm^2-m^2 (in^2-ft^2)
z_{NA}	=	vertical distance of horizontal neutral axis from baseline, in m (ft)
z	=	vertical distance from baseline to considered location (i.e., side hatch coaming top), in m (ft)

The maximum hull girder bending stress range, $\Delta\sigma_w$, in N/mm^2 (kgf/mm^2, psi), for net scantlings is calculated as follows:

$$\Delta\sigma_w = c_f\left|\sigma_{w-Hog} - \sigma_{w-Sag}\right|$$

where

c_f	=	an adjustment factor to reflect a mean wasted condition, taken as 0.95.

The calculated hull girder stress range can be used to establish the long-term stress range distribution in 3/4.1.4.

In most cases, the reference stress range at the critical location of a ship structure can be obtained by means of FE analysis considering different load pairs.

If the IACS Common Structural Rules (CSR) are applied for bulk carriers and oil tankers, the determination of the hot spot stress range refers to 5A-9-4/4.2 of the *Marine Vessel Rules*.

4.1.4 Long-Term Stress Range Distributions

For each load pair defined for a specific vessel in 3/4.1.2, the reference stress range can be calculated by either Rule-based equations or by FE analysis for all those defined load pairs. Then, the long-term stress range distribution of a ship structure, $F(S)$, can be represented by a Weibull probability density function as follows:

$$F(S) = \frac{\gamma}{\delta}\left(\frac{S}{\delta}\right)^{\gamma - 1} \quad exp\left[-\left(\frac{S}{\delta}\right)^{\gamma}\right]$$

where

γ = Weibull shape parameter, which can be determined in Section 3/TABLE 1.

δ = Weibull scale parameter.

= $\frac{S_R}{(lnN_R)^{1/\gamma}}$

N_R = number of cycles equal to 10,000, which corresponds to the probability level of 10^{-4}.

S_R = reference stress range. Value that exceeds on average once every N_R cycles. The value may be determined by taking the greatest stress range caused by load pairs which are based on the location of the structural detail and the type of ship in the ABS Rules.

TABLE 1
Weibull Shape Function

	γ	γ_0	
		$150 < L < 305 \quad m$	$305 \quad m < L$
Oil Tanker	$\gamma = \gamma_0$	$1.40 - 0.2\alpha L^{0.2}$	$1.54 - 0.245\alpha^{0.8}L^{0.2}$
Bulk Carrier	$\gamma = m_s\gamma_0$		
Containership			
Liquified Gas Carrier	$\alpha(1.1 - 0.35(L - 100)/300)$	-	-

Note: m_s, and α are location dependent factors which are referred to in 5C-1-A1/5.5 of the *Marine Vessel Rules*, 5C-3-A1/5.5 of the *Marine Vessel Rules*, 5C-5-A1/5.5 of the *Marine Vessel Rules*, and A3/5.5 of the *LGC Guide* for oil tanker, bulk carrier, containership, and liquified gas carrier, respectively. L is the ship scantling length, and D is the ship molded depth.

With the consideration of all load pairs for a specific vessel, the total long-term stress range distribution is:

- Equal to that in a load pair where the greatest stress range occurs, which is defined in 3/4.1.2 for oil tankers, containerships, bulk carriers
- To combine those for all load pairs with occurrence probabilities (e.g., 1/6 for load pair 1, 1/6 for load pair 2, 1/3 for load pair 3, and 1/3 for load pair 4) for liquified gas carriers.

If the IACS Common Structural Rules (CSR) are applied for bulk carriers and oil tankers, the reference stress range is given at the probability level of exceedance equal to 10^{-2} and determined in accordance with 5A-9-3/3 of the *Marine Vessel Rules*. Weibull shape parameter is taken to be a unity, referring to 5A-9-1/3 of the *Marine Vessel Rules*.

4.2 Offshore Structures

For ship shaped offshore structures such as FPSOs at a specific site, a simplified approach is used to determine the long-term stress range distribution. The long-term stress range distributions are assumed to follow a two-parameter Weibull distribution and are characterized using a modified long-term stress distribution parameter. The shape parameter in the Weibull distribution function is defined in accordance with the *FPI Rules*. Total stress assessment method is used to calculate the reference stress range for determination of the scale parameter in the Weibull distribution function. In FE analysis, gross scantlings are used according to the *FPI Rules*. Hot spot stresses are calculated following the method discussed in 2/2.2, referring to Appendix 5A-3-A2 of the *FPI Rules*.

For non-ship shaped offshore structures, such as jacket structures and semi-submersibles at a specific site, a simplified long-term distribution of stress ranges is determined based on the simplified wave height distribution.

4.2.1 Loads

The following high cycle loads due to dynamic loadings are usually considered for calculation of the long-term distribution of stress ranges:

- Hull girder loads (i.e., vertical and horizontal wave bending moments and shear forces)
- Dynamic wave pressure
- Dynamic tank pressure loads resulting from installation motion

For offshore installations built for periodically loading and offloading substantial cargo weight, low cycle fatigue load due to the following static loads need to be considered:

- Static cyclic loads due to cargo loading and offloading

The procedure to construct the stress range distribution due to high cycle loads and low cycle loads is discussed in 3/4.2.2 and 3/4.2.3, respectively.

4.2.2 Stress Range Distribution due to High Cycle Loads

For ship-shaped offshore structures such as FPSOs, the procedure to obtain the stress range distribution due to high cycle loads stated in 3/4.2.1 is the same as that for ship structures mentioned in 3/4.1. For each load pair defined for a specific vessel in 3/4.1.2, the long-term stress range distribution of a vessel structure may be represented by the Weibull probability density function.

For a specific vessel, the total long-term stress range distribution should combine those for all load pairs with occurrence probabilities given in Section 3/TABLE 2.

TABLE 2
$f_{i,j\text{-}k}$ Factors(1,2,3)

Loading Pair, j-k	*1-2*	*3-4*	*5-6*	*7-8*
Direction	*0*	*90*	*60*	*30*
A	0.40	0.10	0.20	0.30
B	0.60	0.00	0.10	0.30
C	1.00	0.00	0.00	0.00

Notes:

1 When an installation's mooring system type and arrangement, and heading orientation have not been determined prior to application of these requirements, cases A, B and C should be investigated and more onerous results should be used.

2 If an installation's mooring system type and arrangement have been determined, but the actual heading information is not available, case A and B should be used for installations with spread mooring, or, installations with turrets located more than 25% of the installation length aft of the bow, or for locations with non-colinear wind, wave and current conditions regardless of the mooring system. The more onerous results of these two cases should be used.

3 If an installation's mooring system type and arrangement has been determined, but the actual heading information is not available, Case B and C should be applied for installations with turrets located less than 25% of the installation length aft of the bow. The more onerous results of these two cases should be used.

For non-ship shaped offshore structures such as jacket structures and semi-submersibles, a simplified long-term distribution of stress ranges is determined based on a simplified wave height distribution. The simplified long-term exceedance diagram distribution of wave heights, as shown in Section 3/FIGURE 6, is assumed as:

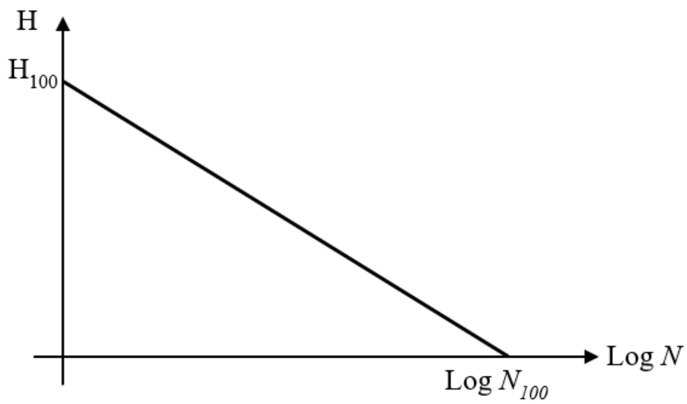
$$H = H_{100} \times \left(1 - \frac{\log N}{\log N_{100}}\right)$$

for the number of waves N exceeding a wave height H.

H_{100} = most probable largest wave height in 100 years.

N_{100} = total number of waves in 100 years.

FIGURE 6
Simplified Long-Term Wave Height Distribution



For example, in a 100-year duration, the number of waves is about 5×10^8 for North Sea conditions. The relation between wave height and stress range can be assumed to be the form of:

$$\Delta\sigma \infty H^{\alpha}$$

The long-term distribution of stress ranges can be given by:

$$\Delta\sigma = \Delta\sigma_{100} \times \left(1 - \frac{\log N}{\log N_{100}}\right)\alpha$$

where

$\Delta\sigma_{100}$ = stress range caused by the 100-year return period wave.

α = constant which is dependent of the type of structure and environmental conditions. The value can be obtained by a curve-fitting procedure based on a known distribution.
For North Sea conditions:
$1.6 < \alpha < 1.8$ for Jacket structures
$1.3 < \alpha < 1.6$ for Concrete gravity structures
$1.0 < \alpha < 1.3$ for Semi-submersibles

4.2.3 Special Application Cases

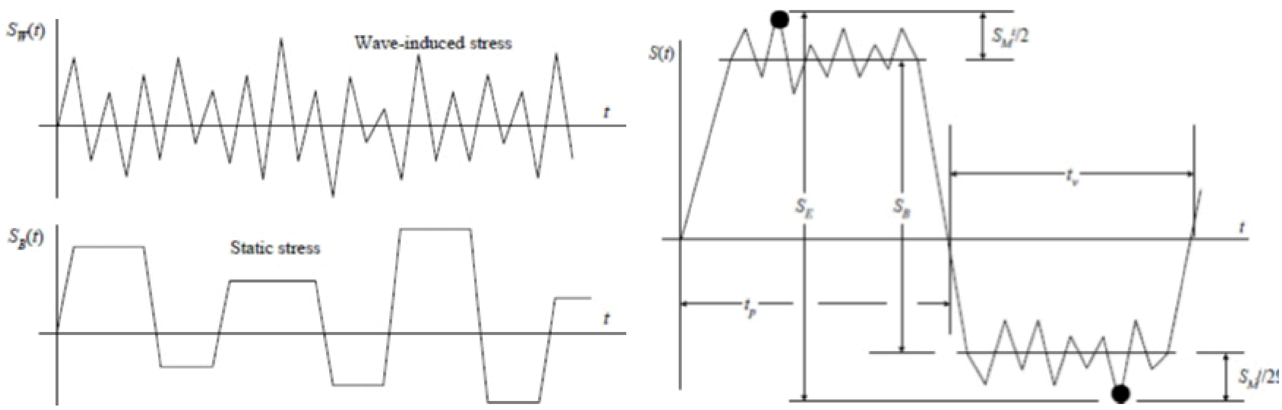
4.2.3(a) Low Cycle Loads due to Loading/Offloading.

When fatigue crack propagation is of concern, structural responses are assumed to result from two external sources, the wave loading on the vessel and the process of loading and offloading the vessel. This loading and offloading process produces static loads in a very low frequency including oscillatory still-water bending moment (SWBM) and still-water pressure. Thus, such loads should be included in static cyclic loads.

As shown in Section 3/FIGURE 7, referring to 5A-3-A2/17.5.1 of the *FPI Rules*, the stress process in certain structural components of a floating terminal can be considered as a superposition of wave-induced stresses, $S_W(t)$, and stresses associated with static load, $S_B(t)$. The cycles of $S_B(t)$ result from the loading/offloading process. The total or net stress process will be:

$$S(t) = S_B(t) + S_W(t)$$

FIGURE 7
Combination of Wave-induced and Static Stresses



In one cycle of the static process, as shown in Section 3/FIGURE 7, the total stress range associated with this cycle is S_E,

$$S_E = S_B + 0.5\left(S_M^i + S_M^j\right)$$

where

S_B = static stress range resulted from the loading and offloading conditions for this cycle

S_M^i = median of the largest stress range of wave-induced load for i-th load condition

S_M^j = median of the largest stress range of wave-induced load for j-th load condition

From extreme value theory, the median largest stress range S_M^i in n cycles is given as:

$$\frac{S_M^i}{\delta} = \left[-ln\left(1 - 0.5^{1/n}\right)\right]^{1/\gamma}$$

where γ and δ are the long-term stress shape and scale factors, respectively. n may be computed by taking the estimated time for a half cycle divided by the estimated wave period.

4.2.3(b) Fluctuating Stresses Due to Wave-Induced Vessel Motion.

Topside structures installed on offshore units may have a high frequency response due to wave-induced vessel motion resulting in high stress fluctuations at critical locations. The simplified approach can be applied to assess the topside structure assuming that the stress range distribution follows the Weibull distribution. The stresses in the topside structure may not be directly calculated from the FE model with the hull structure since the topside structure is normally not considered as a part of the main hull structure. In such cases, the topside structure behavior is deemed to be excited by the vessel motion, and the relative acceleration load can be calculated and applied to the topside structure for stress calculation.

Using a topside structure installed on an FPSO as an example, seakeeping analysis is performed to determine all acceleration components at the center of gravity of the topside structure due to wave loads under environmental conditions. An FE model of the topside structure is generated with the wave-induced acceleration components acting on the model as shown in Section 3/TABLE 3. Four load pairs with eight load cases are selected corresponding to in-situ wave heading direction distributions related to the orientation of the offshore structure, as shown in Section 3/FIGURE 8. For each load pair, acceleration components with their load factors, as shown in Section 3/TABLE 4, are applied to the topside structure, and the resulting reference stress range is calculated to construct the long-term stress range distribution following the Weibull distribution. Finally, the total long-term stress range distribution is determined considering occurrence probabilities of all load pairs according to in-situ wave heading direction distributions.

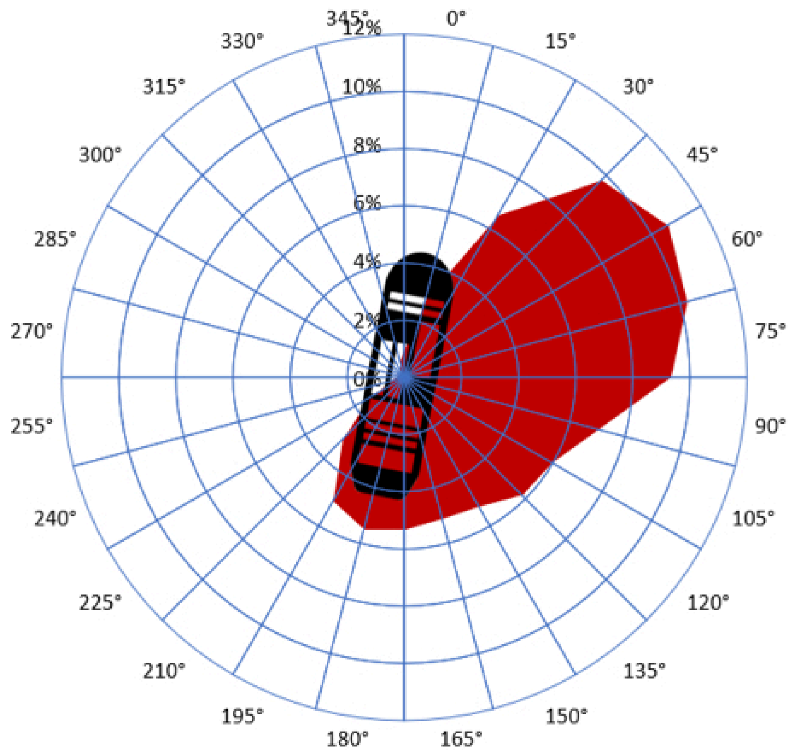
TABLE 3
Accelerations Corresponding to 1-Year Return Period Wave Conditions

Acceleration	*Longitudinal*	*Transverse*	*Vertical*
1-year RP	a_x	a_y	a_z

TABLE 4
Load Pairs

Pairs	*1*		*2*		*3*		*4*	
Load Case	LC1	LC2	LC3	LC4	LC5	LC6	LC7	LC8
Longitudinal a_x	-1	1	0.7	-0.7	0.7	-0.7	0	0
Transverse a_y	0	0	-0.7	0.7	0.7	-0.7	-1	1
Vertical a_z	-1	1	1	-1	1	-1	-1	1

FIGURE 8
Example of Wave Heading Distribution



SECTION 4

Vibration-Induced Loads and Stress Range Distribution

1 General

Marine vessels and ship-shaped offshore structures may experience vibration behavior due to wave impact loads, oscillatory mechanical loads, or other loads. These loads may directly or indirectly cause the vibration of the appurtenance structure (e.g. rudder, flare tower, etc.) leading to high stress fluctuations conducive to crack initiation and propagation until final failure. Subsection 4/2 describes the procedure to calculate hydrodynamic loads that cause vibrations. Subsection 4/3 addresses two methods to derive stress range distributions due to vibration-induced loads. 4/3.1 introduces the direct calculation approach, which calculates the stress and time history using forced vibration analysis. Section 4, FIGURE 1 presents the flowchart of the direct calculation approach. When sensors are installed on the structure providing measurement data of the structural response, the measurement-based approach using the modal decomposition method, as described in 4/3.2, can be used to derive the stress and time history at critical locations. Section 4, FIGURE 2 presents the flowchart of the measurement-based approach.

FIGURE 1
Direct Calculation Approach Flowchart

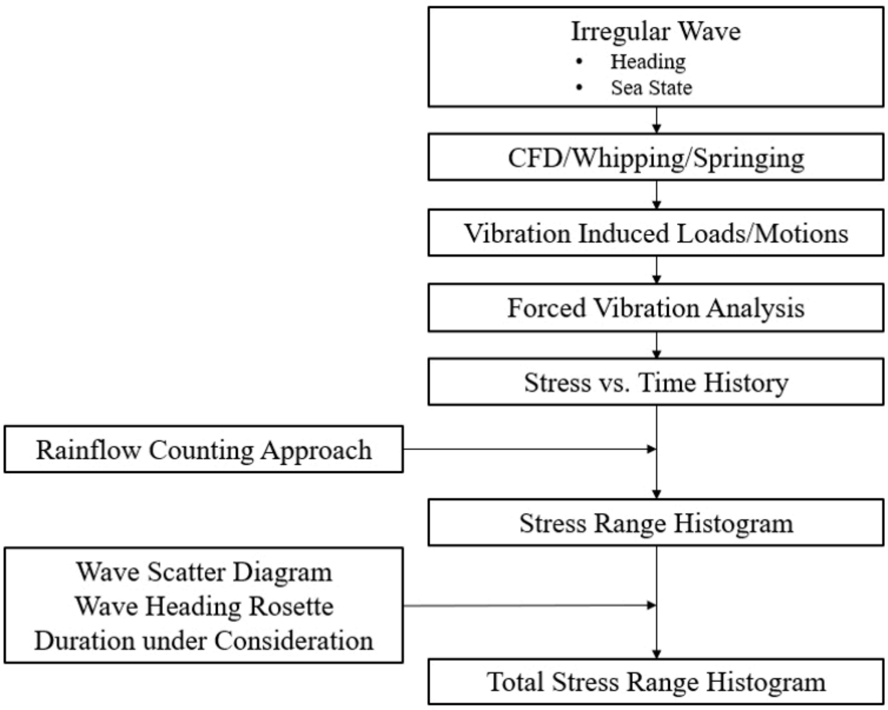
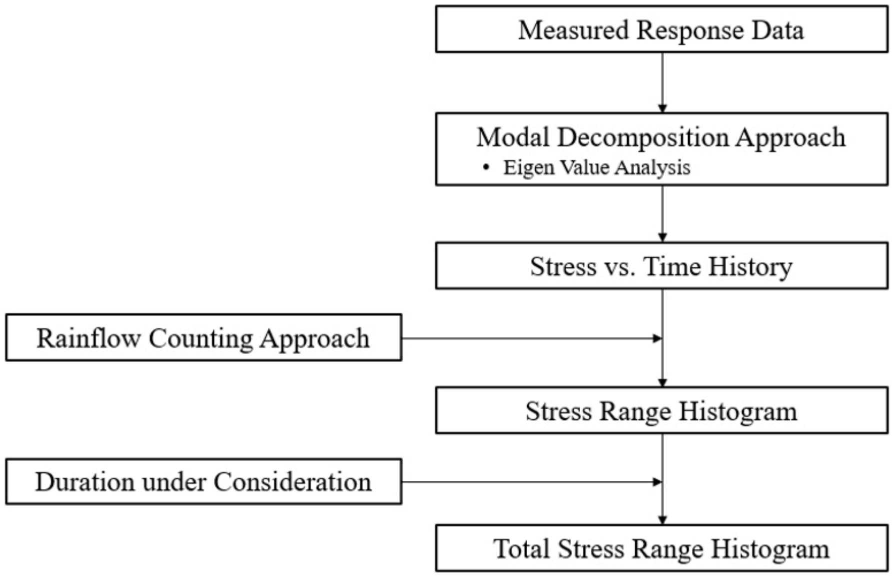


FIGURE 2
Measurement Based Approach Flowchart



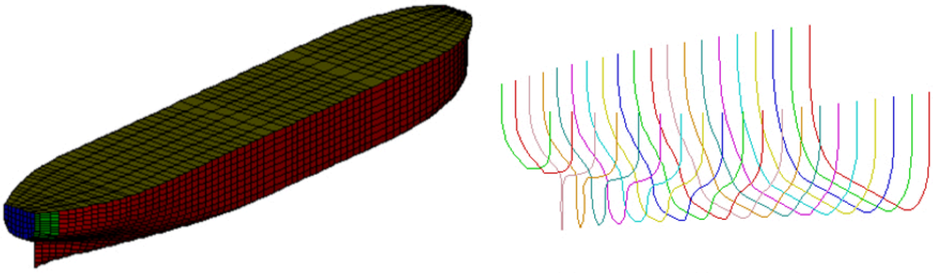
2 Hydrodynamic Loads

Computational Fluid Dynamics (CFD) is usually used to simulate the flow behavior to calculate the transient hydro-pressure distribution acting on a structure. Then, the hydrodynamic pressure history can be applied to a FE Model to determine the stress-time history at critical location.

Among all complicated hydrodynamic behaviors, springing and whipping are two special vibration-related wave effects. Springing is the continual hull girder vibration as the result of waves exciting resonant hull girder frequencies, which may last a significant period once being initiated. Whipping is a rapid vibration of the hull girder as the result of wave slamming on the hull (e.g., bow flare, stern bottom), which can introduce cyclic oscillations of the hull girder with high frequency, but usually decays rapidly after several wave periods. If a flaw exists in a structure on a vessel that experiences springing or whipping, a fracture mechanics analysis should be performed to evaluate the acceptance of the flaw with the consideration of crack propagation under fluctuating stresses.

As an example, whipping analysis involves the use of motion analysis using a nonlinear time-domain panel method and hull girder vibration analysis under whipping condition. A hydro panel model is used to calculate the hydro pressure, and a discrete geometry is used to calculate the sectional slamming force, as shown in Section 4, FIGURE 3. Sectional slamming impact force is calculated using a wedge approximation from the time rate change of momentum. Then, the resultant hydro pressure and slamming force can be applied to a one-dimensional finite element beam model to obtain the transient hull girder vibration response (a structural damping of 1.5-3% is recommended in whipping analysis).

FIGURE 3
Hydro Panel Model and Geometry of Stern Sections



Hydro panel model of the hull   Geometry of stern sections

3 Stress Analysis and Stress Range Distribution

For marine and offshore structures, there are two common approaches to obtain the long-term distribution of stress ranges under vibration-induced loads. The direct calculation approach is used to determine the stress-time history in the structure under hydrodynamic loads using forced vibration analysis, as described in 4/3.1. The measurement-based approach is used to determine the stress-time history in the structure through the measured response data using the modal decomposition approach, as described in 4/3.2.

3.1 Direct Calculation Approach

A forced vibration can occur when a structure is subjected to a time-varying disturbance (load, displacement, or velocity). The disturbance can be a periodic and steady-state input, a transient input, or a random input. The periodic input can be a harmonic or random disturbance. For linear systems, the frequency of the steady-state vibration response resulting from the application of a periodic and harmonic input is equal to the frequency of the applied force or motion.

In the direct calculation approach, transient response analysis on the structure under the vibration is performed using the FE modeling. A structural damping coefficient should be considered in dynamic analysis. The purpose of a transient response analysis is to compute the response behavior of a structure subjected to time-varying excitation. The transient excitation is explicitly defined in the time domain. The computed results from a transient analysis are typically displacements, velocities, and accelerations at nodes, as well as forces and stresses in elements. The transient response analysis in the direct calculation approach includes:

- Direct Explicit Method
- Modal Analysis Method

The direct explicit method is based on the implementation of an explicit integration rule together with the use of diagonal ("lumped") element mass matrices. The equations of motion for the body are integrated using the explicit central-difference integration rule as:

$$\dot{u}^N_{i+\frac{1}{2}} = \dot{u}^N_{i-\frac{1}{2}} + \frac{\Delta t_{i+1} + \Delta t_i}{2}\ddot{u}^N_i$$

$$u^N_{i+1} = u^N_i + \Delta t_{i+1}\dot{u}^N_{i+\frac{1}{2}}$$

where refers to the degree of freedom (Displacement/Rotation) number N, subscript i refers to the increment number, Δt is the time-step. $\dot{u}$ and $\ddot{u}$ are velocity and accelerations of the previous time step. The explicit procedure integrates through time by using many small-time increments. The central-difference operator is conditionally stable, and the stability limit for the operator (with no damping) is given by the highest frequency of the system.

The modal analysis method is used to solve the motion equation in the projected modal coordinate system, and it is particularly suitable to deal with a structure subjected to long-term excitation loads.

$$[m]\ddot{\tilde{q}} + [c]\dot{\tilde{q}} + [k]\tilde{q} = \tilde{p}$$

where

$[m]$	=	projected modal mass matrix
$[c]$	=	projected modal damping matrix
$[k]$	=	projected modal stiffness matrix
$\tilde{p}$	=	projected modal load vector
$\tilde{q}$	=	modal generalized displacement vector

This method requires performing the natural mode analysis (also known as eigenvalue analysis) in advance to solve the eigenvalue problem of the structure in undamped condition and extract natural modes and corresponding natural frequencies. In the case of an insufficient set of natural modes being used, the use of residual mode may be considered to correct mode truncation error and increase result accuracy.

In the dynamic modal analysis, the forced vibration analysis can be categorized into three scenarios:

- External Forcing
- Base Excitation
- Rotor Excitation

The External Forcing model addresses the behavior of a structure which has a time varying force acting on it. An example is an offshore structure subjected to wave loads. The Base Excitation model deals with the behavior of a vibration isolation system. The base of the system is given with a prescribed motion causing the connected structure to vibrate. The Rotor Excitation model addresses the effect of a rotating machine mounted on a structure causing the connected structure to oscillate usually at a constant angular velocity. The appropriate method should be used to determine the fluctuating stress history caused by vibrating loads or motions.

For an appurtenance structure which is subjected to the forced vibration with low frequencies and the vibration source is solely from its foundation connected to the marine vessel or the offshore structure, the use of Base Excitation is recommended for calculation of its vibration responses, including stress and stress range histories. The prescribed base excitation in terms of displacement, velocity, or acceleration can be derived from the numerical results by CFD simulations or seakeeping analysis (e.g., whipping analysis).

3.2 Measurement-based Approach

In the measurement-based approach, the modal decomposition method is employed, which assumes that the dynamic structural behavior can be expressed as a linear superposition of a small set of its natural modes weighted by corresponding modal amplitudes, as shown below. This method is particularly useful when the loading frequency is relatively low compared to the natural frequencies of the structure since the maximum number of natural modes will be limited by the number of sensors installed on board.

$$\tilde{U}(t) = \sum_{i=1}^{n}\left(\tilde{\tilde{\phi}}^{i} \cdot q_i(t)\right)$$

where

$\widetilde{U}(t)$ = nodal solution vector

$\tilde{\tilde{\phi}}^i$ = modal shape of i-th natural mode

$q_i(t)$ = modal coordinate or modal amplitude of i-th natural mode

The unknown modal amplitude can be calculated in accordance with 4/3.1 when the external excitation force is given. However, when a structure of interest is in operation, the loads most possibly cannot be obtained.

In such scenario, if there are sensors deployed on board, the sensor data can be used to determine the modal amplitudes in accordance with the process introduced as follows.

A local FE model is built to contain the topside structure and its foundation. Fine mesh should be casted in the area of interest, typically where the structure is prone to the presence of flaws. Natural Modes Analysis is performed with boundary conditions for calculation of a set of natural modes and natural frequencies of the structure. At a given time point, the total structural response at each sensor location is decomposed to a number of fractional amounts contributed from each natural mode. If the number of the installed sensors equals to the number of selected natural modes, the modal decomposition equations listed above can be solved to obtain each modal amplitude, $q_i(t)$, corresponding to its natural mode. Thereafter, the entire structural responses, including any stress components, can be calculated using the natural modes and formerly solved modal amplitudes. Section 4, FIGURE 4 shows an example of the comparison of principal stress history results between forced vibration analysis and modal decomposition approach.

FIGURE 4
Sample Calculated Stress vs. Time History:
Forced Vibration Analysis vs. Modal Decomposition Approach

3.3 Long-Term Stress Range Distribution

Using the stress vs. time history results obtained from either the direct calculation approach or modal decomposition approach, the rainflow counting approach is employed to determine the stress range histogram for a specified duration (e.g., one hour). The annual or long-term stress range histogram can be generated through the multiplication of hourly stress range histograms. In fatigue crack propagation analysis, when applying the stress range histogram to a flaw, the loading sequence effect should be considered. For example, the total stress range distribution should be divided into an appropriate number of groups to remove the effect of loading sequence on the crack propagation.

SECTION 5
Fracture Mechanics Analysis

1 General

Fracture mechanics theory has been developed for crack propagation analysis through calculating the driving force on a flaw using analytical/numerical methods and determining the material resistance to fracture and fatigue crack growth rate using experimental methods. The linear elastic fracture mechanics (LEFM), which is based on the Griffith theory of fracture, has been widely applied in the integrity assessment of engineering structures containing defects. The basic principle is that a crack may initiate and propagate until unstable growth occurs leading to structural failure under static or dynamic loads. These Guidance Notes introduce the basic concept of fracture mechanics, which covers stress intensity factor calculation for typical flaw configurations, fatigue crack propagation based on Paris' law, and material fracture/fatigue properties including fracture toughness and fatigue crack growth rate.

In addition to these Guidance Notes, the guidance is supplemented by industry standards to address fracture analysis for engineering applications. The first recommended document is BS 7910, which provides guidance for assessing the acceptance of flaws in metallic structures using fracture mechanics principles. The technique is also referred to as an engineering critical assessment (ECA) or damage tolerance method and is complementary to the weld quality assurance. Another standard is API 579-1/ASME FFS-1, which is used in a wide range of process, manufacturing, and power generation industries. This standard addresses the fitness-for-service assessment of pressure equipment and covers a wide range of flaws and damage mechanisms including local metal loss, pitting corrosion, blisters, weld misalignment, and fire damage other than just crack-like flaws.

1.1 Modes of Failure

In engineering applications, the modes of failure and damage mechanisms due to the presence of flaws include (refer to BS 7910 5/5.1):

i) Failure by fracture and plastic collapse

ii) Damage by fatigue

iii) Damage by creep and creep fatigue

iv) Failure by leakage of containment vessels

v) Damage by corrosion and/or erosion

vi) Damage by environmentally assisted cracking

vii) Failure by instability (buckling)

These Guidance Notes address three typical failure modes *i)*, *ii)*, and *iv)* for marine and offshore applications, which are collectively discussed in Section 6.

1.2 Types of Flaws

The general flaws, which could cause structural failures, are defined in Section 4 of BS7910 including:

i) Planar flaws:

a) Cracks

b) Lack of fusion or penetration, and

c) Undercut, root undercut, concavity and overlap (on some occasions, undercut and root undercut in welds are treated as shape imperfections)

ii) Non-planar flaws:

a) Cavities

b) Solid inclusions (on some occasions cavities and solid inclusions are treated as planar flaws)

c) Local thinning (e.g., due to corrosion), and

d) Porosity

iii) Shape imperfections:

a) Misalignment, and

b) Imperfect profile

These Guidance Notes address four typical planar flaws: through thickness flaw, surface flaw, edge flaw, and embedded flaw.

1.3 Nondestructive Testing

Nondestructive testing (NDT) is an essential part of a fitness-for-service assessment (refer to Section 6.3.1 of BS 7910). The ABS *Guide for Nondestructive Inspection* can also be referred to for the applicable requirements for nondestructive testing. The NDT technique(s) used for flaw evaluation should be chosen to provide the type of information necessary for an acceptable degree of accuracy. Such information should include some or all of the following items:

i) Flaw length

ii) Flaw height

iii) Flaw position

iv) Flaw orientation with respect to the principal stress direction

v) Description of the flaw cross-section as either planar or non-planar

Typical NDT methods for the detection of surface-breaking flaws and embedded flaws are listed in Section 6.3.2 and 6.3.3 of BS 7910. For guidelines on implementations of various NDT methods and treatments of uncertainties, refer to Section 6.3.4 of BS7910. For a region of a structure that cannot be inspected, refer to Section 6.3.5 of BS 7910.

1.4 Flaw Dimensions and Interaction

To evaluate effective flaw dimensions for a single flaw or multiple flaws in close proximity, flaw characterization is conducted in accordance with Section 7.1.2 of BS 7910. When multiple flaws exist in close proximity, flaw alignment checks should be assessed in accordance with the alignment criteria to form coplanar flaws. Flaw interaction check is then performed to combine the coplanar flaws into a single effective flaw against the combination criteria. Further consideration for interaction of a combined flaw with the neighboring flaws is usually not required. It is normally not necessary to apply flaw interaction criteria for fatigue assessment.

Flaw interaction is normally assessed at the start and at the end of the evaluation interval incorporating any sub-critical crack growth during that interval. Then, the fracture assessment should be carried out at these two stages using the derived flaw dimensions. For cases of high strength/low toughness steels where cleavage is a concern, refer to Section 7.1.2.4 of BS 7910.

2 Stress Intensity Factor Solution

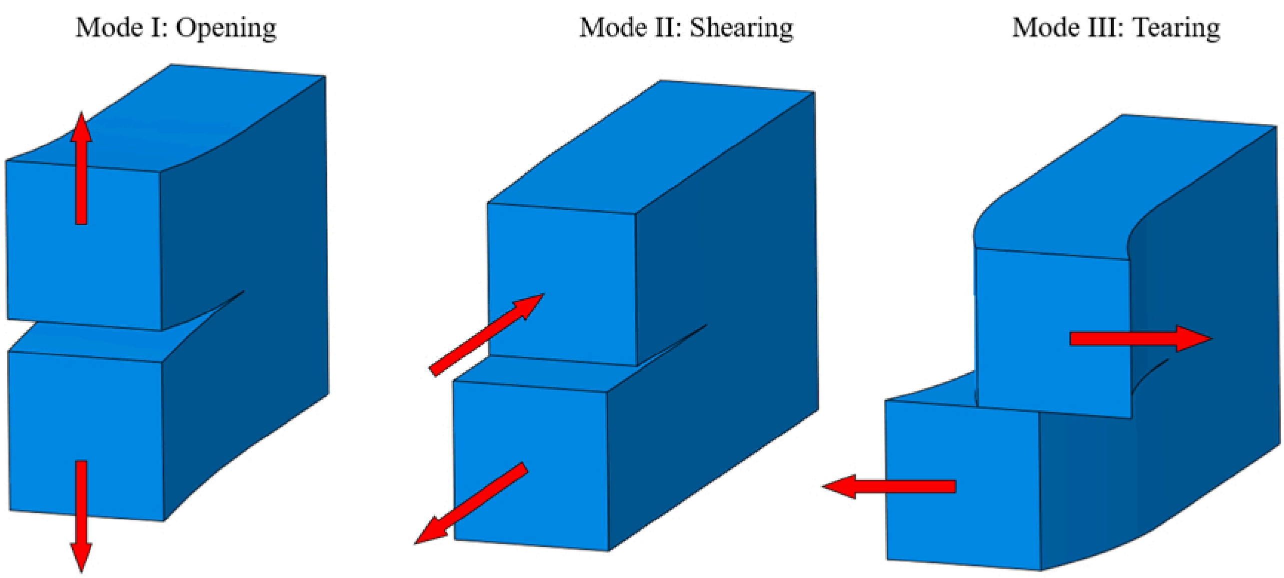
2.1 General

In fracture mechanics, there are three fundamental crack loading modes as shown in Section 5, Figure 1.

- Mode I – Opening mode (a tensile stress normal to the crack surface).
- Mode II – Shearing mode (a shear stress parallel to the crack surface and perpendicular to the crack front).
- Mode III – Tearing mode (a shear stress parallel to the crack surface and parallel to the crack front).

Mode I (opening) is the dominant cracking mode in most failure cases. The superposition of the three cracking modes can be used to describe a general cracking case if the structure is subjected to a complicated loading condition. In most cases in engineering applications, Mode I cracking is considered for structural integrity assessment.

FIGURE 1
Definition of Loading Modes



The stress intensity factor for a flaw is one of the most fundamental and useful parameters in LEFM. The stress intensity factor describes the stress state at a crack tip, which can be used to analyze the crack propagation and to establish failure criteria due to fracture. Referring to Annex M/M.2 of BS7910, the general form of the Model I stress intensity factor solution is given by:

$$K_I = (Y\sigma)\sqrt{\pi a}$$

For fatigue assessments the corresponding stress intensity factor range is expressed as:

$$\Delta K_I = (Y \Delta \sigma)\sqrt{\pi a}$$

For fracture assessments the following equation applies:

$$Y\sigma = (Y\sigma)_p + (Y\sigma)_s$$

These are calculated as follows:

$$(Y\sigma)_p = Mf_w\{k_{tm}M_{km}M_mP_m + k_{tb}M_{kb}M_b[P_b + (k_m - 1)P_m]\}$$

$$(Y\sigma)_s = M_mQ_m + M_bQ_b$$

For fatigue assessments the following equation applies:

$$(Y\,\Delta\,\sigma)_p = Mf_w\{k_{tm}M_{km}M_m\,\Delta\,P_m + k_{tb}M_{kb}M_b[\,\Delta\,P_b + (k_m - 1)\,\Delta\,\sigma_m]\}$$

The expressions for M, f_w, M_m and M_b are given in Annexes M.2 to M.10 of BS 7910 for different types of flaws in different configurations.M_{km} and M_{kb} apply when the flaw is in a region of local stress concentration and are given in Annex M.1 of BS7910. Guidance on k_{tm}, k_{tb} and k_m is given in Clause 6.4.4 and Annex D of BS7910.

2.2 Stress for Flaw Assessment

To perform fracture and fatigue calculations, stress distributions in the area containing the flaw, determined in the absence of flaw, are used. The actual stress distributions may be used, or the stresses (or stress ranges) may be linearized. Care should be taken of the primary membrane and bending stresses, the secondary stresses and the magnification of the primary stresses caused by local/gross discontinuities or misalignment.

Primary stresses are stresses that can, if sufficiently high, contribute to plastic collapse, while secondary stresses do not. Secondary stresses are self-equilibrating stresses necessary to satisfy compatibility in the structure. An alternative description is that they can be relieved by local yielding or heat treatment. Thermal and residual stresses are usually, but not always, secondary. In some situations, thermal and residual stresses, which can be self-balancing throughout a structure, can act as primary stresses on an individual component. This occurs when the flaw is small compared with the zone of influence of the thermal or residual stress.

Referring to 7/7.1.10 of BS 7910, for a structure in the as-welded condition, with a flaw lying in a plane parallel to the welding direction (i.e., the stresses to be considered are perpendicular to the weld), the tensile residual stress should initially be assumed to be equal to the lesser of the room temperature yield strengths of the weld and the parent metal. For a structure in the as-welded condition, with a flaw lying in a plane transverse to the welding direction (i.e., the stresses to be considered are parallel to the weld), the tensile residual stress should initially be assumed to be equal to the room temperature yield strength of the material in which the flaw is located.

The presence of gross structural discontinuities (e.g., the intersections in tubular structures) causes an increase in stresses normally quantified via a stress concentration factor (SCF). This type of stress concentration usually decays over distances greater than the section thickness. Referring to Annex B/B.2 of BS 7910, fatigue cracks can develop under axial and/or bending loads along the weld toe of tubular joints typically used to connect circular brace and chord members (such as T, DT, X, Y, K, KT or multi planar joints). A global FE analysis of the whole structure should be performed to determine the stress distributions corresponding to wave loading at the flaw location. The local stresses at the tubular joints are generated by the nominal brace axial and bending loads, which are reacted to by the chord. High secondary bending stresses are developed due to the local deformation of the tubular walls such that high stress concentrations and through-thickness stress gradients develop at the brace/chord intersection. Thus, each hot-spot stress (or stress range) component is determined from the nominal stress (or stress range) and the appropriate SCF. The latter are usually estimated using published parametric equations, such as those provided in the ABS *Guide for the Fatigue Assessment of Offshore Structure*. Alternatively, FE analysis using reasonably refined meshing at hot-spot locations may be used to determine local stress distributions and corresponding SCFs

Discontinuities due to misalignment or deviation from intended shape cause bending stresses which are usually calculated via a stress magnification factor. This type of stress magnification usually decays over distances greater than the section thickness.

Stress concentrations due to local structural discontinuities (e.g., holes, notches, sharp corners, or weld toes) usually decay over distances less than the hole or notch radius, which could be a small proportion of the wall thickness. For sharp corners, where the theoretical stress concentration factor can be large, a stress intensity magnification factor is used to quantify the local increase in stress in the area containing the flaw.

The following Paragraphs provide guidance on stress intensity factor calculation for three types of flaws observed in marine and offshore structures: through-thickness flaws, semi-elliptical surface flaws, and edge flaws.

2.3 Through-Thickness Flaws in Plates

Referring to Annex M/M.3.1 of BS 7910 for a through-thickness flaw, as shown in Section 5, Figure 2, the stress intensity factor solution for Mode I can be calculated using the above general form of equations with relevant parameters as follows:

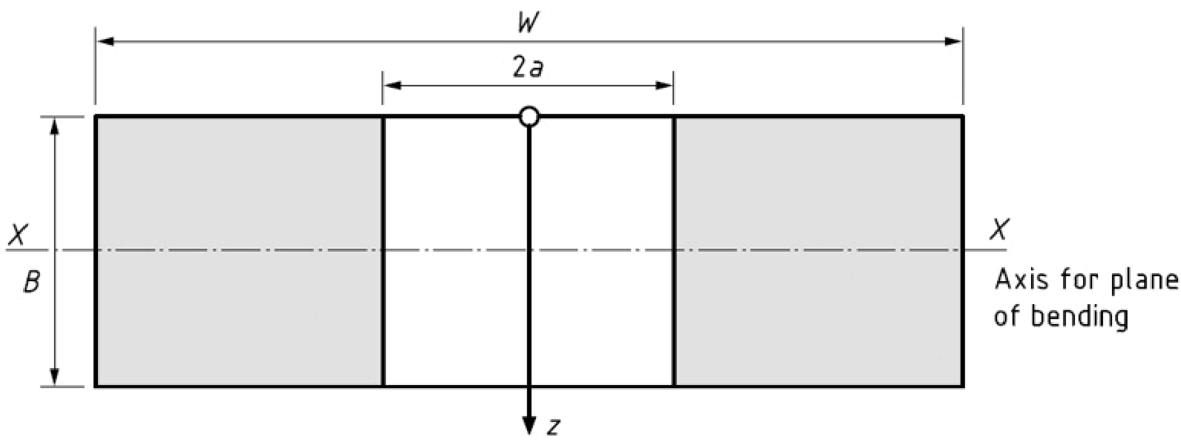
$M = M_m = 1$

$f_w = \sqrt{sec(\pi a/W)}$

$M_b = 1 - \frac{2z}{B}$

If $z = 0$, $M_b = 1$.

FIGURE 2
Through-Thickness Flaw



2.4 Semi-Elliptical Surface Flaws in Plates

Referring to Annex M/M.4.1.2 of BS 7910 for a semi-elliptical surface flaw under membrane loading, as shown in Section 5, FIGURE 3, the stress intensity factor solution for Mode I can be calculated using the above general form of equations with relevant parameters as follows:

$M = 1$

$f_w = \left\{sec\left[\left(\frac{\pi c}{W}\right)\left(\frac{a}{B}\right)^{0.5}\right]\right\}^{0.5}$ which equals 1.0 if $a/2c = 0$

Note: This equation for f_w is applicable up to $2c/W = 0.8$.

When the following conditions apply,

$0 < \frac{a}{2c} \leq 1.0$

$0 \leq \theta \leq \pi$

$\frac{a}{B} < 1.25\left[\frac{a}{c} + 0.6\right]$ for $0 < \frac{a}{2c} \leq 0.1$

$\frac{a}{B} < 1.0$ for $0.1 < \frac{a}{2c} \leq 1.0$

The solution is as follows:

$M_m = [M_1 + M_2(a/B)^2 + M_3(a/B)^4] \cdot g \cdot f_\theta/\Phi$

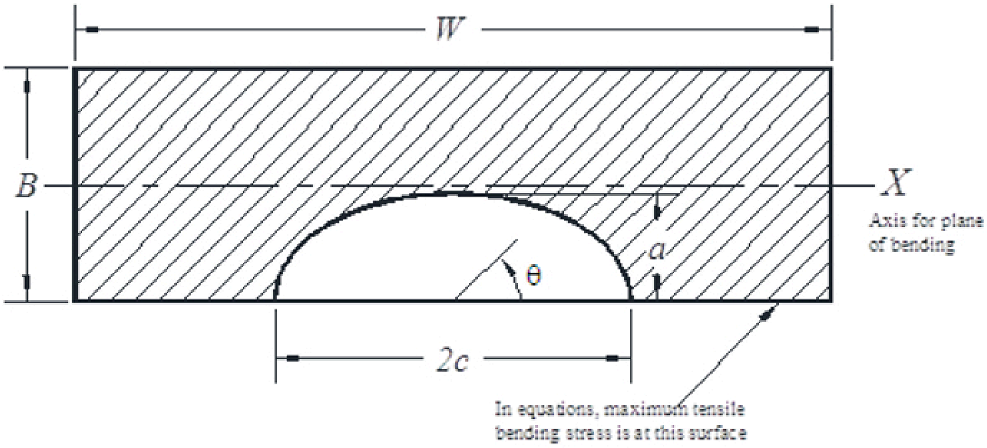
where

M_1	=	$1.13 - 0.09(a/c)$	for $0 \leq a/2c \leq 0.5$
M_1	=	$(c/a)^{0.5}[1 + 0.04(c/a)]$	for $0.5 < a/2c \leq 1.0$
M_2	=	$0.89/(0.2 + a/c) - 0.54$	for $0 \leq a/2c \leq 0.5$
M_2	=	$0.2(c/a)^4$	for $0.5 < a/2c \leq 1.0$
M_3	=	$0.5 - 1/(0.65 + a/c) + 14(1 - a/c)^{24}$	for $0 \leq a/2c \leq 0.5$
M_3	=	$-0.11(c/a)^4$	for $0.5 < a/2c \leq 1.0$
g	=	$1 + [0.1 + 0.35(a/B)^2](1 - sin\theta)^2$	for $0 \leq a/2c \leq 0.5$
g	=	$1 + [0.1 + 0.35(c/a)(a/B)^2](1 - sin\theta)^2$	for $0.5 < a/2c \leq 1.0$
f_θ	=	$[(a/c)^2 cos^2\theta + sin^2\theta]^{0.25}$	for $0 \leq a/2c \leq 0.5$
f_θ	=	$[(c/a)^2 sin^2\theta + cos^2\theta]^{0.25}$	for $0.5 < a/2c \leq 1.0$
Φ	=	$\sqrt{1 + 1.464(a/c)^{1.65}}$	for $0 \leq a/2c \leq 0.5$
Φ	=	$\sqrt{1 + 1.464(c/a)^{1.65}}$	for $0.5 < a/2c \leq 1.0$
B	=	section thickness in the plane of the crack	
W	=	section width in the plane of the crack	

It should be noted that stress intensity factors are usually calculated at the deepest point θ = 90°, and both end points, θ = 0° and 180° on the crack front for fracture assessment.

Alternatively, graphical solutions for M_m are given in Annex M/M.4.1.2.2 of BS7910 for assessed locations at θ = 90° and θ = 0°, respectively.

FIGURE 3
Semi-Elliptical Surface Flaw



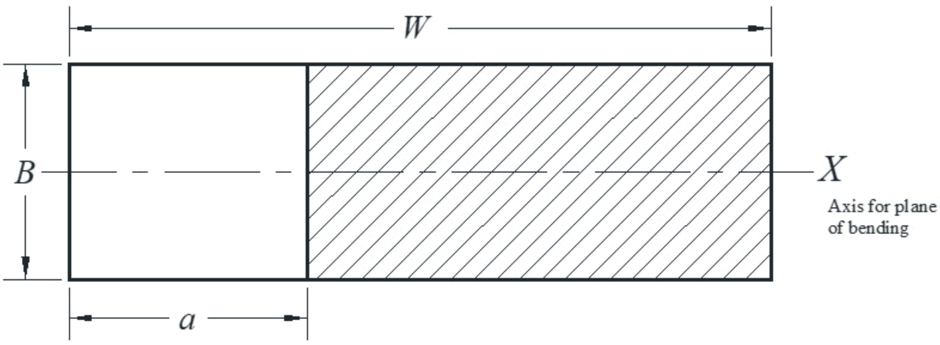
2.5 Edge Flaws in Plates

Referring to Annex M/M.3.2 of BS 7910 for an edge flaw, as shown in Section 5, Figure 4, the stress intensity factor solution for Mode I, where $a/W \leq 0.6$, can be calculated using the above general form of equations with relevant parameters as follows:

$M = 1$

$$M_m = M_b = 1.12 - 0.23a/W + 10.6(a/W)^2 - 21.7(a/W)^3 + 30.4(a/W)^4$$

FIGURE 4
Edge Flaw



2.6 Embedded Flaws in Plates

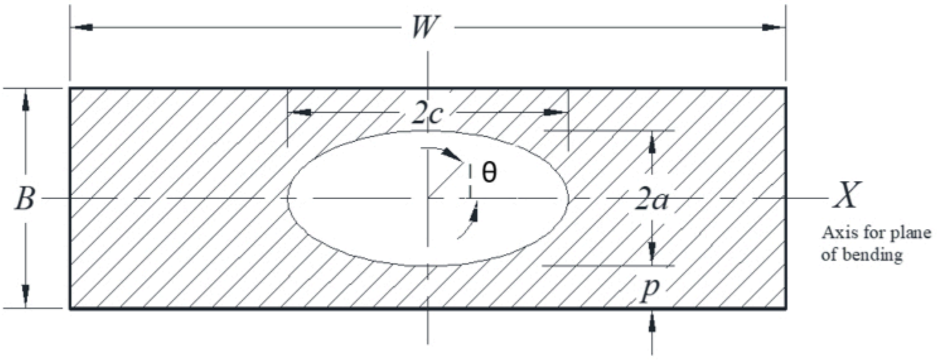
Referring to Annex M/M.4.5 of BS 7910 for embedded flaws in plates as shown in Section 5, Figure 5, the stress intensity factor solution for Mode I, where $2c/W \leq 0.8$, can be calculated using the above general form of equations with relevant parameters as follows:

$M = 1$

$$f_w = \sqrt{sec\left[(\pi c/W)(2a/B^e)^{0.5}\right]}$$

where B^e is the effective thickness, equal to $2(a + p)$.

FIGURE 5
Embedded Flaw



For a membrane loading, the following conditions apply:

$0 < \frac{a}{2c} \leq 1.0$

$\frac{2c}{W} < 0.5$

$-\pi \leq \theta \leq \pi$

$a/B^e < 0.625(a/c + 0.6)$ for $0 \leq a/2c \leq 0.1$

Under the above conditions, M_m is given by:

$$M_m = [M_1 + M_2(2a/B^e)^2 + M_3(2a/B^e)^4] g f_\theta / \Phi$$

where

$M_1 = 1$ for $0 < a/2c \leq 0.5$

$M_1 = (c/a)^{0.5}$ for $0.5 < a/2c \leq 1.0$

$M_2 = \frac{0.05}{0.11 + (a/c)^{1.5}}$

$M_3 = \frac{0.29}{0.23 + (a/c)^{1.5}}$

$g = 1 - \left[\frac{(2a/B^e)^4\left[2.6 - \sqrt{4a/B^e}\right]}{1 + 4a/c}\right] |\cos \theta|$

$f_\theta = \left[(a/c)^2 \cos^2 \theta + \sin^2 \theta\right]^{0.25}$ for $0 < a/2c \leq 0.5$

$f_\theta = \left[(c/a)^2 \sin^2 \theta + \cos^2 \theta\right]^{0.25}$ for $0.5 < a/2c \leq 1.0$

$\Phi = \sqrt{1 + 1.464(a/c)^{1.65}}$ for $0 < a/2c \leq 0.5$

$\Phi = \sqrt{1 + 1.464(c/a)^{1.65}}$ for $0.5 < a/2c \leq 1.0$

Note: For the solution of M_m, if $a/2c > 1.0$, use the solution for $a/2c = 1.0$.

Alternatively, graphical solutions for M_m are given in Annex M/M.4.5.2.2 of BS7910.

For a bending loading, the following conditions apply:

$0 < \frac{a}{2c} \leq 0.5$

$\theta = \pi/2$ (i.e., solution only refers to the ends of the minor axis of the elliptical flaw)

Under the above conditions, M_b is given by:

$$M_b = \left[\lambda_1 + \lambda_2\left(p/B\right) + \lambda_3\left(a/B\right) + \lambda_4\left(pa/B^2\right)\right]/\Phi$$

where

$\lambda_1 = 1.044$; $\lambda_2 = -2.44$; $\lambda_3 = 0$; $\lambda_4 = -3.166$ for $p/B \leq 0.1841$

$\lambda_1 = 0.94$; $\lambda_2 = -1.875$; $\lambda_3 = -0.1146$; $\lambda_4 = -1.844$ for $p/B > 0.1841$ and $a/B \leq 0.125$

$\lambda_1 = 1.06$; $\lambda_2 = -2.20$; $\lambda_3 = \lambda_4 = -0.6666$ for $p/B > 0.1841$ and $a/B > 0.125$

Alternatively, graphical solutions for M_b are given in Annex M/M.4.5.3.1 of BS7910.

3 Fatigue Crack Propagation

3.1 Paris' Law

Paris' Law is one of industry-recognized constitutional models used to describe the relation between crack growth and the driving force caused by applied cyclic loads.

For a through-thickness flaw, as shown in Section 5, Figure 3, crack propagation is expressed as follows:

$$\frac{da}{dN} = C(\Delta K)^m \quad \text{for} \quad \Delta K > \Delta K_{th}$$

$$\frac{da}{dN} = 0 \quad \text{for} \quad \Delta K \leq \Delta K_{th}$$

where

a = half flaw length

N = number of stress cycles

C = material constant to define crack propagation rate

m = material constant to define crack propagation rate

ΔK = stress intensity factor range in a stress cycle

ΔK_{th} = threshold value of stress intensity factor range

For a semi-elliptical surface flaw, crack propagation is expressed as follows:

$$\frac{da}{dN} = C(\Delta K_a)^m \quad \text{for} \quad \Delta K > \Delta K_{th}$$

$$\frac{dc}{dN} = C(\Delta K_c)^m \quad \text{for} \quad \Delta K > \Delta K_{th}$$

where

a = flaw height

c = half flaw height

$\Delta K_a =$ stress intensity factor ranges at the deepest point on the crack front

$\Delta K_c =$ stress intensity factor ranges at the ends of the crack

The fatigue crack propagation path is assumed to be perpendicular to the principal stress direction.

3.2 Constant Amplitude Crack Growth

For a through-thickness flaw, the total number of cycles, N_T, to develop from an initial length, a_i, to a critical length, a_f, can be determined through the integration of Paris' equation as follows:

$$\int_{a_i}^{a_f} \frac{da}{Y^m (\pi a)^{m/2}} = C\,\Delta\sigma^m N_T$$

In the case of a simple Y-function, the above integral can be calculated analytically, but generally numerical integration may be needed. If assuming that Y is independent of a,

$$N_T = \frac{a_f^{\,1-m/2} - a_i^{\,1-m/2}}{C \cdot \left(1 - \frac{m}{2}\right) \cdot Y^m \cdot \pi^{m/2} \cdot \Delta\sigma^m} \qquad (m \neq 2)$$

3.3 Variable Amplitude Crack Growth

Over its service life, a marine or offshore structure is subjected to dynamic cyclic loads such as wave-induced loads and vibration-induced loads resulting in variable amplitude loading. For example, the long-term stress range distributions are obtained using the spectral approach, deterministic approach, or simplified approach for wave-induced loads in Section 3, and the long-term stress range distributions are determined through the rainflow counting processing based on the stress vs. time history caused by vibration-induced loads in Section 4. Variable amplitude loading causes more challenges, such as loading sequence effect, when predicting the remaining life. The Subparagraphs below introduce the cycle-by-cycle approach and the equivalent stress range approach for the crack growth calculation.

3.3.1 Cycle-by-Cycle Approach

The flaw length after n cycles:

$$a_n = a_0 + \sum_{i=1}^{n} \Delta a_i$$

where

$$\Delta a_i = a_i = \left(\frac{da}{dN}\right)_i = C(\Delta K_i)^m$$

In the above formulae, the interaction (i.e., acceleration or retardation) is not considered. Additionally, the crack propagation should be dependent of the sequence of loads. If batches of stress amplitudes are large, it makes a difference whether low stress amplitudes occur earlier or later in the batch. Normally, if low stress amplitudes occur earlier, it produces a larger crack growth.

A cycle-by-cycle integration with stress amplitudes in the following sequences is suggested to be applied in crack propagation prediction: 1) low - high; 2) high - low; 3) high - low - high; 4) low - high - low; 5) random sequences.

3.3.2 Equivalent Stress Range Approach

In the Equivalent Constant Amplitude Stress Range approach, a variable amplitude stress history is represented by an equivalent constant amplitude stress range which is assumed to cause the same amount of crack propagation, as shown in Section 5, Figure 3.

The equivalent stress range can be expressed by:

$$\Delta\sigma_{eq} = \left[\int_0^\infty f(\Delta\sigma)\cdot\Delta\sigma^\beta\cdot d\Delta\sigma\right]^{1/\beta}$$

or

$$\Delta\sigma_{eq} = \left[\sum_{i=1}^{K} f_i\cdot\Delta\sigma_i^\beta\right]^{1/\beta}$$

where

$f(\Delta\sigma)$	=	probability density function of stress range
f_i	=	occurrence frequency of stress range
	=	$\frac{n_i}{N_T}$
K	=	number of intervals in histogram
n_i	=	number of cycles within interval "i"
N_T	=	total number of cycles
β	=	empirical or calibration constant

If $\Delta\sigma$ follows a two-parameter Weibull distribution, $\Delta\sigma_{eq}$ is given by:

$$\Delta\sigma_{eq} = A\left[\Gamma\left(1+\frac{\beta}{\gamma}\right)\right]^{1/\beta}$$

where Γ(.) is the gamma function expressed as:

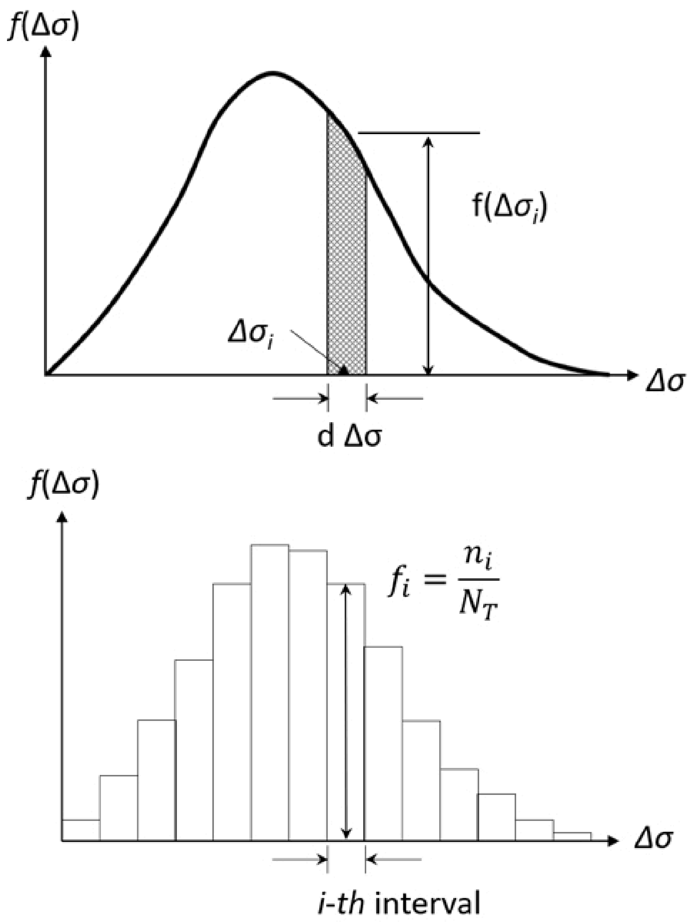
$$\Gamma(k) = \int_0^\infty e^{-u}u^{k-1}du$$

and A is a constant related to the reference stress range.

For a through-thickness flaw, $2a_i$, similar to constant amplitude crack growth, if assuming that Y is independent of a, the remaining life until final failure is:

$$N_T = \frac{a_f^{1-m/2} - a_i^{1-m/2}}{C\cdot\left(1-\frac{m}{2}\right)\cdot Y^m\cdot\pi^{m/2}\cdot\Delta\sigma_{eq}^m} \qquad (m \neq 2)$$

FIGURE 6
Stress Range Distribution and Histogram



4 Material Fracture and Fatigue Properties

4.1 Fracture Toughness

Fracture toughness characterizes the material's resistance to initiation of crack propagation and unstable crack growth. Fracture toughness should be established in accordance with recognized national testing standards (e.g., BS 7448, ISO 12135, BS EN ISO 15653, BS 8571, ASTM E1820, ASTM E1921). Several fracture toughness parameters are available, including critical stress intensity factor K_{IC}, the critical value of the J-Integral J_{crit}, and the critical crack tip opening displacement CTOD or δ_{crit}. All these parameters can be used for a fracture assessment of a component containing crack-like flaws. For most materials covered by these Guidance Notes, fracture toughness can be measured for brittle materials or thick sections. It is possible, however, to infer "equivalent" K_{IC} (or K_{mat}) values from J and CTOD data by exploiting the relationships among these three parameters under plane strain linear elastic conditions (see K_J and K_δ expressions below). Compact tension (CT) specimens and Single-Edge-Notch-Bending (SENB) specimens are used extensively for fracture mechanics material testing.

Referring to 7/7.1.4.6 of BS 7910, the following approach can be used to convert the fracture toughness into a critical stress intensity factor when fracture toughness has been determined using J-integral, *J*:

$$K_J = \sqrt{\frac{EJ}{1 - \nu^2}}$$

When fracture toughness has been obtained in terms of crack tip opening displacement (CTOD or δ) using deeply notched, high constraint bend specimens:

$$K_\delta = \sqrt{\frac{m\sigma_Y \delta E}{1 - \nu^2}}$$

where E and σ_Y are required at the same temperature as the fracture toughness test

$$m = 1.517\left(\frac{\sigma_Y}{\sigma_U}\right)^{-0.3188} \quad \text{for } 0.3 < \sigma_y/\sigma_u,\ 0.98$$

$= 1.5$ if above equation cannot be used.

.

Notes:

1 This conversion from CTOD is intended for applications when historical data are available and it is not possible to determine the J-integral from the test record (fracture toughness testing standards such as BS 7448, BS EN ISO 15653, ISO 12135 and ASTM E1820 describe appropriate procedures for determining J-integral).

2 Equations of m determination ware derived from experimental tests conducted on deeply notched bend specimens. It is considered that conservative results will be obtained if the equation is applied to CTOD results obtained from SENT specimens. However, SENT tests conducted to BS 8571 enable J to be determined directly.

3 If tensile properties are not available at the fracture toughness test temperature, information on the variation of E, σ_Y and σ_U with temperature is given in 7.1.3.3 and 7.1.3.4 of BS 7910:2190.

When fracture toughness data for the material is unavailable and direct determination of fracture toughness by testing is not feasible, an estimate of fracture toughness may be obtained from correlations with Charpy V-notch impact test data taken from material of the same general microstructural type (e.g., weld metal, HAZ, parent material) in which the flaw is situated. The orientation of the Charpy V-notch specimens should be such as to reproduce the fracture path that would result from the flaw under consideration. Annex J of BS 7910 contains three fracture toughness-Charpy V correlations as follows:

1) A lower bound relation for near lower shelf behavior, where Charpy energy has been obtained at a single temperature.

2) A relation for lower transitional behavior based upon the Master Curve approach, where the Charpy temperature for an energy of 27 J or 40 J (T27J or T40J) has been established.

3) A relation that limits K_{mat} (estimated in accordance with either of the above correlations) so that materials with low upper shelf Charpy energy are not assumed to have high fracture toughness. An alternative equation is provided for modern low carbon, low sulfur steels.

A detailed procedure and underlying assumptions used to determine the fracture toughness should be submitted for review.

4.2 Fatigue Crack Growth Rate

Fatigue analysis based on fracture mechanics is typically used to identify the maximum tolerable initial flaw size for a specified design life and/or to predict the remaining life through crack propagation analysis for a structure with a pre-existing flaw. Such an analysis assumes that a flaw can be idealized as a sharp tipped crack which propagates in accordance with the law relating the crack growth rate, da/dN, and the range of stress intensity factor, ΔK, for the material containing the flaw.

The crack growth law expressed as fatigue crack growth rate (FCGR), can be determined experimentally by testing the material under appropriate environmental conditions. Alternatively, the FCGR can be based on published data. The FCGR is often expressed as a function of stress intensity factor range, ΔK, and two parameters C and m according to the central portion of the Paris' law, which is typically represented by one or two straight lines. Section 5, TABLE 1 below includes values of the constants C and m, which are recommended in BS 7910 for:

- Steels (ferritic, austenitic or duplex ferritic-austenitic) with yield or 0.2% proof strengths ≤ 700 MPa
- Operation in air or other non-aggressive environments at temperatures up to 100°C

Unless justification for using different values is provided, the upper bound (mean + 2SD) values for $R \geq 0.5$ should be used for all assessments of flaws in welded joints. The fatigue crack growth rate curve for steels in air is illustrated in Section 5, FIGURE 7a).

TABLE 1
Recommended Fatigue Crack Growth Laws for Steels in Air[1]

R	*Stage A*				*Stage B*				*Stage A/Stage B transition point* ΔK*, MPa-m*$^{1/2}$	
	Mean Curve		*Mean + 2SD*		*Mean Curve*		*Mean + 2SD*			
	C[2]	*m*	*C*[2]	*m*	*C*[2]	*m*	*C*[2]	*m*	*Mean Curve*	*Mean + 2 SD*
<0.5	2.10×10^{-17}	8.16	7.59×10^{-17}	8.16	8.32×10^{-12}	2.88	1.41×10^{-11}	2.88	11.5	10.0
≥0.5	2.14×10^{-13}	5.10	9.38×10^{-13}	5.10	1.22×10^{-11}	2.88	2.70×10^{-11}	2.88	6.2	4.6

Notes:

1 Mean + 2SD for $R \geq 0.5$ values recommended for assessing welded joints.

2 For da/dN in m/cycle and ΔK in MPa-m$^{1/2}$.

Section 5, Table 2 below includes values of the constants *C* and *m*, which are recommended in BS 7910 for:

- Low strength steels (excluding austenitic and duplex stainless steels) with yield or 0.2% proof strengths ≤ 600 MPa;
- Operation in marine environments at temperatures up to 20°C.

The fatigue crack growth rate curve for steels in marine environment is illustrated in Section 5, FIGURE 7b).

TABLE 2
Recommended Fatigue Crack Growth Laws for Steels in Marine Environment[1]

R	*Stage A*				*Stage B*				*Stage A/Stage B transition point* ΔK*, MPa-m*$^{1/2}$	
	Mean Curve		*Mean + 2SD*		*Mean Curve*		*Mean + 2SD*			
	C[2]	*m*	*C*[2]	*m*	*C*[2]	*m*	*C*[2]	*m*	*Mean Curve*	*Mean + 2 SD*
Steel freely corroding in a marine environment										
<0.5	4.05×10^{-12}	3.42	1.15×10^{-11}	3.42	1.13×10^{-8}	1.30	1.72×10^{-8}	1.30	42.2	31.4
≥0.5	7.24×10^{-12}	3.42	2.32×10^{-11}	3.42	2.62×10^{-8}	1.11	3.46×10^{-8}	1.11	34.7	23.7
Steel in a marine environment with cathodic protection at –850 mV(Ag/AgCl)										
<0.5	2.10×10^{-17}	8.16	7.59×10^{-17}	8.16	5.22×10^{-11}	2.67	1.34×10^{-10}	2.67	14.6	13.7

R	*Stage A*				*Stage B*				*Stage A/Stage B transition point* ΔK, *MPa-m*$^{1/2}$	
	Mean Curve		*Mean + 2SD*		*Mean Curve*		*Mean + 2SD*			
	$C^{(2)}$	*m*	$C^{(2)}$	*m*	$C^{(2)}$	*m*	$C^{(2)}$	*m*	*Mean Curve*	*Mean + 2 SD*
≥0.5	2.14×10^{-13}	5.10	9.38×10^{-13}	5.10	6.07×10^{-11}	2.67	2.04×10^{-10}	2.67	10.2	9.2
Steel in a marine environment with cathodic protection at –1,100 mV(Ag/AgCl)										
<0.5	2.10×10^{-17}	8.16	7.59×10^{-17}	8.16	6.94×10^{-9}	1.40	1.16×10^{-8}	1.40	18.2	16.3
≥0.5	2.14×10^{-13}	5.10	9.38×10^{-13}	5.10	6.61×10^{-9}	1.40	1.28×10^{-8}	1.40	16.3	13.1

Notes:

1 Mean + 2SD for $R \geq 0.5$ values recommended for assessing welded joints.

2 For da/dN in m/cycle and ΔK in MPa-m$^{1/2}$

3 The fatigue crack growth laws given in BS 7910 for steels in a marine environment (with or without cathodic protection) are derived from data obtained at wave frequencies in the range from 0.17 Hz to 0.5 Hz. Fatigue crack growth rates in a corrosive environment are affected by the loading frequency and may be accelerated under lower frequency loading under such environmental conditions.

At low temperatures in marine environments, the fatigue crack growth rate curves for steels may be obtained from fracture property tests.

For preliminary screening assessments, calculations or assessments can be compared directly with calculations based on fatigue design rules for welded steels (see BS 7608). Conservative laws given in 8.2.3.5 of BS 7910 are recommended for steels with yield or 0.2% proof strengths up to 600 MPa. For steels (including austenitics) operating in air or other non-aggressive environments at temperatures up to 100°C, the recommended FCGR constants are as follows:

$m = 3, \quad C = 1.65 \times 10^{-11}$ (for m/cycle, MPa-m$^{1/2}$ unit system)

For steels (including austenitic stainless steels) operating in marine environments at temperatures up to 20°C, with or without cathodic protection, the following FCGR constants are recommended:

$m = 3, \quad C = 7.27 \times 10^{-11}$ (for m/cycle, MPa-m$^{1/2}$ unit system)

For aluminum alloys, multi-branch crack growth relationships for a range of alloys are given in BS EN 1999-1-3. However, for approximate assessments, the recommended FCGR constants referred to 8.2.3.7 of BS 7910 are as follows:

$m = 3; \quad C = 1.65 \times 10^{-11}\left(\frac{E_{steel}}{E}\right)^3$ (for m/cycle, MPa-m$^{1/2}$ unit system)

where

E_{steel}	=	Young's modulus of the steel
E	=	Young's modulus of the nonferrous material to be assessed

Threshold stress intensity factor, ΔK_0, values are strongly dependent on environment and R. ΔK_0 is found to increase as R decreases. For welded joints, recommended ΔK_0 for various conditions in accordance with 8.2.3.6 of BS7910:2019 is provided in Section 5, TABLE 3. For austenitic steels and unprotected steels operating in a marine environment, Section 5, TABLE 3 is also applicable for assessing unwelded components.

For unwelded steel components (excluding austenitic) in air and with cathodic protection in marine environments at temperatures up to 20°C, the following values of ΔK_0 (in MPa-m$^{1/2}$) given in 8.2.3.6 of BS 7910 are recommended:

$\Delta K_0 = 2.0$ for $R \geq 0{:}5$

$\Delta K_0 = 5.4 - 6.8R$ for $0 \leq R < 0{:}5$

$\Delta K_0 = 5.4$ for $R < 0$

However, the value used should not exceed 2.0 MPa-m$^{1/2}$ for assessments of surface-breaking flaws less than 1 mm deep.

For nonferrous materials, the recommended ΔK_0 value can be obtained through modification of steel's fatigue crack growth threshold value, $\Delta K_{0,\ steel}$, as follows:

$$\Delta K_0 = \Delta K_{0,\ steel}\left(\frac{E}{E_{steel}}\right)$$

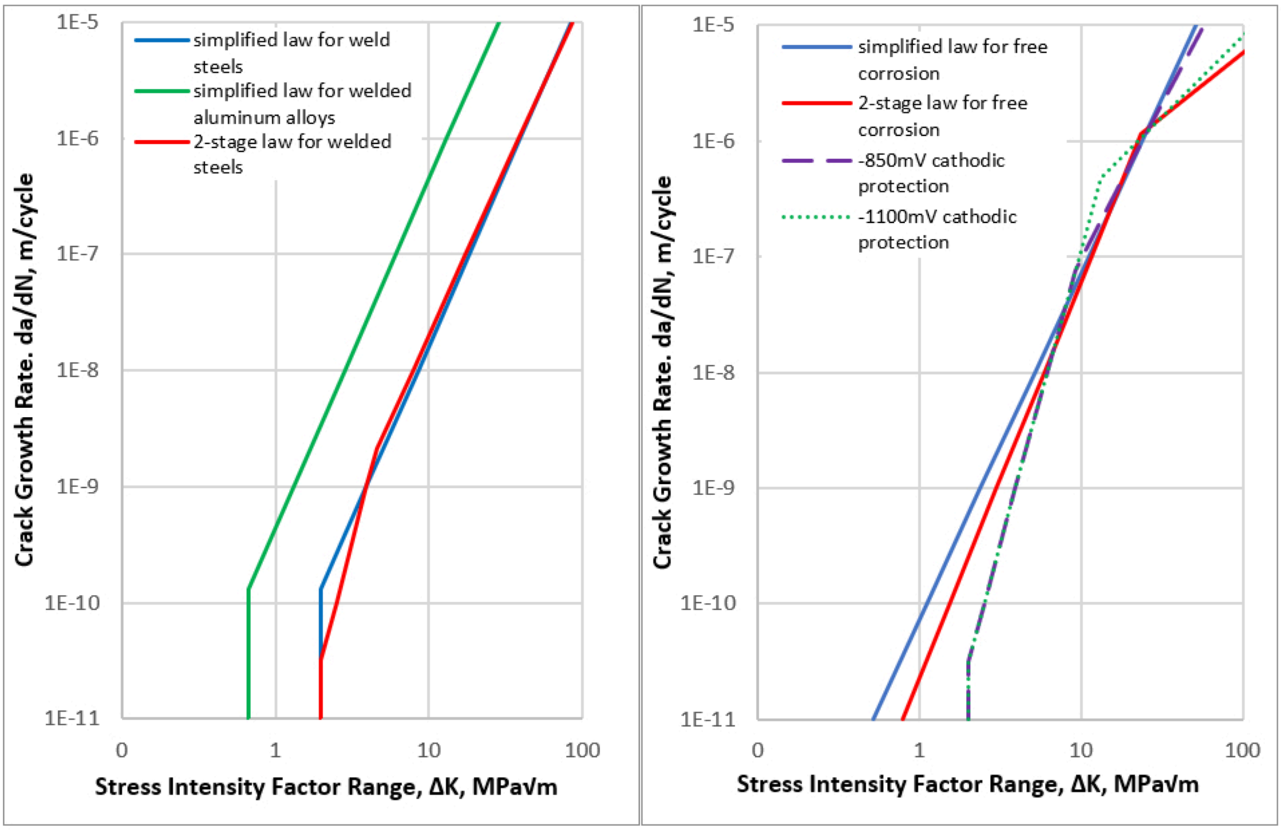
TABLE 3
Recommended Fatigue Crack Growth Thresholds for Assessing Welded Joints

Material	*Environment*	$\Delta K_0,\ MPa - m^{1/2}$
Steels, including austenitic	Air or other non-aggressive environments, up to 100 °C	2.0
Steels, excluding austenitic	Marine with cathodic protection, up to 20 °C	2.0
Steels, including austenitic	Marine, unprotected 0	0
Aluminum alloys	Air or other non-aggressive environments, up to 20 °C	0.7

FIGURE 7
Recommended Fatigue Crack Growth Rate Curves (BS7910)

a) Operation in air and other non-aggressive environments

b) Welded steels (including austenitics) in marine environments



Section 5, Figure 8 gives the curves of crack growth rates with respect to stress intensity factor ranges for stainless steel, aluminum, and 9% Ni materials, which are usually used for gas tanks. Section 5, Table 4 lists the corresponding parameters fitted into Paris' Law for each curve.

FIGURE 8
Crack Growth Rate Curves

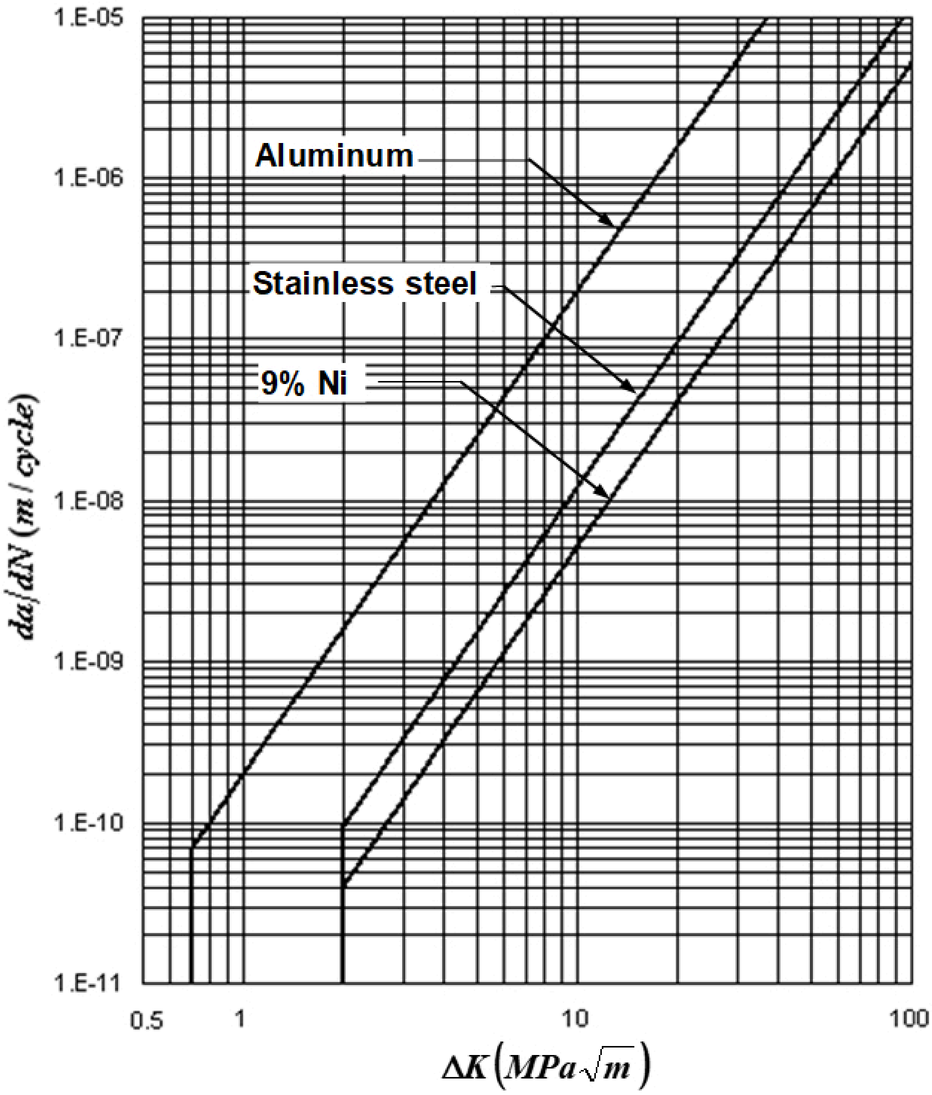


TABLE 4
Parameters of Crack Growth Rate Curves

Material	m	C	$\Delta K_{th},\ MPa - m^{1/2}$
Stainless steel	3.0	1.19×10^{-11}	2.0
Aluminum	3.0	2.03×10^{-10}	0.7
9% Ni	3.0	5.14×10^{-12}	2.0

SECTION 6

Fracture and Fatigue Assessments for In-Service Applications

1 General

This Section provides guidance on fracture and fatigue crack growth assessment procedures. For fracture assessment, the failure assessment diagram (FAD) method is introduced. The FAD method enables the significance of flaws to be evaluated under static loading conditions with reference to failure by fracture and plastic collapse. For structures subjected to cyclic loads, a procedure for assessing fatigue crack propagation is introduced. Crack propagation is calculated following the Paris' Law, which relates crack growth rate to the stress intensity factor range. The fracture and fatigue crack growth procedures can be used to estimate the remaining life of a flawed structure.

2 Severe Sea State

Severe sea states (e.g., the sea state under the worst weather condition during the design life) are needed to be applied in the fracture mechanics analysis for ship and offshore structures. If such information is not available, the severe sea state is chosen to be the worst sea state in the North Atlantic for ship structures or at a specific site for offshore structures. The stress range in such severe sea state is defined in Subsection 3/2.

3 Acceptable Initial Flaw Size

Acceptable initial flaw length is defined as the flaw length that propagates to the acceptable critical flaw length under severe sea state during design life. The acceptable critical flaw length is defined as the flaw length that is determined by the acceptance criteria defined in this Section. In Engineering Critical Assessment (ECA), the acceptable value of the initial flaw length of the structure might take the smaller value of the acceptable initial flaw length calculated herein using fracture mechanics method and the criteria required by applicable ABS Rule or Guide, such as the ABS *Guide for Nondestructive Inspection*. The damages and repairs on ABS Classed vessels/units are to be communicated to ABS in accordance with Section 1-1-8 of the ABS *Rules for Conditions of Classification (Part 1)* or Section 1-1-8 of the ABS *Rules for Conditions of Classification – Offshore Units and Structures (Part 1)*.

4 Failure Assessment Diagram

The fracture assessment of a component that contains a crack-like flaw involves the evaluation of the stability of the flaw under static loading conditions with reference to failure by fracture and plastic collapse. Such a fracture assessment is performed via the failure assessment diagram (FAD) approach which involves the calculation of:

- A fracture parameter, K_r, based on the ratio of the elastic crack driving force to the material's fracture toughness, and

- A plastic collapse parameter, L_r, defined as either the ratio of applied load to the limit load or, equivalently, the ratio of the reference stress (characterizing the increase in stress in the vicinity of a flaw) to the yield strength.

The fracture and plastic collapse parameters are represented on a vertical axis and a horizontal axis, respectively. The axes are joined by a failure assessment line (FAL) which incorporates the effect of plasticity on crack driving force and is given by the equation of a curve, $K_r = f(L_r)$, and a cut-off value of $L_r = L_{r,max}$. There are three options as described in Subsection 6/1 and corresponding FALs. These options are of increasing complexity in terms of the required material and stress analysis data but provide results with increasing accuracy.

If the assessment point, corresponding to the fracture and plastic collapse parameters, falls within the area bounded by the axes, the FAL and the vertical line corresponding to $L_{r,max}$, the flaw is considered acceptable. If it lies on or outside the line, the flaw is unacceptable. In the case of an unacceptable flaw, the analysis may be refined with consideration of the analysis option employed, the input data used (including the materials properties), and taking into account ductile tearing, before conceding that an acceptable case cannot be achieved.

Option 1 in BS 7910 is recommended for fracture assessment in these Guidance Notes. The flowchart for Option 1 fracture assessment is given in Section 6, Figure 1. The schematic of Option 1 Failure Assessment Diagram (FAD) is shown in Section 6, Figure 2. The detailed calculation for the two parameters, L_r and K_r, refers to BS 7910.

FIGURE 1
Flowchart for Option 1 Fracture Assessment

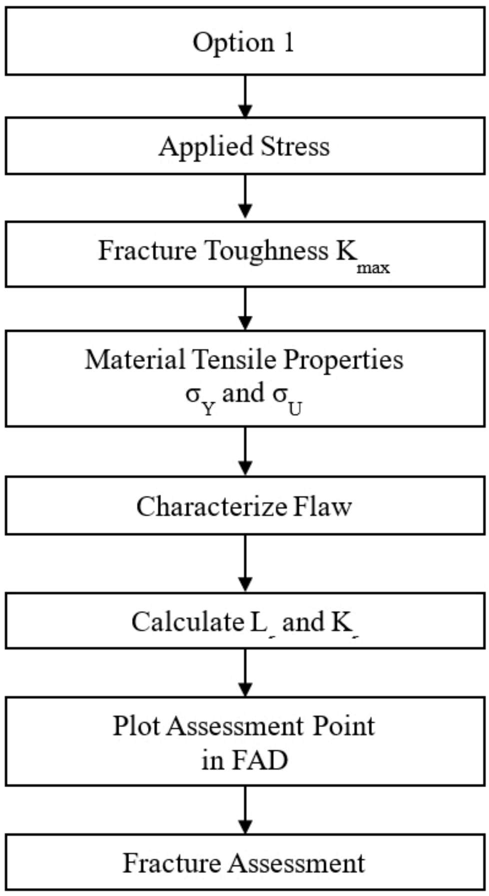
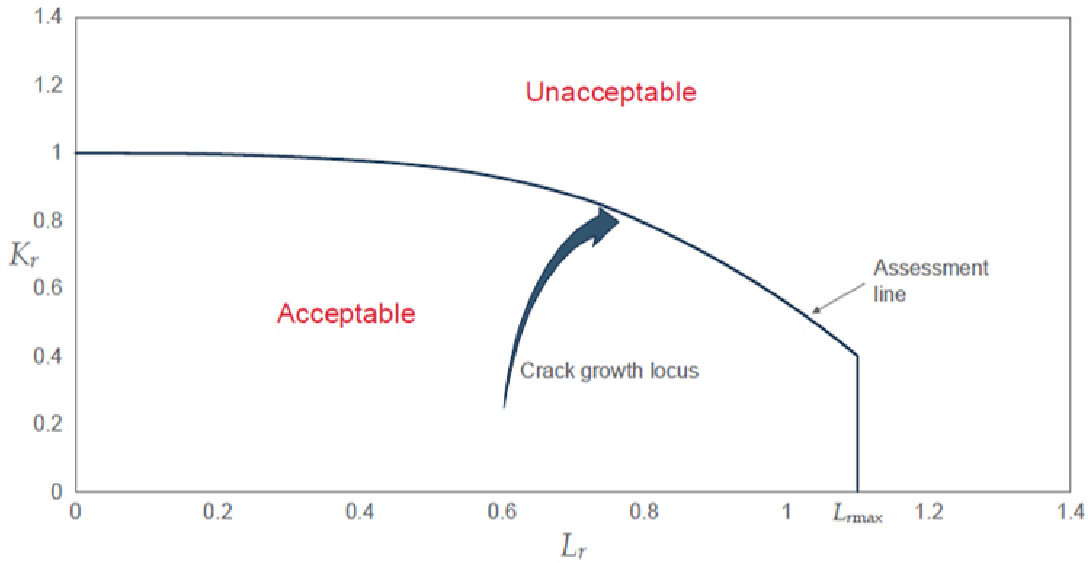


FIGURE 2
Failure Assessment Diagram (FAD)



4.1 Failure Assessment Line

BS 7910 provides three options for construction of Failure Assessment Line in the form of:

$K_r = f(L_r)$

The cut-off is to prevent plastic collapse. It is set at the point at which $L_r = L_{r,\,max}$ and

$L_{r,max} = \frac{\sigma_Y + \sigma_U}{2\sigma_Y}$

Referring to 7/7.3.3 of BS 7910 for the details of construction of the FAL curves, Option 1 recommended in these Guidance Notes, does not require detailed stress-strain data. The set of equations describing the FAL are:

$$f(L_r) = \left(1 + \tfrac{1}{2}L_r^2\right)^{-0.5}\left[0.3 + 0.7\exp\left(-\mu L_r^6\right)\right] \quad \text{for} \quad L_r \le 1$$
$$f(L_r) = f(L_r = 1)L_r^{(N-1)/(2N)} \quad \text{for} \quad 1 < L_r \le L_{r,max}$$
$$f(L_r) = 0 \quad \text{for} \quad L_r \ge L_{r,max}$$

where

$\mu = \min\left(0.001\frac{E}{\sigma_Y},\ \ 0.6\right)$

$N = 0.3\left(1 - \frac{\sigma_Y}{\sigma_U}\right)$

This curve is suitable for materials without having a yield discontinuity.

In Option 2, a material-specific FAL is constructed based on the mean uniaxial tensile true stress-strain curve at the assessment temperature for stresses up to the engineering value of tensile strength. This approach for construction of the Option 2 FAL is used for all metals regardless of the stress-strain behavior.

In Option 3, FAL is constructed through the use of both elastic and elastic-plastic analysis of the flawed structure under loads giving rise to primary stresses. The Option 3 FAL is specific to the material, geometry and loading considered in the analysis of the flawed structure.

Details on construction of Option 1 FAL for materials that exhibit a yield discontinuity and construction of Option 2 or Option 3 FAL are provided in 7/7.3.3 – 7.3.5 of BS 7910.

4.2 Fracture Ratio

The fracture ratio, K_r, is determined by either equation below:

$$K_r = \frac{K_I^P + VK_I^S}{K_{mat}}$$

$$K_r = \frac{K_I^P + K_I^S}{K_{mat}} + \rho$$

where

K_I^P	=	stress intensity factor due to primary stress
K_I^S	=	stress intensity factor due to secondary stress
K_{mat}	=	fracture toughness taking into account any ductile tearing following the crack initiation (referring to 7/7.1.4 of BS 7910)

The terms V and ρ are defined in Annex R of BS 7910 as functions of both the primary and secondary loads and account for plasticity interaction effects.

If K_I^S is negative, then K_I^S and ρ should be set to zero in the equations above. This is conservative for the purposes of assessment.

4.3 Load Ratio

The load ratio is defined based on the applied primary loads or the reference stress as follows:

$$L_r = \frac{P}{P_L(a, \sigma_Y)} = \frac{\sigma_{ref}}{\sigma_Y}$$

where

P	=	applied load
P_L	=	elastic perfectly plastic limit load
a	=	flaw size, including any ductile tearing
σ_Y	=	yield strength

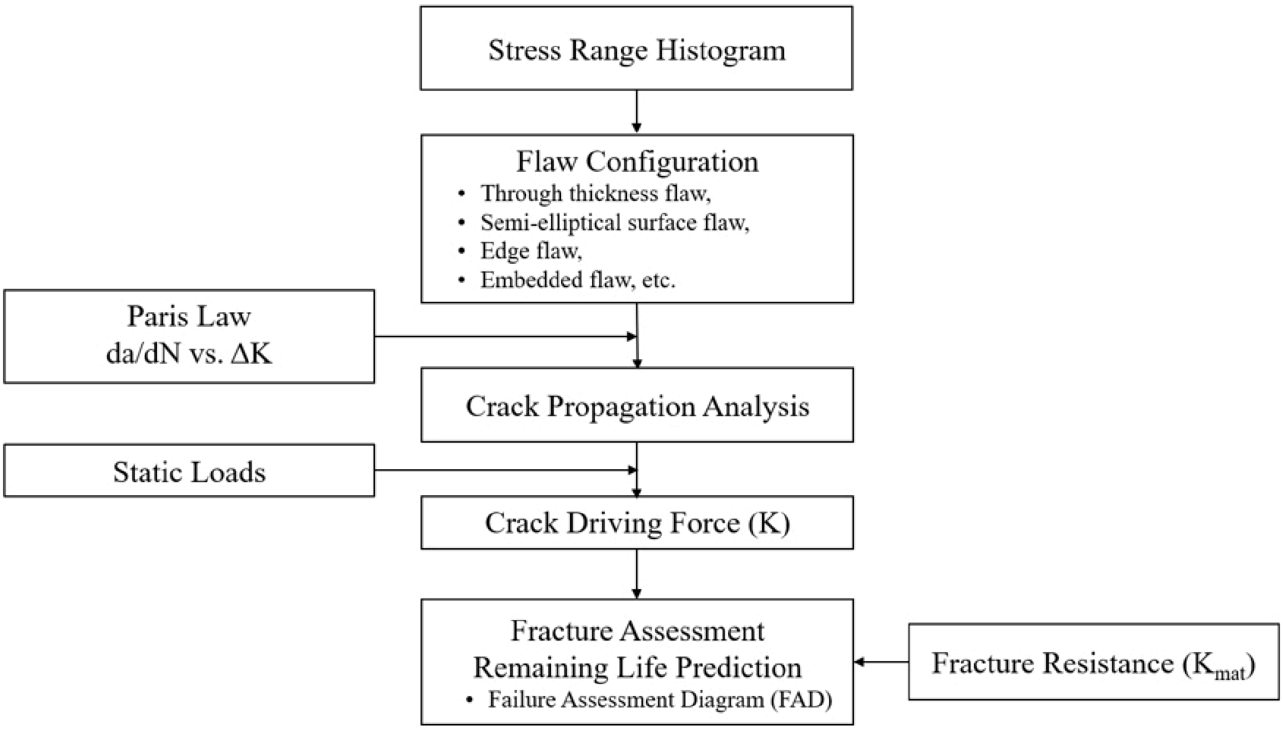
Structural collapse is considered governed by failure of the section containing the flaw. The possibility of premature collapse elsewhere in the structure should be separately investigated. The use of a limit load corresponding to such a remote failure mechanism in an assessment of the section containing the flaw may be overly conservative.

5 Fatigue Crack Propagation Analysis and Fracture Assessment

The stress range histogram, which could be caused by wave-induced loads (see Section 3), vibration-induced loads (see Section 4), or combined loads, is applied for crack propagation analysis following

Paris' law. The fracture assessment is performed at each cycle to evaluate stable or unstable crack growth using the failure assessment diagram. Section 6, Figure 3 gives the flowchart of crack propagation and fracture assessment.

FIGURE 3
Flowchart of Crack Propagation and Fracture Assessment



For a given flaw configuration (e.g., through thickness flaw, semi-elliptical surface flaw, edge flaw, etc.), the detailed procedure of crack propagation and fracture assessment is as follows:

1) The stress range histogram, which is determined by the long-term stress range distribution, due to wave-induced loads (see Section 3), vibration-induced loads (see Section 4), or combined loads is employed to determine the cyclic crack driving force. To remove loading sequence effect on crack propagation, the total stress range distribution should be divided into a certain number of groups (e.g., more than 10). Section 6, Figure 4 gives an example of a modified Weibull distribution, where $\Delta\sigma_o$ is the most probable maximum stress range during the life of the vessel.

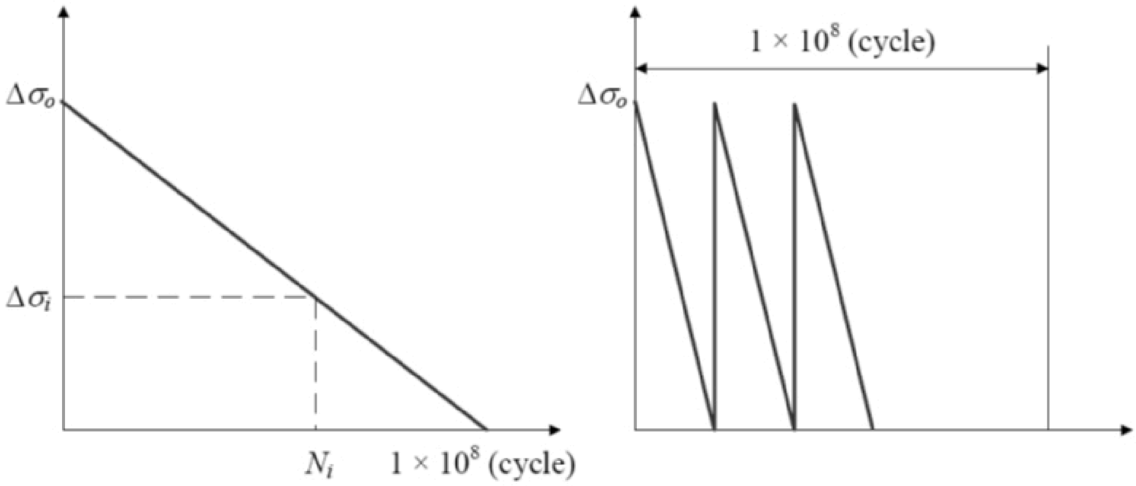
2) For each loading cycle, the stress intensity factor range is derived from the stress range, which is taken from stress range histogram, using fracture mechanics theory (see Section 5). Then, the crack extension is calculated following Paris' law.

3) Based on new crack dimensions, the fracture ratio, and load ratio are determined, according to Subsection 6/4, to conduct failure assessment based on Option 1 FAL.

4) Repeat step 2) and 3) until the crack becomes unstable, which corresponds to the assessment point lying on, or just crossing, the FAL. The number of cycles leading to the unacceptable flaw can be used to calculate the remaining life for the flawed structure.

For example, the fatigue propagation of a semi-elliptical surface flaw under cyclic loads continues until ligament failure resulting from fatigue crack growth through the entire thickness or from snap-through which occurs when the surface flaw reaches a critical size. The resulting through thickness flaw continues to propagate until it reaches a critical length at which rapid crack extension occurs.

FIGURE 4
Modified Weibull Distribution for Long-Term Stress Ranges



In summary, as a flaw or flaws are detected in an in-service marine or offshore structure subjected to dynamic loads, the remaining life of a flawed structure can be estimated following the fracture and fatigue crack growth analysis procedures described in this Section.