Guide for Building and Classing

Liquefied Gas Carriers with Independent Tanks

ABS

May 2023

GUIDE FOR BUILDING AND CLASSING

LIQUEFIED GAS CARRIERS WITH INDEPENDENT TANKS
MAY 2023

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

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Foreword *(1 May 2023)*

The industry and ABS share a large and successful body of experience with liquefied gas carriers with independent tanks. Owners and designers familiar with the benefits of the ABS SafeHull Rule approach in the design and analysis of other vessel types requested that ABS adapt the SafeHull criteria so that it can be used in the Classification of liquefied gas carriers with independent tanks. This Guide is developed and issued in response to the request.

This Guide provides criteria that can be applied in the Classification of the hull structure of a liquefied gas carrier with independent tanks.

The strength criteria contained herein are to be used to verify compliance with the structural analysis requirements in the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) as a condition of classification. These strength criteria are to be considered supplementary to those for corresponding aspects of Classification as given in Part 5C, Chapter 8 of the ABS *Rules for Building and Classing Marine Vessels* (the Rules). The Owner may select to use either this Guide or Part 5C, Chapter 8 of the Rules, however the Classification symbol, **SH**, (signifying compliance with the SafeHull based criteria in this Guide) will only be granted when the design is based on the criteria of this Guide.

After a certain period for trial use, the criteria contained in this Guide will be incorporated and published in the *Marine Vessel Rules*. ABS encourages and welcomes at any time the submission of comments on this Guide.

The ABS *Guide for Liquefied Petroleum Gas Carriers with Type-A Independent Tanks* became effective 1 January 2006.

In May 2009, the criteria was extended to cover liquefied gas carriers with Type B and Type C independent tanks. The 2010 revision added guidelines for hull girder ultimate strength assessment and had an effective date of 1 January 2010.

The June 2011 revision included fatigue, fracture, and thermal analysis for type-B independent tanks which is required by IGC code. Paragraph 6/9.7 and Appendix A5 were added to the Guide. The June 2017 version was updated based on the 2016 revised IGC code and updated Part 5C, Chapter 8 of the Rules and also included updates of fatigue and fracture analysis using a comprehensive methodology in Appendix A5.

The August 2019 version clarified the application of load cases required to calculate accurate loads for the cargo tank supports and chocks.

The November 2019 version modified Note 5 of 4/5 TABLE 1 to specify that the maximum sagging still water bending moment of all the cargo loaded conditions is to be applied to LC 1, 3 and 6 for liquefied gas carriers subject to sagging still water bending moments.

The May 2021 version closed a gap in the required scantlings at 0.125L from FP for bottom slamming in 5/7.21 and aligned the long term distribution factor in A3/5.5 with the formula in 5C-1-A1/5.5 of the *Marine Vessel Rules*.

The August 2021 version aligned requirements for slamming with Part 5C, Chapter 12 of the *Marine Vessel Rules*, allowed the use of the actual maximum draft for cases where the target cargo tank is empty while adjacent tanks are full for LC 4 and 7 if there is an operational restriction in the loading manual, revised the pressure head used by initial scantling calculation of longitudinal bulkhead plating, stiffeners, and main supporting members, and adjusted the required scantlings for side shell plating, bilge strake, bottom plates, inner bottom plating, and internal structures in line with adjustments to the wastage allowances.

The May 2023 version revises 5/9.3.2 to remove thickness increase if chocks are fitted to the tank top plating, to allow 10% reduction of SM for tank spaces loaded on both sides to the same level, to give credit in the corrosion allowance for non-corrosive cargo, and to provide an alternate approach for webs and girders. 6/5.11 is also revised to add an alternative for nonlinear analysis for anti-flotation chocks and surrounding hull structure under the LC 12 flooded condition.

Reference Note

Reference to a paragraph in the *Marine Vessel Rules* is made in the format “P-C-S/ss.p.sp.i” where “P” is the Part, “C” is the Chapter, “S” is the Section, “ss” is the subsection, “p” is the paragraph, “sp” is the subparagraph and “i”is the item .

Reference to a paragraph in this Guide is made in the format “S/ss.p.sp.i”, where “S” is the Section, “ss” is the subsection, “p” is the paragraph and “sp” is the subparagraph and “i” is the item.

Reference to a Figure or Table in this Guide is made, respectively, in the format “S, Figure #”, or “S, Table #” where “S” is the Section in which the figure or table is located.

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LIQUEFIED GAS CARRIERS WITH INDEPENDENT TANKS

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SECTION 1

Introduction

Note: Text in *italics* comes from the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). See 5C-8-1/3 of the *Marine Vessel Rules*.

1 General

1.1 Classification *(1 May 2009)*

In accordance with 1-1-3/3 of the ABS *Rules for Conditions of Classification* and 5C-8-1/2 of the ABS *Rules for Building and Classing Marine Vessels* (the Rules), the classification notation ✠ **A1 Liquefied Gas Carrier with Independent Tanks**, **SH**, **SHCM** is to be assigned to vessels designed for the carriage of liquefied gases, and built to the requirements of this Guide and other relevant sections of the Rules.

1.3 Optional Class Notation for Design Fatigue Life *(1 May 2009)*

Vessels designed and built to the requirements in this Guide are intended to have a structural fatigue life of not less than 20 years. Where a vessel's design calls for a fatigue life in excess of the minimum design fatigue life of 20 years, the optional class notation **FL (year)** is to be assigned at the request of the applicant. This optional notation is eligible provided the excess design fatigue life is verified to be in compliance with the criteria in Appendix A3 "Rule-based Fatigue Strength Assessment." Only one design fatigue life value is published for the entire structural system. Where differing design fatigue life values are intended for different structural elements within the vessel, the **(year)** refers to the least of the varying target lives. The 'design fatigue life' refers to the target value set by the applicant, not the value calculated in the analysis.

The notation **FL (year)** denotes that the design fatigue life assessed according to Appendix A3 "Rule-based Fatigue Strength Assessment" is greater than the minimum design fatigue life of 20 years. The **(year)** refers to the fatigue life equal to 25 years or more (in 5-year increments) as specified by the applicant. The fatigue life will be identified in the *Record* by the notation **FL (year)**; e.g., **FL(30)** if the minimum design fatigue life assessed is 30 years.

1.5 Application

1.5.1 General

In view of the similarity of structural arrangements, this Guide has many cross-references to the general requirements for hull construction in Part 3 of the Rules and the particular requirements in Part 5C, Chapter 8 of the Rules for vessels intended to carry liquefied gases in bulk. These cross-references are presented in a simple format throughout the Guide in order to provide quick reference to the users, (i.e., 1-2-3/4.5.6 of the Rules denotes Part 1, Chapter 2, Section 3/ Subparagraph 4.5.6 of the Rules).

1.5.2 Size and Proportion *(1 May 2009)*

The requirements contained in this Guide are applicable to liquefied gas carriers with independent tanks intended for unrestricted service, having lengths of 90 meters or more, and having parameters within the range as specified in 3-2-1/2 of the Rules.

1.5.3 Vessel Types *(1 May 2009)*

These requirements are intended to apply to steel vessels with machinery aft, engaged in the carriage of liquefied gases in independent tanks (Type A, Type B, and Type C) as defined in 5C-8-4/Part E of the Rules. The technical requirements of the *International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (*IGC Code*) are also to be followed.

For Type A independent tanks, the scantling requirements and strength criteria in the Guide are considered equivalent to those in 5C-8-4/21 of the Rules.

For Type B independent tanks, the requirements in 5C-8-4/22 of the Rules with respect to crack propagation and fatigue failure are to be additionally verified. The scantling requirements and strength criteria in the Guide are considered equivalent to the remaining requirements in 5C-8-4/22 of the Rules.

For Type C independent tanks (pressure vessels), the scantling requirements and strength criteria in 5C-8-4/23 of the Rules are to be verified. The strength criteria in the Guide are considered equivalent to the remaining requirements in 5C-8-4/23 of the Rules.

1.5.4 Direct Calculations

Direct calculations with respect to the determination of design loads and the establishment of alternative strength criteria based on first principles, will be accepted for consideration, provided that all the supporting data, analysis procedures and calculated results are fully documented and submitted for review. In this regard, due consideration is to be given to the environmental conditions, probability of occurrence, uncertainties in load and response predictions, and reliability of the structure in service. For long term prediction of wave loads, realistic wave spectra covering the North Atlantic Ocean and a probability level of 10^{-8} are to be employed.

1.5.5 SafeHull Construction Monitoring Program

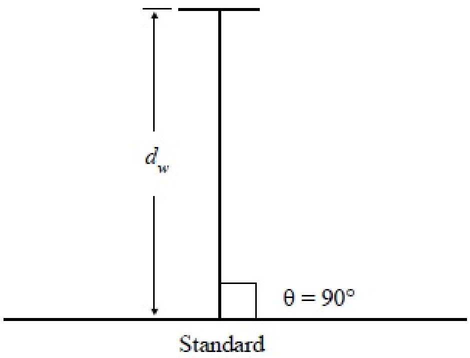
A Construction Monitoring Plan for critical areas, prepared in accordance with the requirements of Appendix 5C-A1-1 of the Rules, is to be submitted for approval prior to commencement of fabrication. See Appendix 5C-A1-1 “SafeHull Construction Monitoring Program” of the Rules.

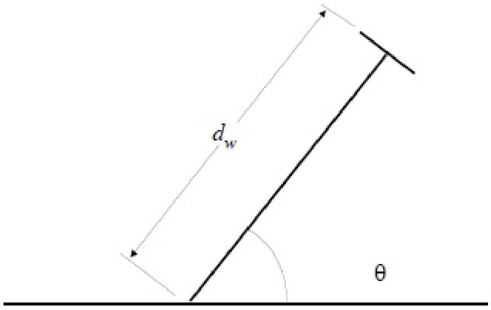
1.7 Internal Members

1.7.1 Section Properties of Structural Members *(1 May 2009)*

The geometric properties of structural members may be calculated directly from the dimensions of the section and the associated effective plating (see 3-1-2/13.3 of the Rules or 5/7.21.3 FIGURE 3, as applicable). For structural members with angle θ (see 1/1.7.1 FIGURE 1) between web and associated plating not less than 75 degrees, the section modulus, web sectional area, and moment of inertia of the “standard” (θ = 90 degrees) section may be used without modification. Where the angle θ is less than 75 degrees, the sectional properties are to be directly calculated about an axis parallel to the associated plating (see 1/1.7.1 FIGURE 1).

FIGURE 1





For longitudinals, frames and stiffeners, the section modulus may be obtained by the following equation:

$SM = \alpha_\theta SM_{90}$

where

α_θ	=	$1.45 - 40.5/\theta$
SM_{90}	=	the section modulus at $\theta = 90$ degrees

Effective section area may be obtained by the following equation:

$A = A_{90}\sin(\theta)$

where

A_{90}	=	effective shear area at $\theta = 90$ degrees

1.7.2 Detailed Design *(1 May 2009)*

The detailed design of internals is to follow the guidance given in 3-1-2/15 of the Rules and in 5/1.3 of this Guide.

See also Appendix A3 “Rule-based Fatigue Strength Assessment”.

1.9 Breaks

Special care is to be taken to provide structural reinforcements against local stresses at the ends of the cargo tank spaces, superstructures, etc., and throughout the structure in general. The main longitudinal bulkheads are to be suitably tapered at their ends. Where effective longitudinal bulkheads are provided in the poop or deckhouse, they are to be located such as to provide effective continuity between the structure in way of and beyond the main cargo spaces.

1.11 Variations *(1 May 2009)*

Liquefied gas carriers with independent tanks of a special type or design, differing from those described in this Guide, will be specially considered on the basis of equivalent strength.

1.13 Loading Guidance

Loading guidance is to be as required by 3-2-1/7 of the Rules.

1.15 Design Vapor Pressure (*1 June 2017*)

The design vapor pressure p_o as defined in 5C-8-4/1.2 of the Rules is to follow:

1.15.1 Type A Independent Tanks

Type A independent tanks are primarily designed using classical ship-structural analysis procedures in accordance with recognized standards. Where such tanks are primarily counstructed of plane surfaces, the design vapor pressure P_o shall be less than 0.07 MPa (0.714 kgf/cm^2).

1.15.2 Type B Independent Tanks

Type B independent tanks are tanks designed using model tests, refined analytical tools and analysis methods to determine stress levels, fatigue life, and crack propagation characteristics. Where such tanks are primarily constructed of plane surfaces (prismatic tanks), the design vapor P_o shall be less than 0.07 MPa (0.714 kgf/cm^2).

1.15.3 Type C Independent Tanks

The design vapor pressure shall not be less than:

$$P_o = 0.2 + AC(\rho_r)^{1.5}(MPa)$$

where:

$$A = 0.00185\left(\frac{\sigma_m}{\Delta\sigma_A}\right)^2$$

where:

σ_m	=	*design primary membrane stress*
$\Delta\sigma_A$	=	*allowable dynamic membrane stress (double amplitude at probability level $Q = 10^{-8}$)*
		- 55 N/mm^2 for ferritic-perlitic, martensitic and austenitic_steel
		- 25 N/mm^2 for aluminum alloy (5083-0)
C	=	*a characteristic tank dimension to be taken as the greatest of the following:* *h; 0.75b; or 0.45 ℓ*
h	=	*height of tank (dimension in ship's vertical direction) (m)*
b	=	*width of tank (dimension in ship's transverse direction) (m)*

ℓ = *length of tank (dimension in ship's longitudinal direction) (m)*

ρ_r = *the relative density of the cargo ($\rho_r = 1$ for fresh water) at the design temperature.*

When a specified design life of the tank is longer than 10^8 wave encounters, $\Delta\sigma_A$ shall be modified to give equivalent crack propagation corresponding to the design life.

1.17 Protection of Structure

For protection of the structure, see 3-2-18/5 of the Rules as appropriate.

1.19 Aluminum Paint

Paint containing aluminum is not to be used in cargo tanks, pump rooms and cofferdams, nor in any other area where cargo vapor may accumulate, unless it has been shown by appropriate tests that the paint to be used does not increase the fire hazard.

1.21 Containment System

Secondary barrier, insulation, materials, construction and testing of the cargo containment system are to comply with the applicable requirements in Section 5C-8-4 of the Rules.

1.23 Determination of Temperature Distribution for Material Selection *(1 May 2009)*

The temperature distribution in the hull and cargo tank structures is to be determined based on the design ambient and cargo temperatures. 1/1.23 TABLE 1 summarizes the design ambient temperatures that are to be commonly used in the temperature distribution calculation. For vessels trading in other cold regions, the design ambient temperatures are to be specially considered.

TABLE 1
Design Ambient Temperatures *(1 May 2009)*

	Air	*Still Sea Water*
IMO IGC World-wide Services (5C-8-4/8.1)	5°C at 0 knots	0°C
USCG Requirements for US Waters except Alaskan Waters (Appendix 5C-8-A2)	–18°C at 5 knots	0°C
USCG Requirements for Alaskan Waters (Appendix 5C-8-A2)	–29°C at 5 knots	–2°C

The design temperature for cargo tanks is the minimum temperature at which cargo may be loaded or transported. The boiling temperatures and corresponding densities are listed in 1/1.23 TABLE 2 for some common liquefied gas cargoes.

The design temperature for cargo piping, cargo process pressure vessels and all associated equipment is the minimum temperature in the systems and components during the cargo operations.

The design temperature for a complete or partial secondary barrier is to be assumed to be the cargo temperature at atmospheric pressure.

For the purpose of determining the temperatures of the internal hull structural members beyond the cargo block, the ambient air temperature in the forebody and engine room spaces may be assumed to be 5°C.

The minimum temperature of the hull structure, tank supports and chocks is to be determined by direct temperature calculations, taking into account the efficiency of any insulation and means of heating if accepted according to 5C-8-4/8.

In absence of direct temperature calculations and for the purposes of material grade selection, the typical internal structural members (excluding tank supports and chocks) in liquefied gas carriers with Type A independent tanks may be determined with the following assumptions:

- The design temperature for the stiffeners is to be the same as that of the attached plating.
- The design temperature for the main supporting members without or away from large openings is to be taken as the average design temperature of the two adjoining plates.
- The design temperature for the main supporting members within large openings is to be the same as that of the attached plating.
- The extent of the low temperature steel for deck plating between the two upper wing tanks is to be based on the 30-degree static heel condition.
- The low temperature steel for the longitudinally continuous plating such as deck, inner bottom, and inner longitudinal bulkheads is to be extended 400 mm beyond the required position of the secondary barrier. The plating adjoining the low temperature steel is to be of E or DH Grade. The extent of such material grade need not be more than 400 mm.

TABLE 2
Cargo Properties of Common Liquefied Gas Cargoes *(1 May 2009)*

Cargo	*Chemical Formula*	*Vapor Detection*	*Boiling Temperature (°C)*	*Density (kg/m³)*
Acetaldehyde	CH_3CHO	F + T	+20.8	780
Ammonia, Anhydrous	NH_3	T	–33.4	680
Butadiene 1.3 (inhibited)	$CH_2CHCHCH_2$	F + T	–4.5	650
Butane, also called N-Butane	C_4H_{10}	F	–0.5	600
Butane/Propane mixtures		F		630
Butylenes		F	–6.3	630
Chlorine	Cl_2	T	–34	1560
Diethyl Ether	$C_2H_5O\ C_2H_5$	F + T	34.6	640
Dimethylamine	$(CH_3)_2NH$	F + T	6.9	670
Ethane	C_2H_6	F + T	–88	550
Ethyl Chloride	CH_3CH_2Cl	F + T	12.4	920
Ethylene	C_2H_4	F	–104	560
Ethylene Oxide	$(CH_2)_2O$	F + T	11	870
Ethylene Oxide/Propylene Oxide Mixture With Ethylene Oxide content of not more than 30% by weight	$(CH_2)O_2 + CH_3\ CHOCH_2$	F + T	27	830
Isoprene(inhibited)	$CH_2C(CH_3)CHCH_2$	F	34.0	680
Isopropylamine	$(CH_3)_2CH\ N\ H_2$	F + T	33.0	670
Methane (LNG)	CH_4	F	–163	420
Methyl Acetylene – Propadiene mixture		F		620
Methyl Bromide	CH_3Br	F + T	4	1730

Cargo	*Chemical Formula*	*Vapor Detection*	*Boiling Temperature (°C)*	*Density (kg/m³)*
Methyl Chloride	CH_3Cl	F + T	–24.0	970
Monoethylamine	$C_2H_3NH_2$	F + T	16.6	690
Nitrogen	N_2	A	–196	808
Pentanes (all Isomers)	$CH_3(CH_2)_3CH_3$	F	29 to 36	626
Pentene (all Isomers)	$CH_3CH_2CH_2CH{=}CH_2$	F	30 to 37	656
Propane	C_3H_8	F	–42.3	590
Propylene	C_3H_6	F	–47.7	610
Propylene Oxide	CH_3CHOCH_2	F + T	+33.9	822
Refrigerant gases			3.6 to –81.4	1410 to 1526
Sulphur Dioxide	SO_2	T	–10	1460
Vinyl Chloride Monomer (VCM)	CH_2CHCl	F + T	–13.9	970
Vinyl Ethyl Ether	$CH_2\text{-}CHOC_2H_5$	F + T	35.5	750
Vinylidene Chloride	$C_2H_2\text{-}CCl_2$	F + T	31.7	1250

Note:
F - Flammable vapor detection
T - Toxic vapor detection
A - Asphixiant

Design Considerations and General Requirements

1 General Requirements

1.1 General

The proposed scantlings are to comply with the requirements specified in this Guide. Owner's extra scantlings (i.e., Owner's specified additional thickness), as included in the vessel's design specifications, are not to be used in the evaluation. The requirements in this Guide are based on the gross scantling approach.

The requirements related to Type-A independent cargo tanks apply only to where non-corrosive cargoes are carried. If corrosive cargoes are carried in these tanks, the scantlings are to be suitably increased or an effective method of corrosion control is to be adopted.

1.3 Initial Scantling Requirements

The initial thickness of plating, the section modulus of longitudinals/stiffeners, and the scantlings of main supporting structures are to be determined in accordance with Section 5. The scantlings that comply with the requirements in Section 5 are to be used for further assessment as required in the following paragraph.

1.5 Strength Assessment – Failure Modes

A total strength assessment of the structures, determined on the basis of the initial strength criteria in Section 5 is to be carried out against the following three failure modes:

1.5.1 Material Yielding

The calculated stress intensities are not to be greater than the yielding state limit given in 6/5 for the applicable load cases specified in 4/3.

1.5.2 Buckling and Ultimate Strength

For each individual member, plate or stiffened panel, the buckling and ultimate strength is to be in compliance with the requirements specified in 6/7 for the applicable load cases specified in 4/3.

1.5.3 Fatigue

The fatigue strength of structural details and welded joints in highly stressed regions, is to be analyzed in accordance with 6/9 for the applicable load cases specified in 4/5

1.7 Structural Redundancy and Residual Strength *(1 May 2009)*

Consideration is to be given to structural redundancy and hull girder residual strength in the early design stages.

The hull structure is to be in compliance with the hull girder ultimate strength requirements specified in 6/7.7.

SECTION 3
Dynamic Load Criteria

1 General

For strength assessment against the yielding and buckling failure modes, the dynamic load criteria represent the long-term extreme values for the North Atlantic, corresponding to a probability of exceedance of 10^{-8}. For vessels serving in more severe seas, the dynamic load criteria are to be modified. These dynamic load criteria have an implied ship speed of zero knots in extreme sea conditions with exception of the impact load criteria. The ship speed used to calculate bow wave impact, bow flare slamming, flat bottom slamming, green water and cargo sloshing is to be taken as 75% of the design speed (MCR).

For strength assessment against the fatigue failure mode, the dynamic load criteria represent the characteristic values for the North Atlantic, corresponding to a probability of exceedance of 10^{-4}. These dynamic load criteria have an implied ship speed equal to 75% of the design speed (MCR).

The following dynamic load components are to be considered in the structural evaluation of the hull, cargo tanks, tank supports and chocks:

- Vertical and horizontal wave-induced bending moments
- Vertical and horizontal wave-induced shear forces
- External pressure
- Internal pressure
- Bow wave impact
- Bow flare slamming for forebody structures
- Bottom slamming for forebody structures
- Green water
- Sloshing loads
- Thermal loads
- Loads corresponding to ship deflection

The load combination factors for the dynamic load components and dominant parameters are included in the load formulae in this Section, but their actual values are specified in Section 4.

3 Definitions

3.1 Symbols

B	molded breadth, in m
C_b	block coefficient at the scantling draft
D	molded depth, in m
d_f	scantling draft, in m
GM	metacentric height, in m
L	scantling length, in m
L_{BP}	length between perpendiculars, in m
V	service speed, in knots
V_d	design speed (MCR), in knots

3.3 Coordinate Systems

Two sets of Cartesian coordinate systems are used to describe dynamic load criteria. When alternative coordinate systems are used, attention is to be paid to the default coordinate systems used in the dynamic load formulae.

3.3.1 Ship Coordinate System for Ship Motion and External Pressure *(1 June 2017)*

Origin	Intersection of the AP section, waterline and centerline planes.
x_T	Longitudinal distance from amidships to the center of gravity of the tank with contents, in m, positive toward the bow.
y_T	Vertical distance from the waterline to the center of gravity of the tank with contents, in m, positive above and negative below the waterline.
z_T	Transverse distance from the centerline to the center of gravity of the tank with contents, in m, positive toward starboard.
x	Longitudinal distance from the AP to the external pressure point considered, in m.
x_o	Longitudinal distance from the AP to the reference station, in m. The reference station is the point along the vessel's length where the wave trough or crest is located and may be taken at the mid-length of the considered tank.

3.3.2 Tank Coordinate System for Internal Pressure *(1 June 2017)*

Origin	Intersection of the vertical, horizontal, and transverse planes that are tangential to the envelope of the tank. This origin is also referred to as the zero dynamic pressure point. For example, the zero dynamic pressure point in 3/3.3.2 FIGURE 1 is located at the upper corner of the aft transverse bulkhead on the port side, and the forward portion of the tank on the starboard side is under high dynamic pressure and is targeted for strength assessment.
x_ℓ	Longitudinal distance from the zero dynamic pressure point of the tank to the pressure point, in m, $x_\ell = x_0 - x_p$
y_ℓ	Vertical distance from the zero dynamic pressure point of the tank to the pressure point, in m, $y_\ell = y_0 - y_p$
z_ℓ	Transverse distance from the zero dynamic pressure point of the tank to the pressure point, in m, $z_\ell = z_0 - z_p$

a_{le}	Dimensionless longitudinal acceleration, positive forward
a_{te}	Dimensionless transverse acceleration, positive starboard
a_{ve}	Dimensionless vertical acceleration, positive upward
x_0	Zero dynamic pressure point, x_0, taken as:

a) Forward bulkhead for $k_{cl} > 0$

b) Aft bulkhead of the tank for $k_{cl} < 0$

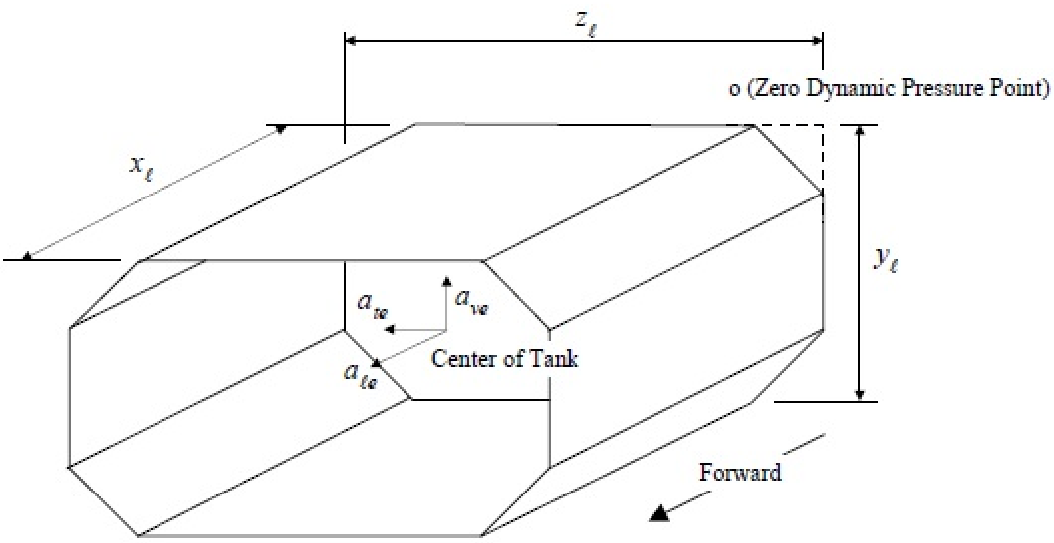
y_0	Zero dynamic pressure point, y_0, always taken as top of tank
z_0	Zero dynamic pressure point, z_0, taken as:

a) Tank top towards port side for $k_{ct} < 0$

b) Tank top towards starboard side for $k_{ct} > 0$

where x_0, y_0, z_0 and x_p, y_p, z_p are the zero dynamic pressure point and pressure point coordinate in ship coordinate system as per 3/3.3.1, respectively. k_{cl} and k_{ct} are the load combination factors for effective longitudinal and transverse acceleration, respectively, as detailed in the load case tables in Section 4.

FIGURE 1
Tank Coordinate System for Internal Pressure



5 Vertical Wave-induced Bending Moment

The vertical wave-induced bending moment, in tf-m, may be obtained from the following equations:

$$M_{ws} = -11.22 k_p k_{cmv} k_s m_v C_1 L^2 B (C_b + 0.7) \times 10^{-3} \qquad \text{Sagging Moment}$$

$$M_{wh} = +19.37 k_p k_{cmv} k_s m_v C_1 L^2 B C_b + 0.7 \times 10^{-3} \qquad \text{Hogging Moment}$$

where

$C_1 = 10.75 - \left(\frac{300 - L}{100}\right)^{1.5}$ $\quad 90 \leq L < 300$

$= 10.75$ $\quad 300 \leq L < 350$

$= 10.75 - \left(\frac{L - 350}{150}\right)^{1.5}$ $\quad 350 \leq L < 500$

k_{cmv} = load combination factor for design vertical wave-induced bending moment

k_p = load factor for adjusting the probability of exceedance

= 1.0 for yielding and buckling strength assessment

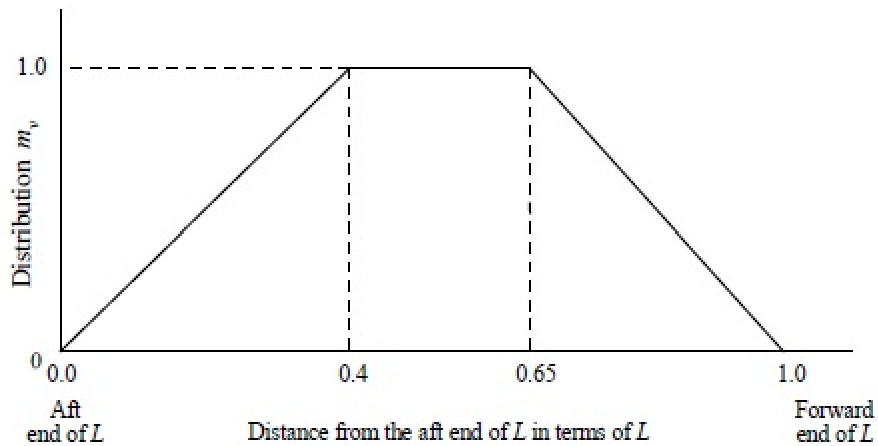
= 0.5 for fatigue strength assessment

k_s = 1.0 for yielding and buckling strength assessment

= $(1.09 + 0.029V - 0.47C_b)^{0.5}$ for fatigue strength assessment

m_v = distribution factor for vertical wave-induced bending moment (see 3/5 FIGURE 2)

FIGURE 2
Distribution Factor for Vertical Wave-induced Bending Moment m_v



7 Horizontal Wave-induced Bending Moment

The horizontal wave-induced bending moment, in tf-m, positive (tension port) or negative (tension starboard), may be obtained from the following equation:

$$M_h = \pm 85.656 k_p k_s k_{cmh} m_h C_1 L^2 D (C_b + 0.7) \times 10^{-4}$$

where

k_{cmh} = load combination factor for design horizontal wave-induced bending moment

k_p = load factor for adjusting the probability of exceedance

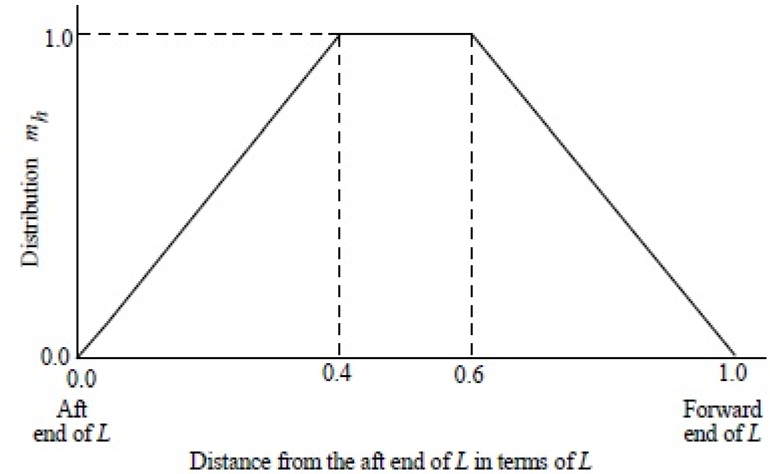
= 1.0 for yielding and buckling strength assessment

= 0.5 for fatigue strength assessment

m_h = distribution factor for horizontal wave-induced bending moment (see 3/7 FIGURE 3)

C_1 and k_s are as given in 3/5.

FIGURE 3
Distribution Factor for Horizontal Wave-induced Bending Moment m_h



9 External Pressure

The external pressure, p_e, positive toward inboard, in kgf/cm^2, with waves approaching the hull from the starboard side can be expressed by the following equation at a given cross section:

$$p_e = \rho(h_s + 1.36 k_p k_s k_{ce} k_d \alpha C_1) \times 10^{-4} \geq 0$$

where

α	=	$0.75 - 1.25\sin\mu$	waterline, port
	=	$0.2 - 0.4\sin\mu + 0.1\cos\mu$	bilge, port
	=	$0.3 - 0.2\sin\mu$	centerline, bottom
	=	$0.4 - 0.1\cos\mu$	bilge, starboard
	=	$1.0 - 0.25\cos\mu$	waterline, starboard

k_d = $\left\{1 - \left[1 - \cos\frac{2\pi(x - x_o)}{L}\right]\cos\mu\right\}[1 + (k_{\ell o} - 1)\cos\mu]$

μ = wave heading angle, to be taken from 0° to 90° (0° for head sea, 90° for beam sea, waves approaching the hull from the starboard side)

h_s = hydrostatic pressure head in still water, in m

k_{ce} = load combination factor for external pressure

k_p = load factor for adjusting the probability of exceedance

= 1.0 for yielding and buckling strength assessment

= 0.5 for fatigue strength assessment

ρ = specific weight of sea water in kgf/m^3

C_1 and k_s are as given in 3/5 and the pressure distribution factor $k_{\ell o}$, may be taken from 3/9 TABLE 1 or 3/9 FIGURE 4. A negative combination factor, k_{ce}, signifies that the wave trough is on the starboard side.

FIGURE 4
Pressure Distribution Function $k_{\ell o}$

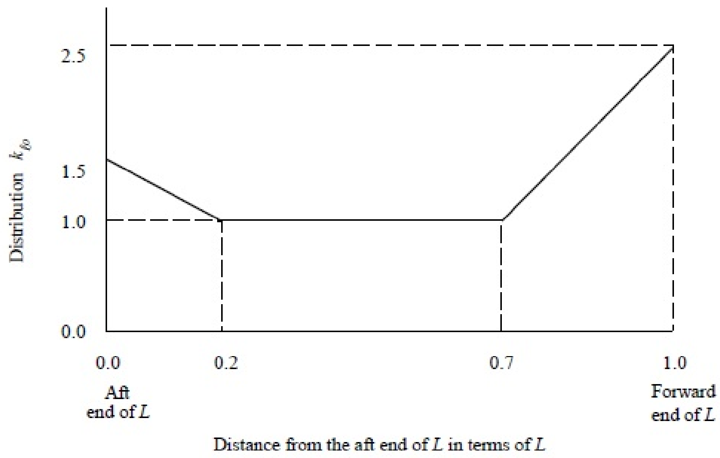


TABLE 1
$k_{\ell o}$ Coefficient

$[x_o - (L_{BP} - L)]/L$	$k_{\ell o}$	$[x_o - (L_{BP} - L)]/L$	$k_{\ell o}$	$[x_o - (L_{BP} - L)]/L$	$k_{\ell o}$
0.000	1.500	0.175	1.063	0.850	1.750
0.025	1.438	0.200 ~ 0.700	1.000	0.875	1.875
0.050	1.375	0.725	1.125	0.900	2.000
0.075	1.313	0.750	1.250	0.925	2.125
0.100	1.250	0.775	1.375	0.950	2.250
0.125	1.188	0.800	1.500	0.975	2.375
0.150	1.125	0.825	1.625	1.000	2.500

The external pressure may be calculated for the reference section at x_o and the pressure variation over the length of the global finite element model may be ignored. The reference section may be taken at the mid-length of the targeted cargo tank. However, the pressure variation along the girth of the reference section is to be accounted for and can be represented by the pressure values at the following five points, as shown in 3/9 FIGURE 5:

E1 waterline, port

E2 bilge, port

E3 centerline, bottom

E4 bilge, starboard

E5 waterline, starboard

A positive dynamic pressure may be assumed to vary linearly above the waterline at E1 on the port side, as illustrated in 3/9 FIGURE 5. The zero pressure point is defined by h_1, which is equal to the dynamic pressure head or freeboard, whichever is less.

When a negative dynamic pressure is found, for example, at the waterline at E5 on the starboard side in 3/9 FIGURE 5, the zero pressure point can be defined by h_2, which can be calculated as follows:

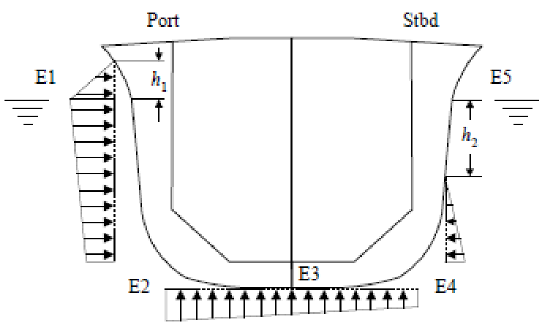
$$h_2 = d_m \frac{p_{E5}}{p_{E5} - p_{E4}}$$

The negative pressure above the zero pressure point is ignored.

The external pressure on the bottom shell plating linearly varies from pressure, p_{E2} (bilge, port), to pressure, p_{E4} (bilge, starboard). d_m is the draft the mid-length of the targeted cargo tank for a specific loading condition, in m.

The term "bottom shell plating" refers to the plating from the keel to the upper turn of the bilge amidships, but the upper turn of the bilge is not to be taken more than 0.2D above the baseline.

FIGURE 5
External Pressure Calculation Points



11 Internal Pressure

11.1 Accelerations *(1 June 2017)*

The accelerations acting on tanks are estimated at their center of gravity. a_{le}, a_{te} and a_{ve} are the maximum dimensionless accelerations (i.e., relative to the acceleration of gravity) in the longitudinal, transverse and vertical directions, respectively and they are considered as acting separately for calculation purposes. a_{ve} does not include the component due to the static weight, a_{te} includes the component due to the static weight in the transverse direction due to rolling and a_{le} includes the component due to the static weight in the longitudinal direction due to pitching. The following formulae are given as guidance for the components of acceleration due to ship's motions in the North Atlantic.

Vertical acceleration:

$$a_{ve} = \pm a_o \sqrt{1 + \left(5.3 - \frac{45}{L}\right)^2 \left(\frac{x_t}{L} + 0.05\right)^2 \left(\frac{0.6}{C_b}\right)^{1.5} + \left(\frac{0.6 z_t K^{1.5}}{B}\right)^2}$$

Transverse acceleration:

$$a_{le} = \pm a_o\sqrt{0.6 + 2.5\left(\frac{x_t}{L} + 0.05\right)^2 + K\left(1 + 0.6K\frac{y_t}{B}\right)^2}$$

Longitudinal acceleration:

$$a_{le} = \pm a_o\sqrt{0.06 + A^2 - 0.25A}$$

with

$$A = \left(0.7 - \frac{L}{1200} + 5\frac{y_t}{L}\right)\left(\frac{0.6}{C_b}\right)$$

where

a_o	=	$k_p\left[0.2\left(\frac{V}{\sqrt{L}}\right) + \frac{(34 - 600/L)}{L}\right]$
k_p	=	load factor for adjusting the probability of exceedance
	=	1.0 for yielding and buckling strength assessment
	=	0.5 for fatigue strength assessment
K	=	1.0 in general. For particular loading conditions and hull forms, determination of K according to the formula below may be necessary.
	=	13GM/B, where $K \geq 1.0$.
GM	=	metacentric height, in m
V	=	10 knots for yielding and buckling strength assessment

Note: The accelerations calculated from the recommended formula in IGC Code at 10 knots are considered representative of the ship's actual accelerations in extreme sea conditions.

= 75% of the design speed for fatigue strength assessment.

11.3 Internal Pressure for Initial Scantling Evaluation *(1 June 2017)*

To determine the inertial forces and added pressure heads for a completely filled cargo tank, the dominating ship motion parameters induced by waves are to be calculated. The internal pressure p_{eq} resulting from the design vapor pressure p_o *or* p_h, *plus the maximum associated dynamic* liquid pressure p_{gd}, but not including effects of liquid sloshing loads.

p_{eq} is to be the greater of p_{eq1} and p_{eq2} calculated as follows:

p_{eq1}	=	$p_o + (p_{gd})\max$
p_{eq2}	=	$p_h + (p_{gd\,site})\max$

Where (p_{gd})max is the associated liquid pressure determined using the maximum design accelerations; $(p_{gd\,site})$ max is the associated liquid pressure determined using site specific accelerations.

Note:

For the various tank types, a vapor pressure p_h higher than p_o may be accepted for site specific conditions (harbor or other locations), where dynamic loads are reduced.

The internal liquid pressures are those created by the resulting acceleration of the center of gravity of the cargo due to the motions of the ship referred to in 5C-8-4/14.1 of the Rules. The value of internal liquid pressure p_{gd} resulting from combined effects of gravity and dynamic accelerations is to be calculated as follows:

$$p_{gd} = \rho a_{\beta} Z_{\beta} 10^{-4}$$

Note:

For initial scantling evaluation, the cargo tank pressure is to be determined based on the full load condition corresponding to the scantling draft.

where

ρ	=	specific weight of ballast or cargo in kgf/m^3
a_{β}	=	dimensionless acceleration (i.e., relative to the acceleration of gravity), resulting from gravitational and dynamic loads, in an arbitrary direction β (see 3/11.3 FIGURE 6).
Z_{β}	=	largest liquid height (m) above the point where the pressure is to be determined, measured from the tank shell in the direction β (see 3/11.3 FIGURE 7).

Tank domes considered to be part of the accepted total tank volume are to be taken into account when determining Z_{β} unless the total volume of tank domes V_{dom} does not exceed the following value:

$$V_{dom} = V_{tank}\left(\frac{100 - FL}{FL}\right)$$

where

V_{tank}	=	tank volume without any domes
FL	=	filling limit according to Section 5C-8-15 of the Rules

The direction which gives the maximum value $(p_{gd})_{max}$ of p_{gd} is to be considered for the scantling requirements of plating and stiffeners of cargo tank boundaries. Where acceleration components in three directions need to be considered, an ellipsoid is to be used instead of the ellipse in 3/11.3 FIGURE 7. The above formula applies only to full tanks.

FIGURE 6
Acceleration Ellipse *(1 June 2017)*

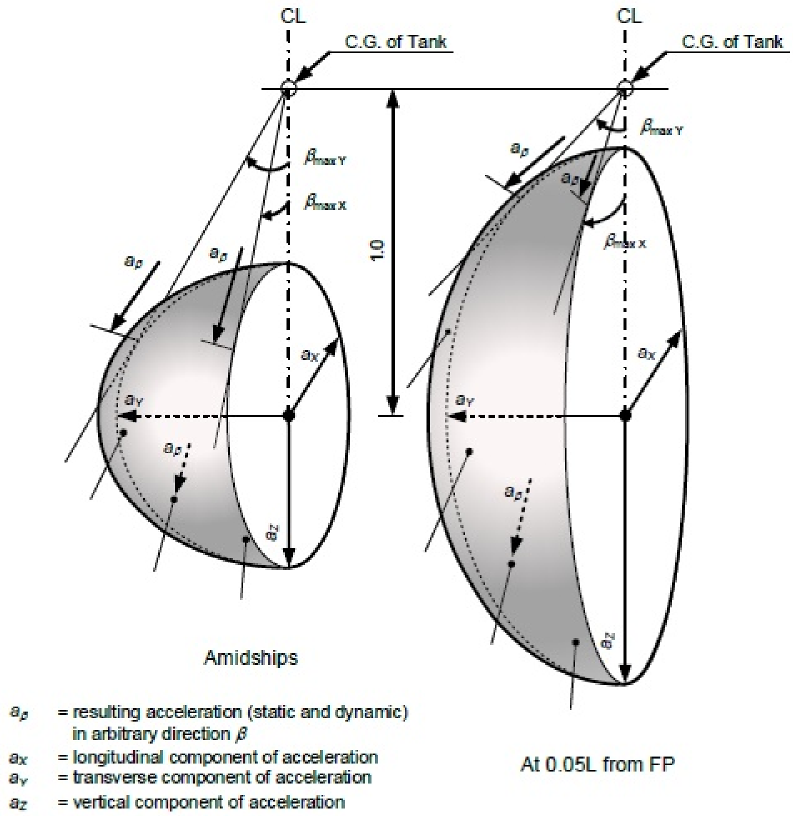
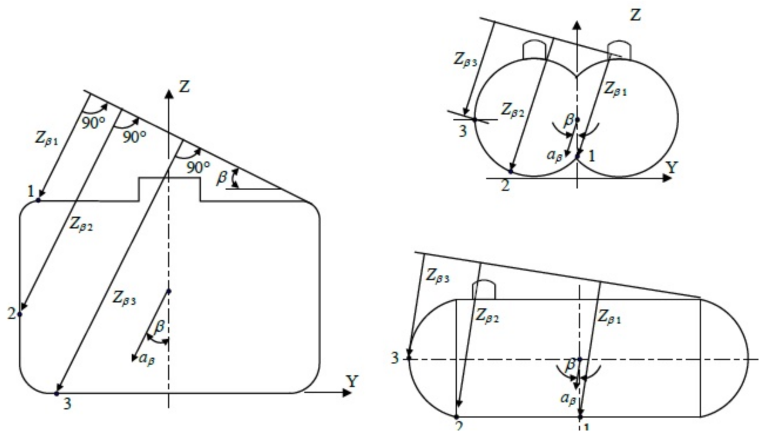


FIGURE 7
Determination of Internal Pressure Heads *(1 June 2017)*



Note: Small tank domes not considered to be part of the accepted total volume of the cargo tank need not be considered when determining Z_β

.

11.5 Internal Pressure Formula for Strength Assessment

For finite element strength assessment, the internal pressure acting on cargo and ballast tanks corresponds to the instantaneous value when one dominant load parameter attains its maximum value. The internal pressure, p_i, positive toward outboard, for a completely filled tank, in kgf/cm², may be obtained from the following formula:

$$p_i = \rho[(k_{cl}a_{le}x_\ell + k_{ct}a_{te}z_\ell + k_{cv}a_{ve}y_\ell) + y_\ell] \times 10^{-4} + p_o$$

where

$k_{c\ell}$ = load combination factor for effective longitudinal acceleration

k_{ct} = load combination factor for effective transverse acceleration

k_{cv} = load combination factor for effective vertical acceleration

ρ = specific weight of ballast or cargo in kgf/m³; for ballast water, 1025 kgf/m³ is to be used.

For a ballast tank, the design vapor pressure p_o is to be taken as the static pressure head corresponding to two thirds of the distance from the top of the tank to the top of the overflow.

11.7 Internal Pressure Due to Fire Incidents *(1 June 2017)*

The cargo containment systems shall sustain without rupture the rise in internal pressure specified in 5C-8-8/4.1 of the Rules under the fire scenarios envisaged therein.

13 Impact Loads

13.1 Impact Loads on Bow

When experimental data or direct calculations are not available, the nominal wave-induced bow pressure in kgf/cm² above the water line (LWL) in the region from the forward end to the collision bulkhead may be obtained from the following equation:

$$p_{bij} = 0.01045C_k\left\{1 + \cos^2\left[\frac{\pi}{2}\left(\frac{F_{bi} - 2a_{ij}}{F_{bi}}\right)\right]\right\}^{1/2}\left(0.515V\sin\alpha_{ij} + L^{1/2}\right)^2\sin\gamma_{ij}$$

where

V = 75% of the design speed, V_d, in knots. V is not to be taken less than 10 knots.

γ_{ij} = local bow angle measured from the horizontal, not to be taken less than 50°

= $\tan^{-1}\left(\tan\beta_{ij}/\cos\alpha_{ij}\right)$

α_{ij} = local waterline angle measured from the centerline, see 3/13.1 FIGURE 8, not to be taken less than 35°

β_{ij} = local body plan angle measure from the horizontal, see 3/13.1 FIGURE 8, not to be taken less than 35°

F_{bi} = freeboard from the highest deck at side to the LWL at station i, see 3/13.1 FIGURE 8

a_{ij} = vertical distance from the LWL to WL_j, see 3/13.1 FIGURE 8

C_k = 0.7 at collision bulkhead and 0.9 at 0.0125L, linear interpolation for in between

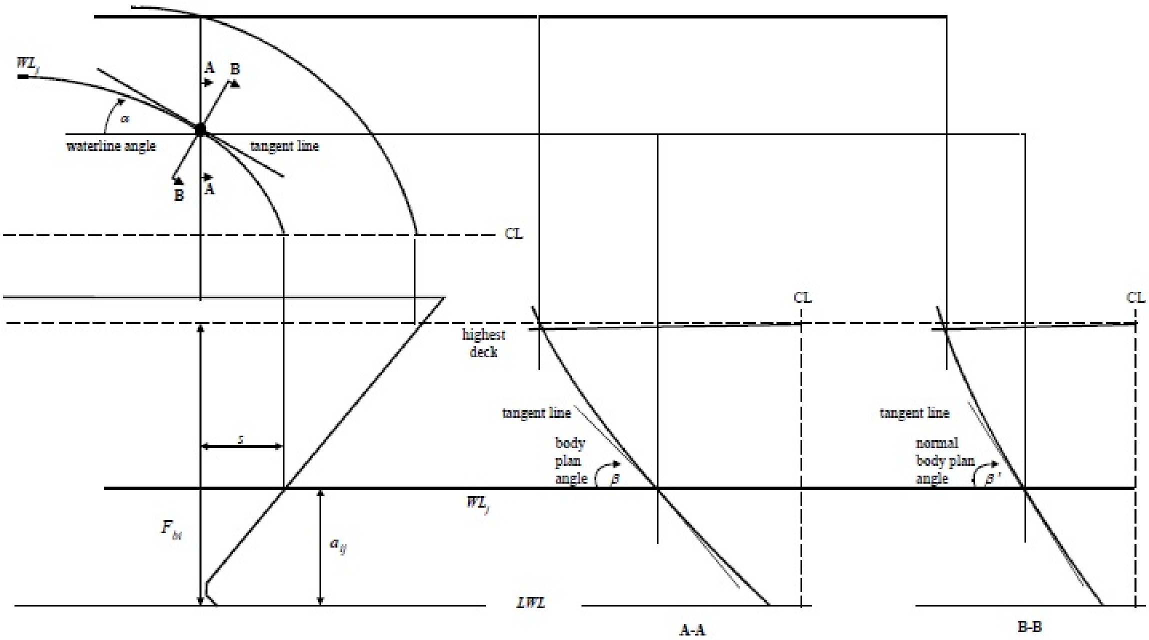
= 0.9 between 0.0125L and the FP

= 1.0 at and forward of the FP

i, j = station and waterline at the pressure calculation point.

To assess the strength of the plating and stiffeners, a load factor of 1.1 is to be applied to the nominal pressure given above. To assess the strength of the main supporting members, a load factor of 0.71 is to be applied to the nominal pressure given above.

FIGURE 8
Definition of Bow Geometry *(1 May 2009)*



13.3 Bottom Slamming Pressure *(1 August 2021)*

For a liquefied gas carrier with the heavy weather ballast draft forward less than 0.04L, bottom slamming pressure is to be considered as per 5C-12-3/13.3 of the *Marine Vessel Rules*.

To assess the strength of the double bottom floors and girders, the nominal pressure uniformly distributed over the flat bottom of the foremost cargo tank may be taken as:

$$p_{nslam} = \left(1.185 \times 10^{-3} L + 0.485\right) \frac{\sum_{i=1}^{N} b_i^* s_i p_{si}}{\sum_{i=1}^{N} b_i^* s_i}$$

where

N = number of floors in the double bottom of the fore cargo tank

p_{si} = bottom slamming pressure at the $i-$th section, in kgf/cm²

p_{nslam} = nominal slamming pressure for double bottom structure, in kgf/cm²

s_i = sum of one half of floor spacings on both sides of the $i-$th floor, in m

b_i^* = half width of flat of bottom at the $i-$th section, in m

To assess the strength of the main supporting members, a load factor of 1.0 is to be applied to the nominal pressure given above.

13.5 Bowflare Slamming *(1 May 2009)*

For vessels possessing bowflare and having a shape parameter A_r greater than 21 m, in the forebody region, bowflare slamming loads are to be considered for assessing the strength of the side plating and the associated stiffening system in the forebody region of the vessel at its scantling draft.

A_r = the maximum value of A_{ri} in the forebody region.

A_{ri} = bowflare shape parameter at a station i forward of the quarter length, up to the FP of the vessel, to be determined between the load waterline (LWL) and the upper deck/forecastle. Bowflare shape parameter A_{ri} is to be calculated for five stations

$$= \left(\frac{\sum_{j=1}^{n} b_j}{\sum_{j=1}^{n} s_j}\right)^2 \sum_{j=1}^{n} b_j\left[1+\left(\frac{s_j}{b_j}\right)^2\right]^{1/2}, j = 1 \ldots \quad n, n \geq 4$$

where

n = number of segments

b_j = local change (increase) in beam for the $j-$th segment at station i (see 3/13.5 FIGURE 9)

s_j = local change (increase) in freeboard up to the highest deck for the $j-$th segment at station i forward (see 3/13.5 FIGURE 9).

When experimental data or direct calculation is not available, the nominal bowflare slamming pressure in kgf/cm^2 may be determined by the following equations:

$P_{ig} = P_{oij}$ or P_{bij} as defined below, whichever is greater

$$P_{oij} = 0.1\left(9M_{ri} - h_{ij}^2\right)^{2/3}$$

$$P_{bij} = 0.01045k_3\left[39.2 + K_{ij}B_iM_{Ri}(1 + E_{ni})\right]$$

where

k_3 = 1 for $h_{ij} \leq h_b^*$

= $1 + \left(h_{ij}/h_b^* - 1\right)^2$ for $h_b^* < h_{ij} < 2h_b^*$

= 2 for $h_{ij} \geq 2h_b^*$

E_{ni} = $8.653 + 0.5\ln \quad B_i - h_{ij}^2/M_{Ri,}$ if $E_{ni} < 0$, $P_{bij} = 0$

M_{Ri} = $0.44A_i(VL/C_b)^{1/2}$

V = 75% of the design speed, V_d, in knots. V is not to be taken less than 10 knots.

C_b = as defined in 3/3.1 and not to be less than 0.6.

h_{ij} = vertical distance measured from the LWL at station i to the waterline WL_j on the bowflare. The value of h_{ij} is not to be taken less than h_b^*.

P_{bij} at a location between LWL and h_b^* above LWL need not be taken greater than p_{bij}^*.

h_b^* = $0.005(L-130)+3.0$ (m) for $L<230$ m

= $7.143\times10^{-3}(L-230)+3.5$ (m) for 230 m $\leq L<300$ m

= 4.0 (m) for $L\geq 300$ m

p_{bij}^* = $p_{bi}^*\sqrt{\beta_i^*/\beta_{ij}'}$

p_{bi}^* = P_{bij} at h_b^* above LWL

K_{ij} = $f_{ij}\left[r_j/\left(bb_{ij}+0.5h_{ij}\right)\right]^{3/2}\left[\ell_{ij}/r_j\right]\left[1.09+0.029V-0.47C_b\right]^2$

r_j = $(M_{Ri})^{1/2}$

bb_{ij} = $b_{ij}-b_{i0}>2.0$ m

b_{ij} = local half beam of WL_j at station i.

b_{i0} = local waterline half beam at station i

ℓ_{ij} = longitudinal distance of WL_j at station $i$measured from amidships.

f_{ij} = $\left[90/\beta_{ij}'-1\right]^2\left[\tan^2\left(\beta_{ij}'\right)/9.86\right]\cos\gamma$

β_{ij}' = normal local body plan angle, See 3/13.1 FIGURE 8

= $\tan^{-1}\left[\tan\left(\beta_{ij}\right)/\cos\left(\alpha_{ij}\right)\right]$

α_{ij} = waterline angle as in 3/13.1 FIGURE 8

β_{ij} = local body plan angle measured from the horizontal, in degrees, as in 3/13.5 FIGURE 9

β_{ij}^* = β_{ij}' at h_b^* above LWL

γ = ship stem angle at the centerline measured from the horizontal, 3/13.5 FIGURE 10, in degrees, not to be taken greater than 75 degrees.

A_i and B_i are as given in 3/13.3 TABLE 3.

For performing structural analyses to determine overall responses of the hull structures, the spatial distribution of instantaneous bowflare slamming pressures on the forebody region of the hull may be expressed by multiplying the calculated maximum bowflare slamming pressures, P_{ij}, at forward ship stations by a factor of 0.71 for the region between the stem and 0.3L from the FP.

FIGURE 9
Definition of Bowflare Geometry for Bowflare Shape Parameter

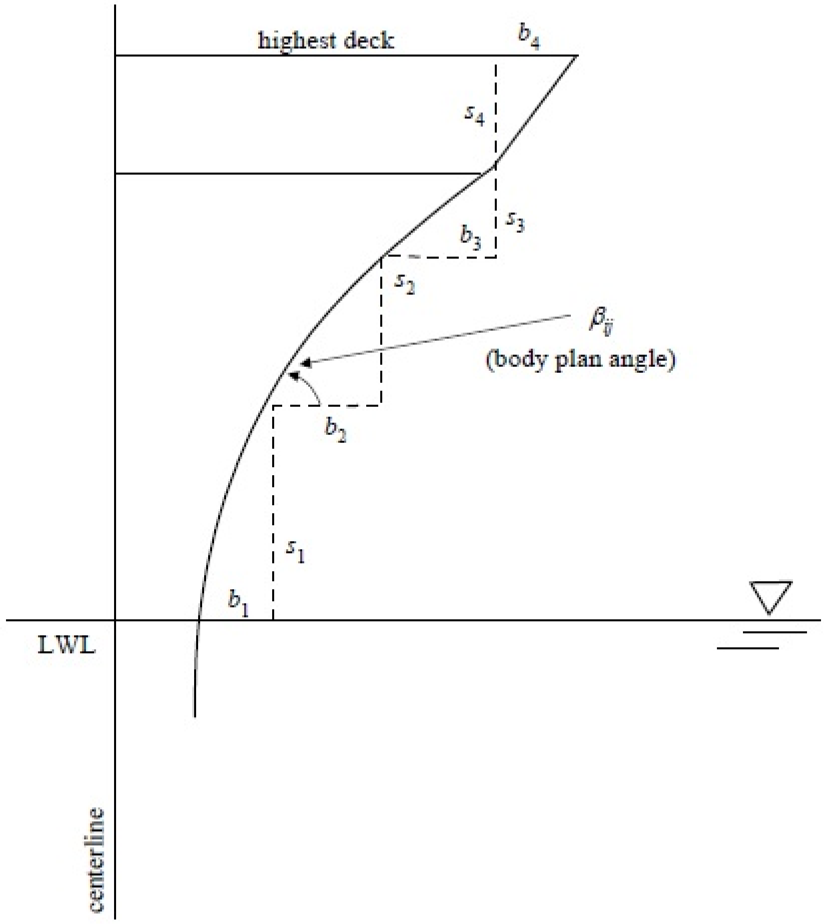
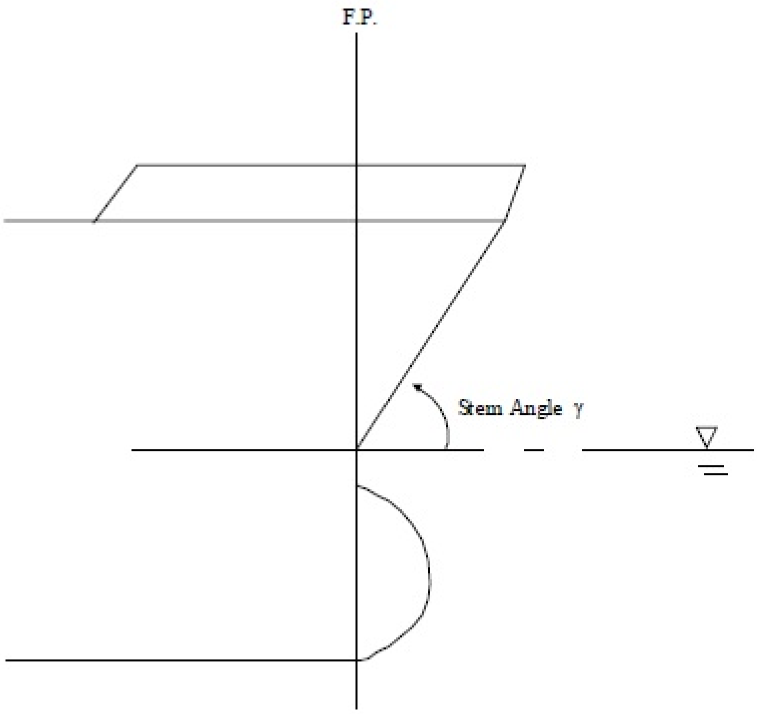


FIGURE 10
Ship Stem Angle, γ



13.7 Green Water

The nominal green water pressure imposed on the deck in the region from the FP to $0.25L$ aft, including the extension beyond the FP, may be calculated at the reference section:

$$p_{gi} = 0.2\left[0.44A_i\left(\frac{VL}{C_b}\right)^{1/2} - F_{bi}\right]^{1/2}, \text{not to be less than } 0.21\ \text{kgf/cm}^2$$

where

V	=	75% of the design speed, V_d, in knots. V is not to be taken less than 10 knots.
F_{bi}	=	freeboard from the highest deck at side to the load waterline (LWL) at station i, see3/13.1 FIGURE 8

A_i is given in 3/13.3 TABLE 3

13.9 Sloshing Loads

Except for tanks that are situated wholly within the double side or double bottom, the natural periods of liquid motions are to be examined to assess the possibility of excessive liquid sloshing against boundary structures for all cargo tanks which will be partially filled between $0.5h_\ell$ (or $0.1h$, if lesser) and $0.9h$ (h_ℓ and h are as defined in 3/13.9 FIGURE 11). For each of the anticipated loading conditions, the "critical" filling levels of the tank are to be avoided so that the natural periods of fluid motions in the longitudinal and transverse directions will not synchronize with the natural periods of the vessel's pitch and roll motions, respectively. The natural periods of the fluid motions in the tank, for each of the anticipated filling levels, are to be at least 20% greater or smaller than that of the relevant ship's motion.

The natural period of the fluid motion may be approximated by the following equations:

$T_x = (\ell)^{1/2}/k$ seconds in the longitudinal direction

$T_y = (b_f)^{1/2}/k$ seconds in the transverse direction

where

ℓ	=	length of the tank, as defined in 3/13.9 FIGURE 11, in m
b_f	=	breadth of the liquid surface at d_o, as defined in 3/13.9 FIGURE 11, in m
k	=	$[(\tanh H_1)/(4\pi/g)]^{1/2}$
H_1	=	$\pi d_o/\ell$ or $\pi d_o/b_f$
d_o	=	filling depth, as defined in 3/13.9 FIGURE 11, in m
g	=	acceleration of gravity = 9.8 m/sec^2

The natural periods given below for pitch and roll of the vessel, T_p and T_r, using the actual draft and GM, if available, may be used for this purpose. In absence of these data, the vessel's draft may be taken as $2/3d_f$.

The pitch natural period:

$T_p = 3.5\sqrt{C_b d_i}$ seconds

where

d_i	=	draft amidships for the relevant loading conditions

The roll natural motion period:

$T_r = 2k_r/GM^{0.5}$ seconds

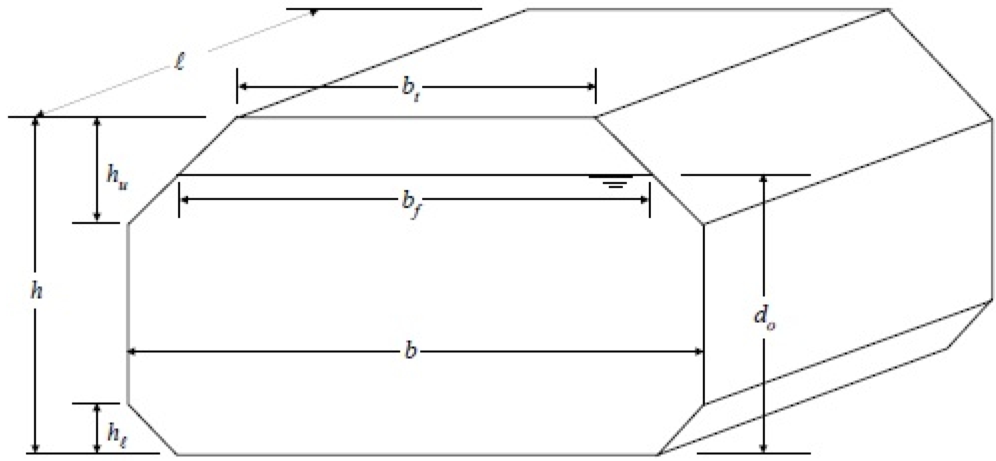
where

k_r	=	roll radius of gyration, in m, and may be taken as $0.35B$ for full load conditions and 0.45 B for ballast conditions.	
GM	=	metacentric height, in m, to be taken as:	
	=	GM(full)	for full draft
	=	$1.5GM$(full)	for $3/4d_f$
	=	2.0 GM(full)	for $2/3d_f$
GM (full)	=	metacentric height for fully loaded condition	
	=	$0.12B$	in case GM (full) is not available.

If the "critical" filling levels of the tank cannot be avoided, the tank is to have a non-tight bulkhead (i.e., swash bulkhead) to eliminate the possibility of resonance. The non-tight bulkhead may be waived if it can be demonstrated through the application of model experiments or numerical simulation using three-dimensional flow analysis that sloshing impacts do not occur.

Alternatively, the tank boundary structures can also be designed to withstand liquid sloshing. The design sloshing pressures are to be explicitly considered in the scantling requirements of cargo tank plating and stiffeners. In addition, additional sloshing load cases are to be included in the structural analysis of the main supporting members of cargo tanks. Sloshing loads may also be determined by model experiments. Methodology and procedures of tests and measurements are to be fully documented and referenced. They are to be submitted for review by ABS.

FIGURE 11
Definition of Tank Geometry



15 Thermal Loads

Transient thermal loads during cooling down periods are to be considered for cargo tanks intended for cargo temperatures below -55°C.

Stationary thermal loads are to be considered for tanks where design supporting arrangement and operating temperature may give rise to significant thermal stresses.

17 Loads Associated with Construction and Installation *(1 June 2017)*

Loads or conditions associated with construction and installation (e.g., lifting) are to be considered.

SECTION 4
Standard Design Load Cases

1 Symbols *(1 June 2017)*

d_f	scantling draft, in m
d_{flood}	draft at the mid-tank for the flooded condition
d_b	ballast draft at the middle of foremost cargo tank, in m
D_f	imaginary freeboard depth, in m
k_{ce}	load combination factor for external pressure
$k_{c\ell}$	load combination factor for effective longitudinal acceleration
k_{cmh}	load combination factor for horizontal wave-induced bending moment
k_{cmv}	load combination factor for vertical wave-induced bending moment
k_{ct}	load combination factor for effective transverse acceleration
k_{cv}	load combination factor for effective vertical acceleration
μ	wave heading angle, to be taken from 0° to 90° (0° for head sea, 90° for beam sea, waves approaching the hull from the starboard side)

3 Standard Design Load Cases for Yielding and Buckling Strength Assessment *(1 May 2009)*

To assess the yielding and buckling strength of hull and cargo tank structures, the standard design load cases described in this Section are to be analyzed. These load cases can be categorized into the following groups:

- Dynamic sea load cases (LC1 ~ LC9 in 4/5 TABLE 1)
- Port condition load case (LC10 in 4/5 TABLE 2)
- Flooded load case for transverse bulkhead (LC11 in 4/5 TABLE 2)
- Accidental load cases for supports and chocks (LC12 ~ LC15 in 4/5 TABLE 2)

For forebody hull and cargo tank structures, a design load case for bottom slamming is also to be considered. Additional load cases may be required, as warranted.

4/5 FIGURE 1 shows the direction of the inertia load due to acceleration. The loading patterns are shown in 4/5 FIGURE 2. For each dynamic sea load case (LC1 to LC9), the load combination factors are specified for individual dynamic load components and motion parameters in 4/5 TABLE 1. The waves approach the vessel from the starboard side. If the hull structure is unsymmetrical with respect to the vessel's centerline, additional load cases mirroring those of the unsymmetrical load cases in 4/5 TABLE 1 are to be analyzed. The dominant load parameter for each dynamic sea load case corresponds to a probability of exceedance of 10^{-8}, while the load combination factors for other load parameters represent phasing between all the load parameters.

The standard load cases in 4/5 TABLE 1 and 4/5 TABLE 2 are specified for the midship finite element model. The cargo tank within 0.4L amidships that experiences higher ship motion is to be targeted for the strength evaluation. For the forebody finite element model, tanks forward of the collision bulkhead may be assumed empty in the standard load cases. Likewise, for the aftbody finite element model, tanks aft the hull transverse bulkhead bordering the aftmost cargo tank may be assumed empty in the standard load cases.

5 Standard Design Load Cases for Fatigue Strength Assessment

To assess the critical details of the hull, cargo tanks and supporting structures, the accumulative fatigue damage may be calculated from the vessel operating in full cargo and ballast loading conditions. For each loading condition, eight dynamic sea load cases are to be analyzed to determine the stresses at critical details. These load cases are specified in 4/5 TABLE 3 and 4/5 TABLE 4. The stress ranges to be used for the accumulative fatigue damage are to be calculated from the following four pairs of the load cases:-

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

The dominant load parameter for each dynamic sea load case corresponds to a probability of exceedance of 10^{-4}, while the load combination factors for other load parameters represent phasing between all the load parameters.

The standard load cases in 4/5 TABLE 3 and 4/5 TABLE 4 are specified for the midship finite element model. For the forebody finite element model, tanks forward of the collision bulkhead may be assumed empty in the standard load cases. Likewise, for the aftbody finite element model, tanks aft the hull transverse bulkhead bordering the aftmost cargo tank may be assumed empty in the standard load cases.

TABLE 1
Standard Design Load Cases for Yielding and Buckling Strength Assessment (Load Combination Factors for Dynamic Load Components) *(1 August 2021)*

	LC 1	*LC 2*	*LC 3*	*LC 4*	*LC 5*	*LC 6*	*LC 7*	*LC 8*	*LC 9*
Dominant Load Parameter	maximum sagging BM	maximum hogging BM	maximum internal pressure	maximum external pressure	maximum transverse acceleration	maximum horizontal BM	maximum horizontal BM	maximum internal pressure	flat bottom slamming
Wave Heading (μ)	0° head	0° head	0° head	0° head	90° beam	60° oblique	60° oblique	0° head	0° head
Draft (d_m)	d_f	d_f	d_f	d_f (note 7)	3/4d_f	3/4d_f	d_f (note 7)	d_b	d_b
External Pressure k_{ce}	-0.50	0.50	-0.50	1.00	1.00	-0.50	1.00	-0.50	N/A

	LC 1	*LC 2*	*LC 3*	*LC 4*	*LC 5*	*LC 6*	*LC 7*	*LC 8*	*LC 9*
Longitudinal Acceleration $k_{c\ell}$	0.00	0.00	0.00	0.60	0.00	-0.40	0.40	0.00	0.00
Vertical Acceleration k_{cv}	0.50	-0.50	1.00	-0.80	-0.60	0.60	-0.60	1.00	-0.50
Transverse Acceleration k_{ct}	N/A	N/A	N/A	N/A	0.80	-0.70	0.70	N/A	N/A
Vertical BM k_{cmv}	1.00 sagging	1.00 hogging	0.70 sagging	0.70 hogging	0.30 hogging	0.30 sagging	0.30 hogging	0.70 sagging	N/A
Horizontal BM k_{cmh}	N/A	N/A	N/A	N/A	0.225 port (+)	0.75 port (-)	1.00 port (+)	N/A	N/A
Frictional Coefficient	N/A	N/A	N/A	N/A	0.10	0.10	N/A	N/A	N/A

Notes:

1 LC 9 is the bottom slamming load case and only applicable to forebody hull and cargo tank structures.

2 port (+) and port (–) represents the port side of the hull structure is in tension and compression, respectively.

3 The frictional coefficient in Section 4, Table 1 for LC5 and LC6 is the representative value for the global finite element model. For the fine mesh finite element models representing individual supports or chocks, the frictional coefficient is to be taken as 0.3. Alternatively, the frictional coefficient may be determined from the measurement. The details of the support bearing materials, measurement procedure and measurement data are to be submitted for ABS review.

4 (1 May 2009) In LC5 and LC6, the load combination factor for horizontal bending moment is adjusted for the lower draft.

5 Liquefied gas carriers in cargo loaded conditions are typically subject to hogging still water bending moments. The minimum hogging still water bending moment of all the cargo loaded conditions is to be applied to LC 1, 3 and 6. However, the total bending moment used for these load cases are not to be less than 80% of the design sagging wave bending moment. If liquefied gas carriers in cargo loaded conditions are subject to sagging still water bending moments, the maximum sagging still water bending moment of all the cargo loaded conditions is to be applied to LC 1, 3 and 6.

6 *(1 June 2017*) In LC7, the coefficient of external pressure may be taken as 0.50 for forebody hull and cargo tank structures.

7 For LC4 and LC7, the maximum draft corresponding to actual loading condition where the target cargo tank is empty while the adjacent cargo tank(s) are full may be used instead of scantling draft d_f, if there is an operational restriction corresponding to the analyzed condition clearly stated in the loading manual.

TABLE 2
Standard Design Load Cases for Yielding and Buckling Strength Assessment *(1 May 2009)* (Load Combination Factors for Port and Accidental Load Cases)

	LC 10	*LC 11*	*LC 12*	*LC 13*	*LC 14*	*LC 15*
Dominant Load Parameter	port condition one side loaded	flooded condition (transverse bulkhead)	flooded condition (anti-float chocks)	collision condition (forward)	collision condition (afterward)	30° static heel
Draft (d_m)	$1/2d_f$	d_{flood} or *0.8* D_f	d_f	*N/A*	N/A	d_f
Friction Coefficient	N/A	N/A	0.10	0.10	0.10	0.10

	LC 10	*LC 11*	*LC 12*	*LC 13*	*LC 14*	*LC 15*
Longitudinal Inertia Load	N/A	N/A	N/A	0.50g	–0.25g	N/A
Vertical Inertia Load	1.00g	N/A	1.00g	1.00g	1.00g	0.87g
Transverse Inertia Load	N/A	N/A	N/A	N/A	N/A	0.50g
Vertical Still Water BM	N/A	N/A	N/A	N/A	N/A	N/A

Notes:

1 The frictional coefficient in 4/5 TABLE 2 for LC12 and LC15 is the representative value for the global finite element model. For the fine mesh finite element models representing individual supports or chocks, the frictional coefficient is to be taken as 0.3. Alternatively, the frictional coefficient may be determined from the measurement. The details of the support bearing materials, measurement procedure and measurement data are to be submitted for ABS review.

2 For LC10, account is to be taken of an increase of vapor pressure in port condition. This load case may be omitted, if the piping systems are designed to ensure that the cargoes on both sides of the centerline bulkhead can be loaded or discharged at the same rate.

TABLE 3
Standard Design Load Cases for Fatigue Strength Assessment *(1 May 2009)* (Load Combination Factors for Dynamic Load Components for Full Cargo Loading Condition)

Load Case Pair	*LC1 & LC 2*		*LC 3 & LC 4*		*LC 5 & LC 6*		*LC 7 & LC 8*	
Wave Heading (μ)	0° head		0° head		90° beam		60° oblique	
Local Pressure Load Case	*LC 1*	*LC 2*	*LC 3*	*LC 4*	*LC 5*	*LC 6*	*LC 7*	*LC 8*
Draft (d_m)	d_f	d_f	d_f	d_f	d_f	d_f	d_f	d_f
External Pressure k_{ce}	-0.50	0.50	-1.00	1.00	-1.00	1.00	-1.00	1.00
Longitudinal Acceleration $k_{c\ell}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Acceleration k_{cv}	0.50	-0.50	1.00	-1.00	0.40	-0.40	0.20	-0.20
Transverse Acceleration k_{ct}	N/A	N/A	N/A	N/A	-0.70	0.70	-0.40	0.40
Vertical BM Load Case	100% Rule Vertical BM Range		50% Rule Vertical BM Range		20% Rule Vertical BM Range		30% Rule Vertical BM Range	
Horizontal BM Load Case	N/A		N/A		30% Rule Horizontal BM Range		50% Rule Horizontal BM Range	

Notes:

1 Rule vertical bending moment range = $|M_{ws} - M_{wh}|$ (see 3/5 for M_{ws} and M_{wh})

2 Rule horizontal bending moment range = $2 \times M_h$ (see 3/7 for M_h)

3 For each load case pair, the stress range due to local pressure is the difference between the stress values for Local Pressure Load Cases. For example, for Load Case Pair LC1 & LC2, the stress range due to local pressure is the difference between the stress values for LC1 and LC2.

4 For each load case pair, the stress range is the sum of the absolute stress range values due to Vertical BM, Horizontal BM and Local Pressure Load Cases.

5 To account for the mean stress effect on the fatigue damage, the mean stress level can be determined using the static loads for the loading condition.

6 For the global finite element model, the frictional coefficient need not be considered. For the fine mesh finite element models representing supports or chocks, the frictional coefficient is to be taken as 0.3. Alternatively, the frictional coefficient may be taken from the measurement. The details of the support bearing materials, measurement procedure and measurement data are to be submitted for ABS review.

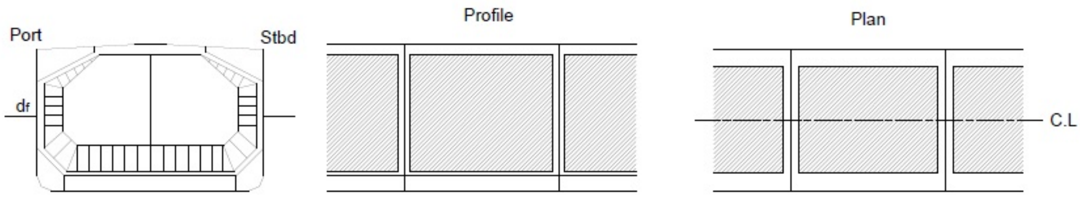


TABLE 4
Standard Design Load Cases for Fatigue Strength Assessment *(1 May 2009)* (Load Combination Factors for Dynamic Load Components for Ballast Loading Condition)

Load Case Pair	*LC1 & LC 2*		*LC 3 & LC 4*		*LC 5 & LC 6*		*LC 7 & LC 8*	
Wave Heading (μ)	0° head		0° head		90° beam		60° oblique	
Local Pressure Load Case	*LC 1*	*LC 2*	*LC 3*	*LC 4*	*LC 5*	*LC 6*	*LC 7*	*LC 8*
Draft (d_m)	d_b	d_b	d_b	d_b	d_b	d_b	d_b	d_b
External Pressure k_{ce}	-0.50	0.50	-1.00	1.00	-1.00	1.00	-1.00	1.00
Longitudinal Acceleration $k_{c\ell}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Acceleration k_{cv}	0.50	-0.50	1.00	-1.00	0.40	-0.40	0.20	-0.20
Transverse Acceleration k_{ct}	N/A	N/A	N/A	N/A	-0.70	0.70	-0.40	0.40
Vertical BM Load Case	100% Rule Vertical BM Range		50% Rule Vertical BM Range		20% Rule Vertical BM Range		30% Rule Vertical BM Range	
Horizontal BM Load Case	N/A		N/A		30% x d_b/d_f Rule Horizontal BM Range		50% x d_b/d_f Rule Horizontal BM Range	

Notes:

1 Rule vertical bending moment range = $|M_{ws} - M_{wh}|$ (see 3/5 for M_{ws} and M_{wh})

2 Rule horizontal bending moment range = $2xM_h$ (see 3/7 for M_h)

3 For each load case pair, the stress range due to local pressure is the difference between the stress values for Local Pressure Load Cases. For example, for Load Case Pair *LC1 & LC2*, the stress range due to local pressure is the difference between the stress values for *LC1* and *LC2*.

4 For each load case pair, the stress range is the sum of the absolute stress range values due to Vertical BM, Horizontal BM and Local Pressure Load Cases.

5 To account for the mean stress effect on the fatigue damage, the mean stress level can be determined using the static loads for the loading condition.

6 For the global finite element model, the frictional coefficient need not be considered. For the fine mesh finite element models representing supports or chocks, the frictional coefficient is to be taken as 0.3. Alternatively, the frictional coefficient may be taken from the measurement. The details of the support bearing materials, measurement procedure and measurement data are to be submitted for ABS review.

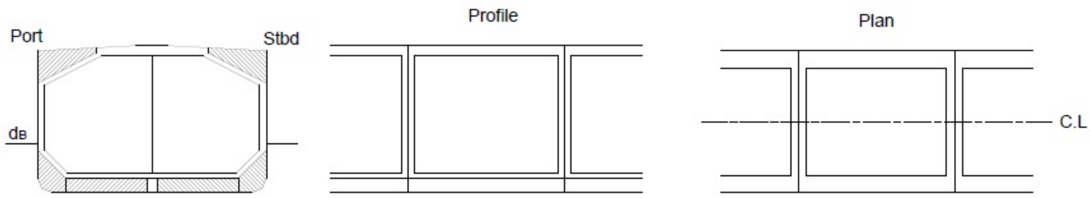


FIGURE 1
Direction of Internal Pressure due to Acceleration

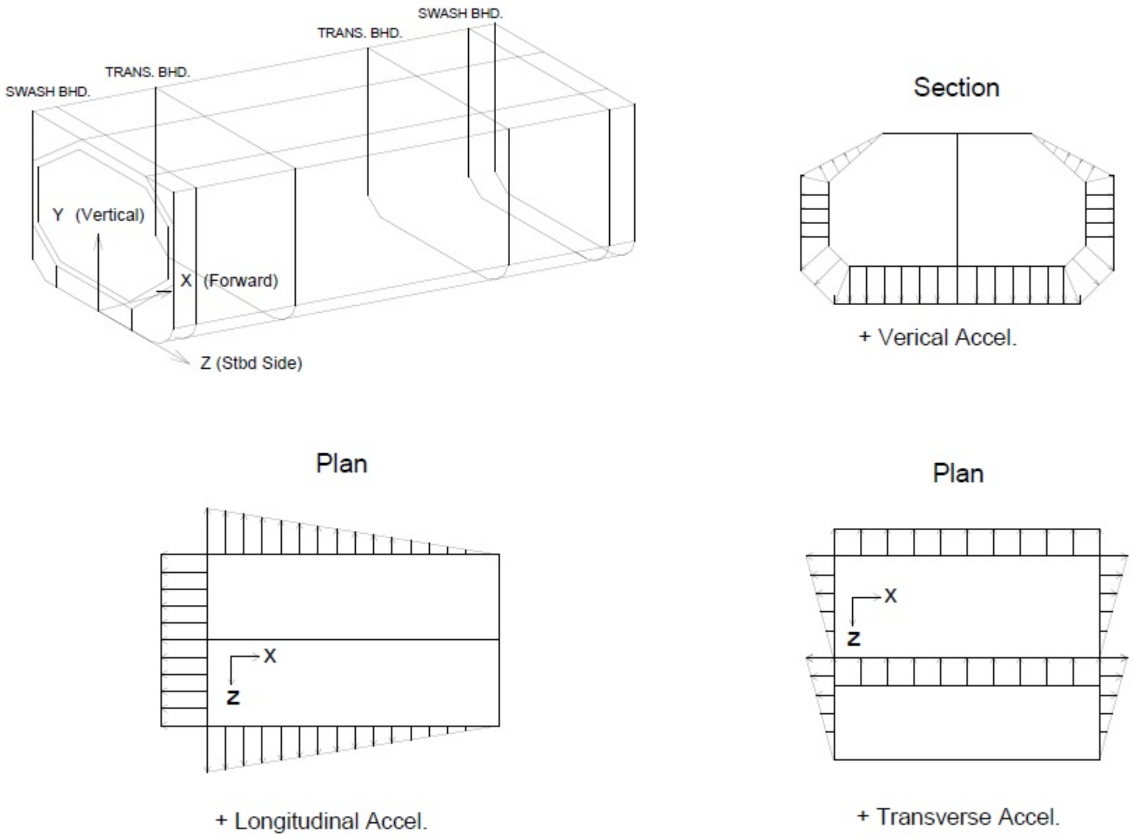
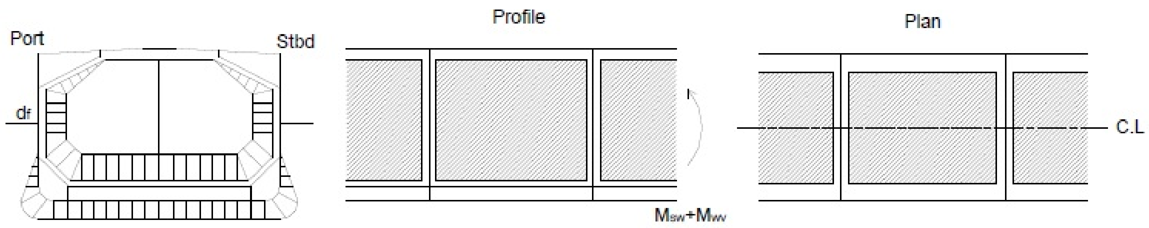


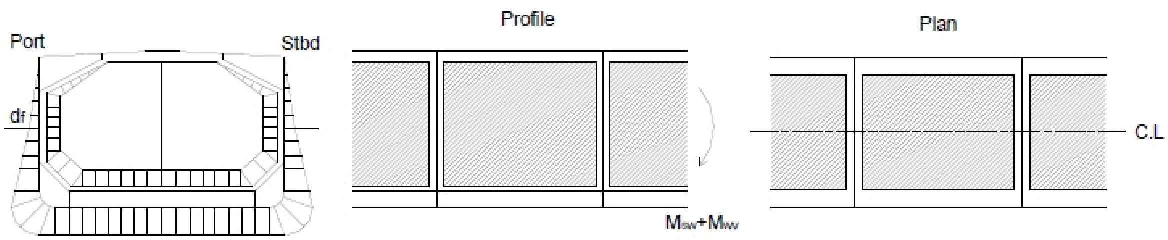
FIGURE 2
Loading Pattern (Yielding and Buckling Strength Assessment) *(1 August 2021)*

Load Case	*1*
Dominant Load Parameter	maximum sagging BM
Wave Heading (μ)	0° head
Draft (d_m)	d_f
External Pressure k_{ce}	-0.50
Longitudinal Acceleration $k_{c\ell}$	0.00
Vertical Acceleration k_{cv}	0.50
Transverse Acceleration k_{ct}	N/A
Vertical BM k_{cmv}	1.00 sagging

Load Case	*1*
Horizontal BM k_{cmh}	N/A
Friction Coefficient	N/A

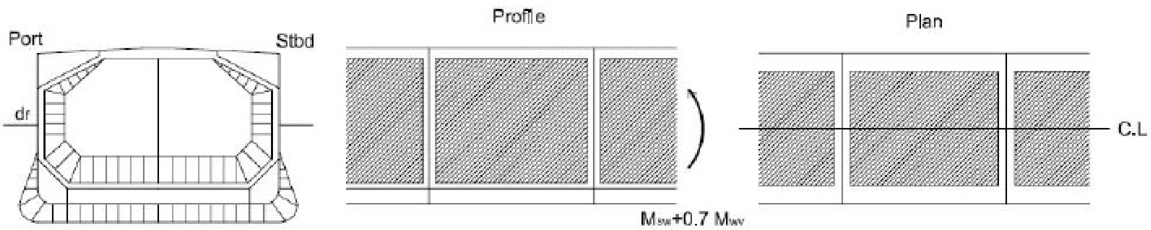


Load Case	*2*
Dominant Load Parameter	maximum hogging BM
Wave Heading (μ)	0° head
Draft (d_m)	d_f
External Pressure k_{ce}	0.50
Longitudinal Acceleration $k_{c\ell}$	0.00
Vertical Acceleration k_{cv}	-0.50
Transverse Acceleration k_{ct}	N/A
Vertical BM k_{cmv}	1.00 hogging
Horizontal BM k_{cmh}	N/A
Friction Coefficient	N/A

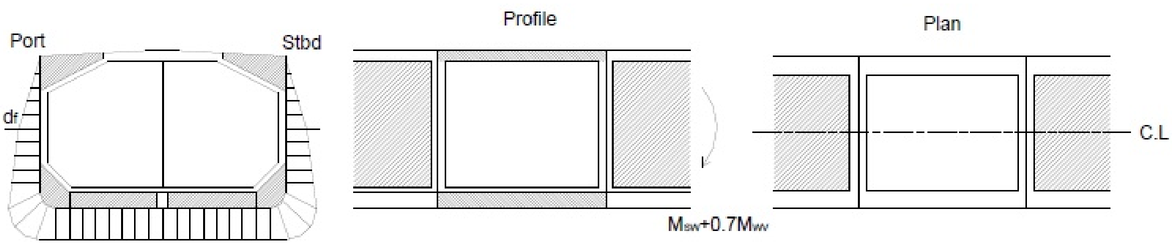


Load Case	*3*
Dominant Load Parameter	maximum internal pressure
Wave Heading (μ)	0° head
Draft (d_m)	d_f
External Pressure k_{ce}	-0.50
Longitudinal Acceleration $k_{c\ell}$	0.00
Vertical Acceleration k_{cv}	1.00

Load Case	*3*
Transverse Acceleration k_{ct}	N/A
Vertical BM k_{cmv}	0.70 sagging
Horizontal BM k_{cmh}	N/A
Friction Coefficient	N/A

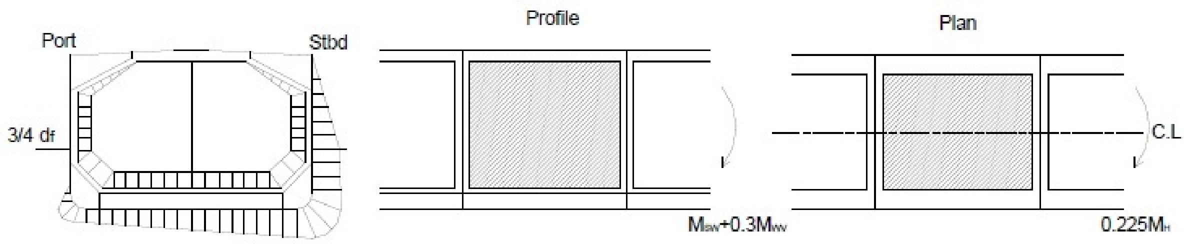


Load Case	*4*
Dominant Load Parameter	maximum external pressure
Wave Heading (μ)	0° head
Draft (d_m)	d_f (note 7)
External Pressure k_{ce}	1.00
Longitudinal Acceleration $k_{c\ell}$	0.60
Vertical Acceleration k_{cv}	-0.80
Transverse Acceleration k_{ct}	N/A
Vertical BM k_{cmv}	0.70 hogging
Horizontal BM k_{cmh}	N/A
Friction Coefficient	N/A

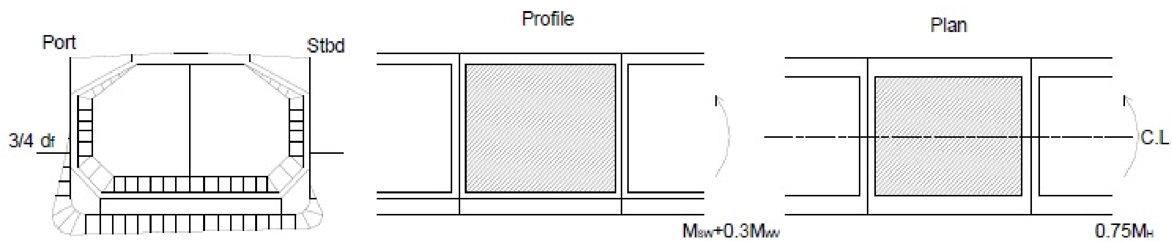


Load Case	*5*
Dominant Load Parameter	maximum transverse acceleration
Wave Heading (μ)	90° beam
Draft (d_m)	$3/4d_f$
External Pressure k_{ce}	1.00

Load Case	*5*
Longitudinal Acceleration $k_{c\ell}$	0.00
Vertical Acceleration k_{cv}	-0.60
Transverse Acceleration k_{ct}	0.80
Vertical BM k_{cmv}	0.30 hogging
Horizontal BM k_{cmh}	0.225 port (+)
Friction Coefficient	0.10

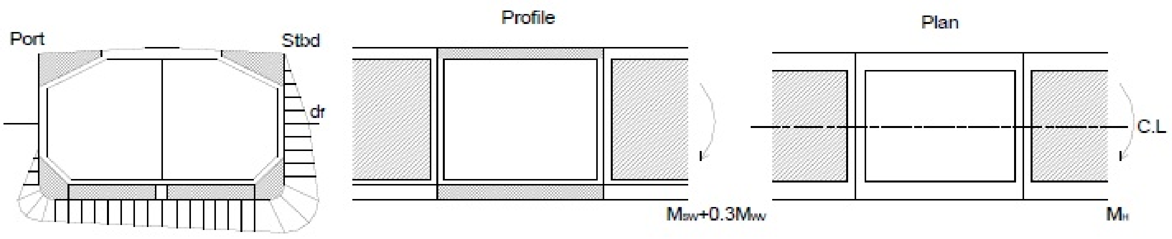


Load Case	*6*
Dominant Load Parameter	maximum horizontal BM
Wave Heading (μ)	60° oblique
Draft (d_m)	$3/4d_f$
External Pressure k_{ce}	-0.50
Longitudinal Acceleration $k_{c\ell}$	-0.40
Vertical Acceleration k_{cv}	0.60
Transverse Acceleration k_{ct}	-0.70
Vertical BM k_{cmv}	0.30 sagging
Horizontal BM k_{cmh}	0.75 port (-)
Friction Coefficient	0.10

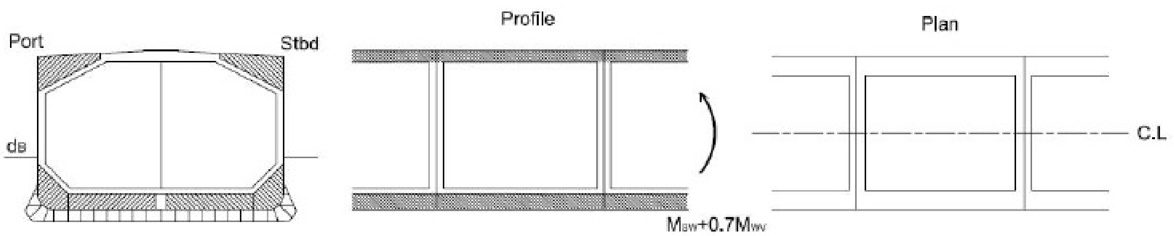


Load Case	*7*
Dominant Load Parameter	maximum horizontal BM
Wave Heading (μ)	60° oblique

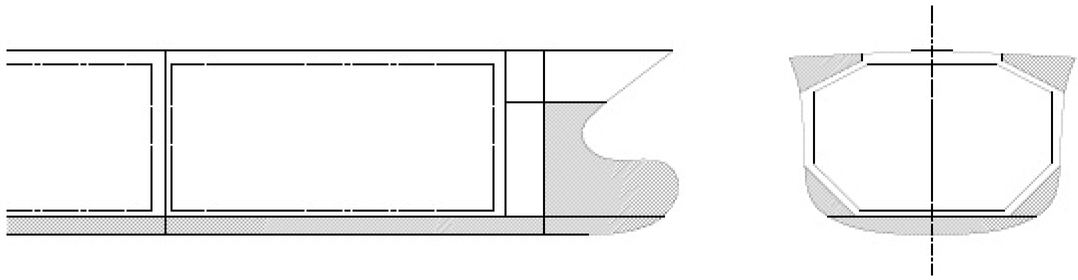
Load Case	*7*
Draft (d_m)	d_f (note 7)
External Pressure k_{ce}	1.00
Longitudinal Acceleration $k_{c\ell}$	0.40
Vertical Acceleration k_{cv}	-0.60
Transverse Acceleration k_{ct}	0.70
Vertical BM k_{cmv}	0.30 hogging
Horizontal BM k_{cmh}	1.00 port (+)
Friction Coefficient	N/A



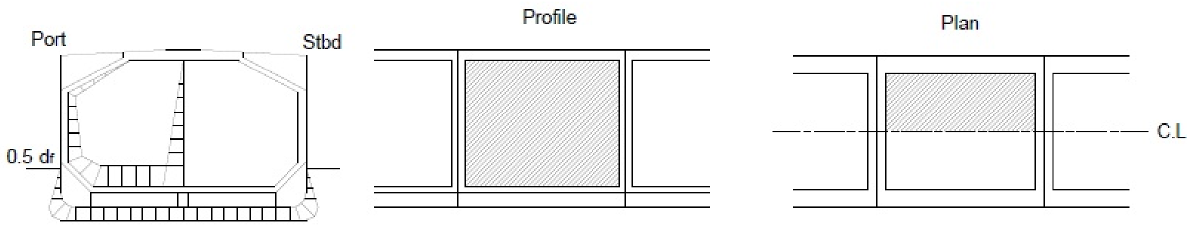
Load Case	*8*
Dominant Load Parameter	maximum internal pressure
Wave Heading (μ)	0° head
Draft (d_m)	d_b
External Pressure k_{ce}	-0.50
Longitudinal Acceleration $k_{c\ell}$	0.00
Vertical Acceleration k_{cv}	1.00
Transverse Acceleration k_{ct}	N/A
Vertical BM k_{cmv}	0.70 sagging
Horizontal BM k_{cmh}	N/A
Friction Coefficient	N/A



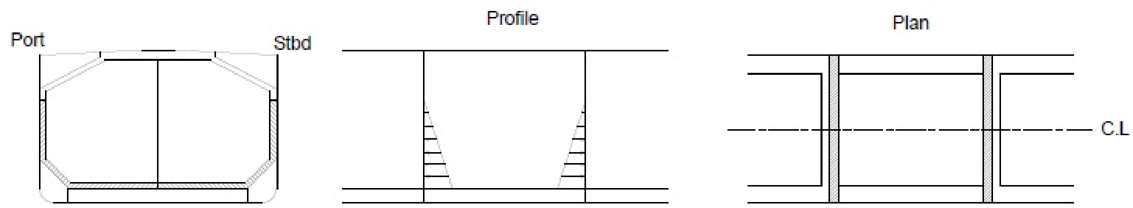
Load Case	*9*
Dominant Load Parameter	flat bottom slamming
Wave Heading (μ)	0° head
Draft (d_m)	d_b
External Pressure k_{ce}	N/A
Longitudinal Acceleration $k_{c\ell}$	0.00
Vertical Acceleration k_{cv}	-0.50
Transverse Acceleration k_{ct}	N/A
Vertical BM k_{cmv}	N/A
Horizontal BM k_{cmh}	N/A
Friction Coefficient	N/A



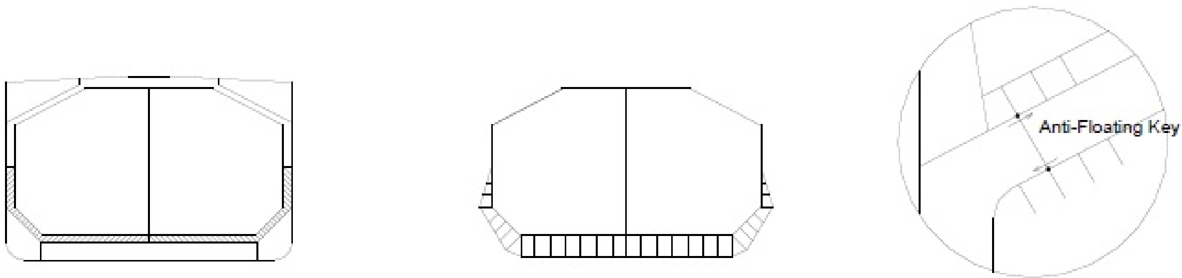
Load Case	*10*
Dominant Load Parameter	port condition one side loaded
Draft (d_m)	$1/2d_f$
Friction Coefficient	N/A
Longitudinal Inertia Load	N/A
Vertical Inertia Load	$1.00g$ (static)
Transverse Inertia Load	N/A
Vertical Still Water BM	N/A



Load Case	*11*
Dominant Load Parameter	flooded condition (transverse bulkhead)
Draft (d_m)	d_{flood} or $0.8D_f$
Friction Coefficient	N/A
Longitudinal Inertia Load	N/A
Vertical Inertia Load	N/A
Transverse Inertia Load	N/A
Vertical Still Water BM	N/A

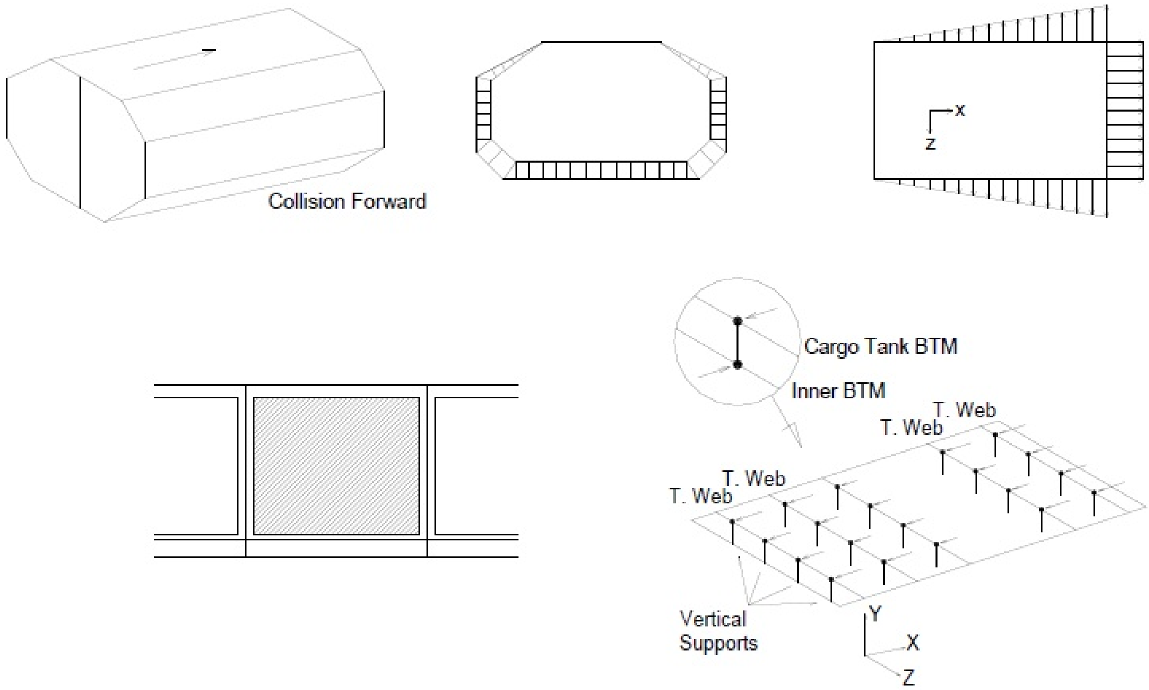


Load Case	*12*
Dominant Load Parameter	flooded condition (anti-float chocks)
Draft (d_m)	d_f
Friction Coefficient	0.10
Longitudinal Inertia Load	N/A
Vertical Inertia Load	1.00g (static)
Transverse Inertia Load	N/A
Vertical Still Water BM	N/A

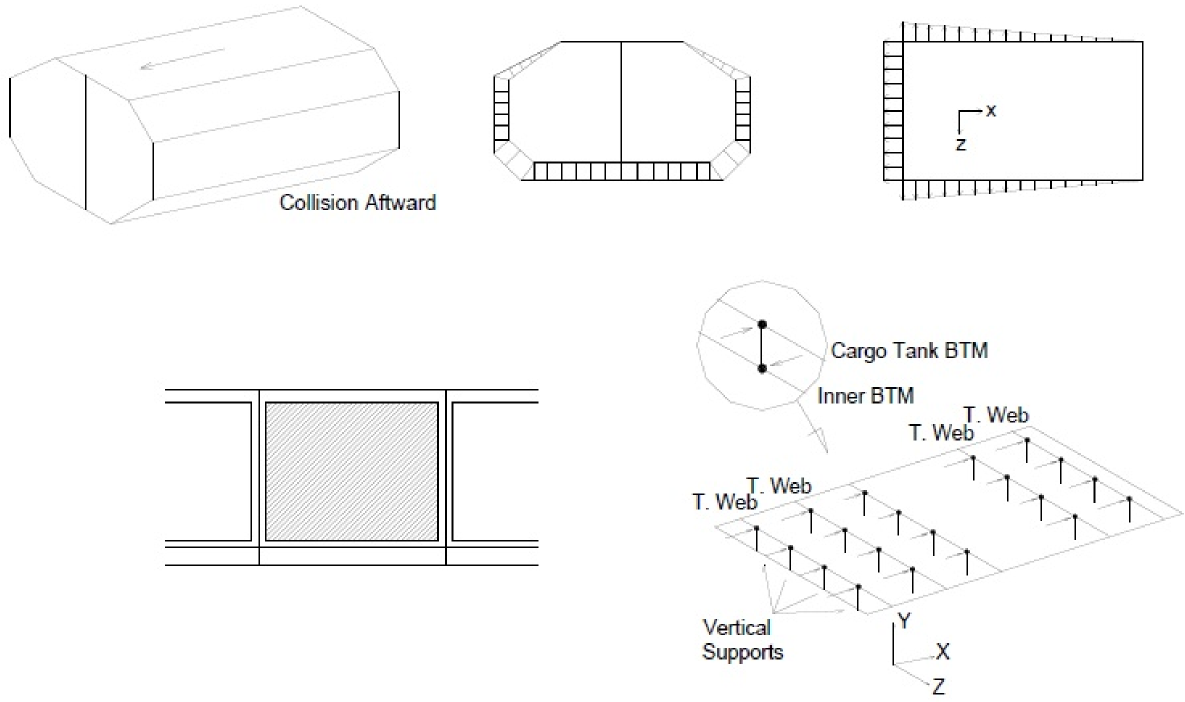


Load Case	*13*
Dominant Load Parameter	collision condition (forward)
Draft (d_m)	*N/A*
Friction Coefficient	0.10
Longitudinal Inertia Load	0.50g (forward)

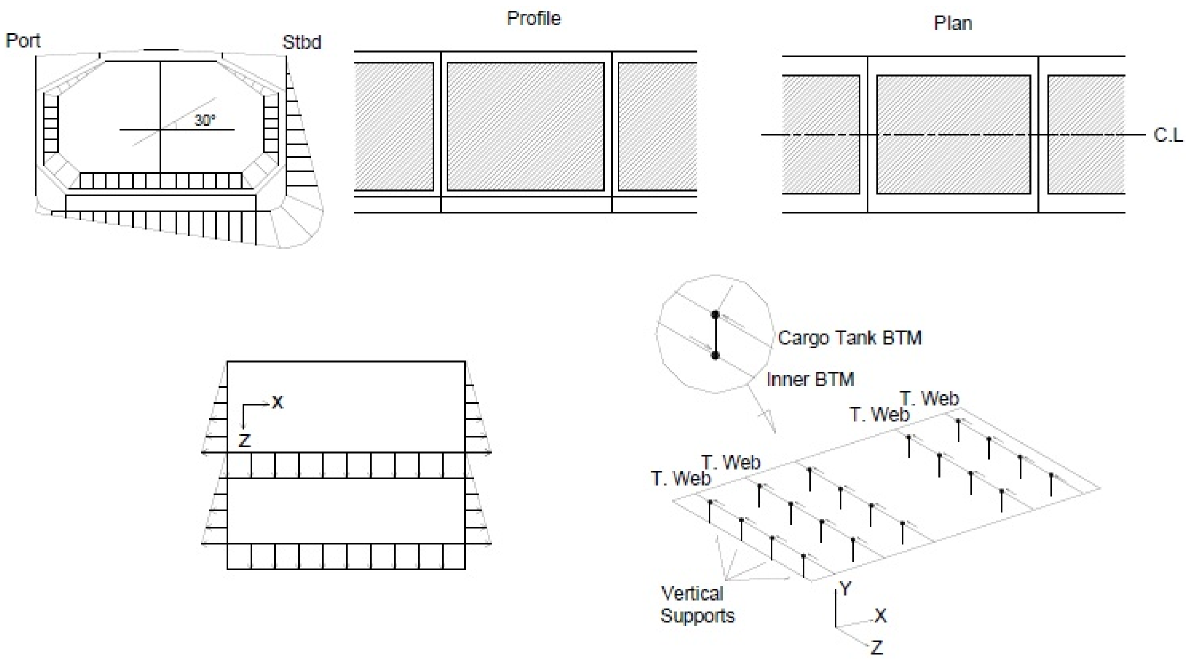
Load Case	*13*
Vertical Inertia Load	1.00g (static)
Transverse Inertia Load	N/A
Vertical Still Water BM	N/A



Load Case	*14*
Dominant Load Parameter	collision condition (aftward)
Draft (d_m)	N/A
Friction Coefficient	0.10
Longitudinal Inertia Load	–0.25g (aftward)
Vertical Inertia Load	1.00g (static)
Transverse Inertia Load	N/A
Vertical Still Water BM	N/A



Load Case	*15*
Dominant Load Parameter	30° static heel
Draft (d_m)	d_f
Friction Coefficient	0.10
Longitudinal Inertia Load	N/A
Vertical Inertia Load	$0.87g$
Transverse Inertia Load	$0.50g$
Vertical Still Water BM	N/A


Port
Stbd
30°
Profile
Plan
C.L
X
Z
Cargo Tank BTM
Inner BTM
T. Web
T. Web
T. Web
T. Web
Vertical Supports
Y
X
Z

SECTION 5
Initial Scantling Criteria

1 General

1.1 Strength Requirements

This section specifies the minimum scantling requirements for the hull and cargo tank structures. These minimum scantlings are to be further evaluated in accordance with the strength criteria in Section 6. The assessment is to be carried out by means of an appropriate structural analysis as described in Appendix A1.

1.3 Structural Details

The requirements specified in this Section and Section 6 are based on assumptions that all structural joints and welded details are properly designed and fabricated, and are compatible with the anticipated working stress levels at the locations considered. It is critical to closely examine the loading patterns, stress concentrations and potential failure modes of structural joints and details during the design of highly stressed regions.

1.5 Evaluation of Grouped Stiffeners

Where several members in a group with some variation in requirement are selected as equal, the section modulus requirement may be taken as the average of each individual requirement in the group. However, the section modulus requirement for the group is not to be taken less than 90% of the largest section modulus required for individual stiffeners within the group. Sequentially positioned stiffeners of equal scantlings may be considered a group.

3 Hull Girder Strength

3.1 Hull Girder Section Modulus

3.1.1 Hull Girder Section Modulus Amidships

The required hull girder section modulus is to be calculated in accordance with 3-2-1/3.7.1, 3-2-1/5, 3-2-1/9 and 3-2-1/17 of the Rules.

3.1.2 Extent of Midship Scantlings

The items included in the hull girder section modulus amidships are to be extended as necessary to meet the hull girder section modulus required at the location being considered. The required hull girder section modulus can be obtained as M_t/f_p at the location being considered except if $(M_t)_{max}/f_p$ is less than SM_{min} in 3-2-1/3.7.1(b) of the Rules. In this case, the required section modulus is to be obtained by multiplying SM_{min} by the ratio of $M_{ti}/(M_t)_{max}$ where M_{ti} is the total bending moment at the location under consideration and $(M_t)_{max}$ is the maximum total bending moment amidships.

3.3 Hull Girder Moment of Inertia

The hull girder moment of inertia is to be not less than required by 3-2-1/3.7.2 of the Rules.

5 Shearing Strength

The shearing strength of the hull structure is to be calculated in accordance with 3-2-1/3.9, 3-2-1/5 and 3-2-1/17 of the Rules.

7 Hull Structures

7.1 Hull Structures in Way of Cargo Tanks

The hull structure in way of cargo tanks, foundations, chocks, keys and sway braces is to be of sufficient strength when subjected to design loadings.

7.3 Bottom Shell Plating and Stiffeners

7.3.1 Bottom Shell Plating and Stiffeners within 0.4L Amidships

7.3.1(a) Bottom Shell Plating. *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-2/1 "General"
- 3-2-2/3.15 "Bottom Shell Plating Amidships"
- 3-2-2/3.17 "Flat Plate Keel"
- 3-2-2/3.15.2 "Minimum Thickness"

Notes:

1 Minimum thickness amidships

2 The bottom shell plating thickness as required in 3-2-2/3.15 and 3-2-2/3.15.2 is to be reduced by 0.5 mm (0.02 in.).

- 3-2-2/5.1 "Minimum Shell Plating Thickness"

Notes:

1 Minimum thickness for all shell plating

2 The bottom shell plating thickness as required in 3-2-2/5.1 is to be reduced by 0.5 mm (0.02 in.).

- 3-2-2/7 "Bottom Shell Plating for Special Docking Arrangement"
- 3-2-2/13 "Bilge Keels"
- 3-2-2/9 "Compensations"
- 3-2-2/15 "Higher-strength Materials" (factor C is to be changed to 3.8 mm (0.15 in.))

7.3.1(b) Bottom Shell Stiffeners. *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-4/1.2 "General"
- 3-2-4/11.1 "General"
- 3-2-4/11.3 "Bottom Longitudinals"
- 3-2-4/17 "Higher-strength Materials"
- 3-2-5/3.17 "Longitudinal Frames"

Notes:

1 Minimum requirements for bottom longitudinals

2 The section modulus of the bottom shell stiffeners as required in 3-2-4/11.3 and 3-2-5/3.17 are to be multiplied by a factor of 0.94.

7.3.2 Bottom Shell Plating and Stiffeners beyond 0.4L Amidships

7.3.2(a) Bottom Shell Plating. *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-2/1 "General"
- 3-2-2/5.1 "Minimum Shell Plating Thickness"
- 3-2-2/5.3 "Immersed Bow Plating"
- 3-2-2/9 "Compensations"
- 3-2-2/7 "Bottom Shell Plating for Special Docking Arrangement"
- 3-2-2/15 "Higher-strength Materials (factor *C* is to be changed to 3.8 mm (0.15 in.))

Note: The bottom shell plating as required in 3-2-2/5.1 and 3-2-2/5.3 is to be reduced by 0.5 mm (0.02 in.).

7.3.2(b) Bottom Shell Stiffeners. *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-4/1.2 "General"
- 3-2-4/11.1 "General"
- 3-2-4/7.3 "Frames & Reverse Frames"

Notes:

1 Applicable to bottom transverse frames

2 The section modulus of the bottom shell stiffeners as required in 3-2-4/7.3 is to be multiplied by a factor of 0.94.

- 3-2-4/17 "Higher-strength Materials
- 3-2-5/3.17 "Longitudinal Frames"

Notes:

1 Minimum requirements for bottom longitudinals

2 The section modulus of the bottom shell stiffeners as required in 3-2-5/3.17 is to be multiplied by a factor of 0.94.

7.5 Side Shell Plating and Stiffeners

7.5.1 Side Shell Plating and Stiffeners within 0.4L Amidships

7.5.1(a) Side Shell Plating. *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-2/1 "General"
- 3-2-2/3.9 "Side Shell Plating"
- 3-2-2/3.13 "Sheerstrake"
- 3-2-2/5.1 "Minimum Shell Plating Thickness"
- 3-2-2/9 "Compensations"
- 3-2-2/13 "Bilge Keels"
- 3-2-2/15 "Higher-strength Materials" (factor *C* is to be changed to 3.8 mm (0.15 in.))

Note: The side shell plating thickness as required in 3-2-2/3.9 and 3-2-2/5.1 is to be reduced by 0.5 mm (0.02 in.).

7.5.1(b) Side Shell Longitudinals. (1 August 2021)

The requirements in the following sections of the Rules are to be complied with:

- 3-2-5/1 "General"
- 3-2-5/3.17 "Longitudinal Frames"
- 3-2-4/17 "Higher-strength Materials"

Note: The section modulus of the side shell longitudinals as required in 3-2-5/3.17 is to be multiplied by a factor of 0.94.

7.5.1(c) Side Frames (1 May 2009).

For a liquefied gas carrier having topside tanks and bottom wing tanks, the section modulus *SM* in cm^3, is not to be less than that obtained from the following equation:

$$SM = 2.7s\left[h + C_1\left(1.09 - 0.65\frac{h}{d}\right)\right]\ell^2 Q$$

where

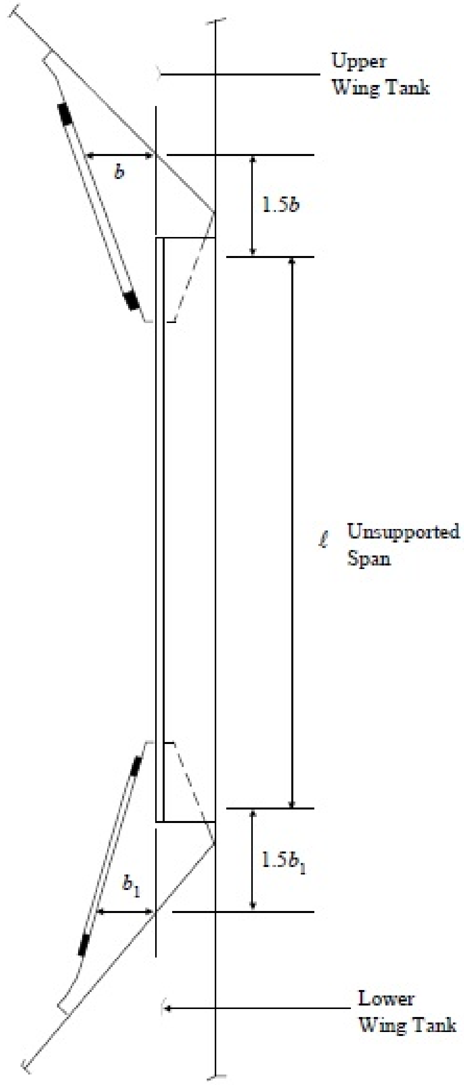
s	=	frame spacing, in m
ℓ	=	unsupported span of frames, in m, as indicated in 5/7.5.1(c) FIGURE 1
h	=	vertical distance, in m, from the middle of ℓ to the load line
d	=	molded draft, in m
C_1	=	as defined in 3-2-1/3.5.1 of the Rules
Q	=	as defined in 3-2-1/5.5 of the Rules

The web depth to thickness ratio is to comply with the requirements of 3-1-2/13.5 of the Rules.

The ratio of outstanding flange breadth to thickness is not to exceed $10/\sqrt{Q}$.

Brackets are to be fitted in the lower and upper wing tanks in line with every side frame. These brackets are to be stiffened against buckling.

FIGURE 1
Unsupported Span of Side Frame



7.5.2 Side Shell Plating and Stiffeners beyond 0.4L Amidships

7.5.2(a) Side Shell Plating. *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-2/1 “Application”
- 3-2-2/5.1 “Minimum Shell Plating Thickness”
- 3-2-2/5.3 “Immersed Bow Plating”
- 3-2-2/5.7 “Forecastle Side Plating”
- 3-2-2/5.9 “Poop Side Plating”
- 3-2-2/5.11 “Bow and Stern Thruster Tunnels”
- 3-2-2/5.13 “Special Heavy Plates”
- 3-2-2/9 “Compensations”
- 3-2-2/11 “Breaks”

- 3-2-2/13 "Bilge Keels"
- 3-2-2/15 "Higher-strength Materials (factor *C* is to be changed to 3.8 mm (0.15 in.))
- 3-2-13/2.1 "Plate Stems"
- 3-2-13/5.11 "Shell Plating"

Note: The plating thickness as required in 3-2-2/5.1, 3-2-2/5.3, 3-2-2/5.7, 3-2-2/5.9 and 3-2-2/5.11 is to be reduced by 0.5 mm (0.02 in.).

7.5.2(b) Side Shell Longitudinals. (1 August 2021)

The requirements in the following sections of the Rules are to be complied with:

- 3-2-5/1 "General"
- 3-2-5/3.17 "Longitudinal Frames"
- 3-2-4/17 "Higher-strength Materials

Note: The section modulus of the side shell longitudinals as required in 3-2-5/3.17 is to be multiplied by a factor of 0.94.

7.5.2(c) Side Frames (1 May 2009).

For a liquefied gas carrier having topside tanks and bottom wing tanks with adequately spaced transverse bulkhead, the section modulus *SM* in cm^3, is not to be less than that obtained from 5/7.5.1(c).

In order to prevent large relative deflection of the side shell plating just aft of the collision bulkhead, the section modulus of the first two frames aft of this bulkhead is to be at least 2.5 times the requirement in 5/7.5.1(c) above. Other means of achieving this, such as brackets in line with forepeak structures, may be considered.

7.7 Inner Bottom Plating and Stiffeners

7.7.1 Inner Bottom Shell Plating *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-4/9 "Inner-bottom Plating"

Note:

The inner-bottom plating thickness as required in 3-2-4/9 is to be reduced by 0.5 mm (0.02 in.) except for the outermost strake of inner bottom plating.

- 3-2-4/17 "Higher-strength Materials" (factor *C* is to be changed as follows:)

C = 2.5 mm (0.1 in.)

= 4.5 mm (0.18 in.) where the plating is required by 3-2-4/9.1 to be increased for no ceiling

7.7.2 Inner Bottom Stiffeners

The requirements in the following sections of the Rules are to be complied with:

- 3-2-4/11.5 "Inner Bottom Longitudinals"
- 3-2-4/17 "Higher-strength Materials"

7.9 Deck Plating, Stiffeners, Girders, and Transverses

7.9.1 Deck Plating

The requirements in the following sections of the Rules are to be complied with:

- 3-2-3/1 "General"

- 3-2-3/3 "Hull Girder Strength"
- 3-2-3/3.11 "Deck Plating"

Note:

The requirement in 3-2-3/5 TABLE 2, equation 2b of the Rules need not be greater than the buckling requirement in Section 3-2-A4 of the Rules

The stringer plate is to be not less than the thickness of the adjacent deck plating.

- 3-2-3/7 "Higher-strength Material"

7.9.2 Deck Stiffeners *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-7/1 "General"
- 3-2-7/3 "Beams"
- 3-2-7/7 "Higher-strength Material"

Note:

The section modulus of deck stiffeners as required in 3-2-7/3 is to be multiplied by a factor of 0.94.

7.9.3 Deck Girders and Transverses *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-8/5 "Deck Girders and Transverses"
- 3-2-8/9 "Higher-strength Material"

Notes:

1. The section modulus of deck girders and transverse as required in 3-2-8/5 is to be multiplied by a factor of 0.94.
2. The thickness of deck girder and transverse webs as required in 3-2-8/5.7 is to be modified as follows:
   - The thickness is not to be less than 1 mm per 100 mm (0.01 in. per in.) of depth plus 3.5 mm (0.14 in.).
   - The thickness is not to be less than:

Face Area	*Thickness*
38.7 cm^2 (6 in^2) or less	8.0 mm (0.32 in.)
64.5 cm^2 (10 in^2)	9.5 mm (0.38 in.)
129 cm^2 (20 in^2)	12.0 mm (0.47 in.)
193.5 cm^2 (30 in^2) or over	14.5 mm (0.57 in.)

The thickness for intermediate area may be obtained by interpolation.

7.11 Double Bottom Floors and Girders *(1 May 2009)*

The minimum depth of the double bottom is to be in compliance with the survivability requirements of Section 5C-8-2 of the Rules. Double bottoms are to be designed to withstand the dynamic forces from the cargo containment system.

The requirements in the following sections of the Rules are to be complied with:

- 3-2-4/1 "Double Bottoms"

- 3-2-4/3 “Center and Side Girders”

  Pipe tunnels may be substituted for centerline girders, provided that the tunnel is suitably stiffened by fitting vertical webs, as may be required. The thickness of each girder forming the pipe tunnel and center girder within the pipe tunnel, if any, is to be not less than that required for the bottom side girder (see 3-2-4/3.7) and for docking brackets (see 3-2-4/3.5), as appropriate.

- 3-2-4/5 “Solid Floors”
- 3-2-4/17 “Higher-strength Materials”
- 3-2-4/19 “Structural Arrangements and Details”

7.13 Frames, Stringers and Web Frames in Fore and After-peak Tanks *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-5/1 “General”
- 3-2-5/7 “Fore-peak Frames”
- 3-2-5/9 “After-peak Frames”
- 3-2-6/1 “General”
- 3-2-6/3 “Web Frames”
- 3-2-6/5 “Side Stringers”
- 3-2-6/7 “Structural Arrangements and Details”
- 3-2-6/9 “Peak Stringers"

Notes:

1. For higher-strength materials, the required *SM* in 3-2-5/7, 3-2-5/9, 3-2-6/3 and 3-2-6/5 may be multiplied by the *Q* factor as defined in 3-2-1/5.5.
2. The section modulus *SM* of frames, stringers and web frames as required in 3-2-5/7, 3-2-5/9, 3-2-6/3, 3-2-6/5 and 3-2-6/9 is to be multiplied by a factor of 0.94.
3. The deep floor thickness as required in 3-2-5/9.1 need not exceed 13.5 mm (0.53 in.).
4. The thickness of web frame web as required in 3-2-6/3.5.2 is to be modified as follows:
   - The thickness is not to be less than 1 mm per 100 mm (0.01 in. per in.) of depth plus 3.0 mm (0.12 in.), but need not exceed 13.5 mm (0.53 in.).
   - Where the webs are in close proximity to boilers, the thickness of the webs, face bars, flanges, etc. are to be increased 1.5 mm (0.06 in.) above the normal requirements
5. The factors C_2 and C_4 of peak stringer-plate thickness as required in 3-2-6/9.1 is to be modified as follows:

   C_2 = 6.7 (0.26)

   C_4 = 8.1 (0.32)

7.15 Plating, Stiffeners, Girders, and Webs on Watertight Boundaries *(1 May 2009)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-9/1 “General”
- 3-2-9/3 “Arrangement of Watertight Bulkheads”
- 3-2-9/5 “Construction of Watertight Bulkheads”

Note:

For determining the scantling requirements of liquefied gas carriers with independent tanks, *h* (pressure head) as defined in 3-2-9/5.1, 3-2-9/5.3 and 3-2-9/5.7 may be measured to the imaginary freeboard deck. This imaginary freeboard deck is to be calculated in accordance with the International Load Line Regulations, assuming that physically there is a deck present at the imaginary freeboard deck level.

For higher-strength materials, the required *SM* for stiffeners, girders and webs may be multiplied by the *Q* factor as defined in 3-2-1/5.5.

The thickness of the watertight plating may be reduced by 10%, but not more than 1.5 mm where the space on one side is intended to be dry at all times. In no case is the thickness of plating to be less than 6.5 mm.

The section modulus of the stiffeners or main supporting members on watertight boundaries may be reduced by 10% where these structural members are located in the space that is intended to be dry at all times.

7.17 Plating, Stiffeners, Girders, and Webs on Deep Tank Boundaries *(1 August 2021)*

The requirements in the following sections of the Rules are to be complied with:

- 3-2-10/1 “General”
- 3-2-10/3 “Construction of Deep Tank Bulkheads”
- 3-2-10/5 “Higher-strength Materials”

Note:

For higher-strength materials, the required *SM* for girders and webs may be multiplied by the *Q* factor as defined in 3-2-1/5.5.

For side shell and bottom longitudinals subject to internal ballast pressure, the effect of the counter-acting still water pressure head on the required section modulus may be considered, provided that the strength of these longitudinals complies with the criteria in 6/7.5. This counter-acting pressure head is not to be taken greater than the minimum ballast draft at the frame location under consideration.

For side shell and bottom plating, the effect of the counter-acting still water pressure head is not to be considered, as the required plate thickness is determined based on the structural response of local plate panels which cannot be completely covered by the strength criteria in 6/7.5.

The thickness of the deep tank plating as required in 3-2-10/3 is to be modified as follows, but in no case is the thickness of plating to be less than 6.5 mm (0.25 in.):

- For the plate where the space on one side is intended to be dry at all times, its thickness can be reduced by 10%, but not more than 1.5 mm (0.06 in.)
- For the plate located in the space except above, its thickness can be reduced by 0.5 mm (0.02 in.)

The section modulus of the stiffeners or main supporting members on deep tank boundaries as required in 3-2-10/3 are to be multiplied by a factor as follows:

- 0.94, except for side shell and bottom longitudinals considering internal ballast pressure and the members locating in the space that is intended to be dry at all times;
- 0.9, for the structural members are located in the space that is intended to be dry at all times.

The web thickness as required in 3-2-10/3.7.2 is to be modified as follows:

- The thickness is not to be less than 1% of the depth plus 2.5 mm (0.10 in.) but need not exceed 11.0 mm (0.43 in.).

7.19 Bulkheads

7.19.1 Transverse Bulkheads

Transverse bulkheads used for ballast or cargo are to comply with the requirements for deep tank boundaries in 5/7.17. Bulkheads not subject to hydrostatic loads are to be in accordance with the requirements for watertight boundaries in 5/7.15.

7.19.2 Cofferdam Bulkheads

Where a transverse cofferdam is used as a tank, the local stiffener and plate scantlings of transverse bulkheads subject to internal hydrostatic pressure are to be in accordance with the requirements for deep tank boundaries in 5/7.17.

Where a cofferdam is of a cellular-type construction and is used as a tank and not subject to a hydrostatic load on external side, the depth of the internal diaphragm plates, either horizontal or vertical, are to be at least 63 mm/m of the lesser of the horizontal or vertical unsupported span of the cofferdam bulkhead and is to be of sufficient depth to provide ready access.

7.19.3 Longitudinal Bulkheads

Scantlings of longitudinal bulkheads forming narrow wing tanks are to be in accordance with the deep tank requirements in 5/7.17, except that the vertical distance h as used in the equations for supporting members may be measured to a point 1.22 m above the deck at the side. Where the wing-tank-space bulkhead to side-shell plating is of a cellular-type construction, the depth of internal diaphragm plates is to be at least 83 mm/m of length and is to be of sufficient depth to provide ready access.

7.19.4 Corrosion Allowances

The thickness of the bulkhead plating described in 5/7.19.1, 5/7.19.2 and 5/7.19.3 may be reduced by 10%, but not more than 1.5 mm where the space on one side is intended to be dry at all times. In no case is the thickness of plating to be less than 6.5 mm.

The section modulus of the bulkhead stiffeners or main supporting members described in 5/7.19.1, 5/7.19.2 and 5/7.19.3 may be reduced by 10% where these structural members are located in the space that is intended to be dry at all times.

7.21 Bottom Slamming

When bottom slamming as specified in 3/13.3 is considered, the bottom structure in the region of the flat of bottom forward of 0.25L from the FP is to be in compliance with the following requirements.

7.21.1 Bottom Plating *(1 August 2021)*

The thickness of the flat of bottom plating forward of 0.25L from the FP is not to be less than obtained from 5C-12-6/7.1.1 with an additional 1.0 mm corrosion margin.

7.21.2 Bottom Longitudinals and Stiffeners *(1 August 2021)*

The section modulus of the stiffener, including the associated effective plating on the flat of bottom plating forward of 0.25L from the FP, is not to be less than that obtained from 5C-12-6/7.1.2. with permissible bending stress f_b changed as follows:

f_b = $0.8\, S_m f_y$ for transverse and longitudinal stiffeners in the region forward of 0.125L from the FP, in kgf/cm^2

= $0.7\, S_m f_y$ for longitudinal stiffeners in the region between 0.2L and 0.25L from the FP, in kgf/cm^2

f_b at intermediate locations between 0.125L and 0.2L, from the FP may be obtained by linear interpolation.

7.21.3 Double Bottom Floors and Girders

The double bottom floors and girders that are exposed to bottom slamming are to be evaluated using the direct engineering analysis using the slamming pressure specified in 3/13.3.

FIGURE 2
Unsupported Span of Longitudinals

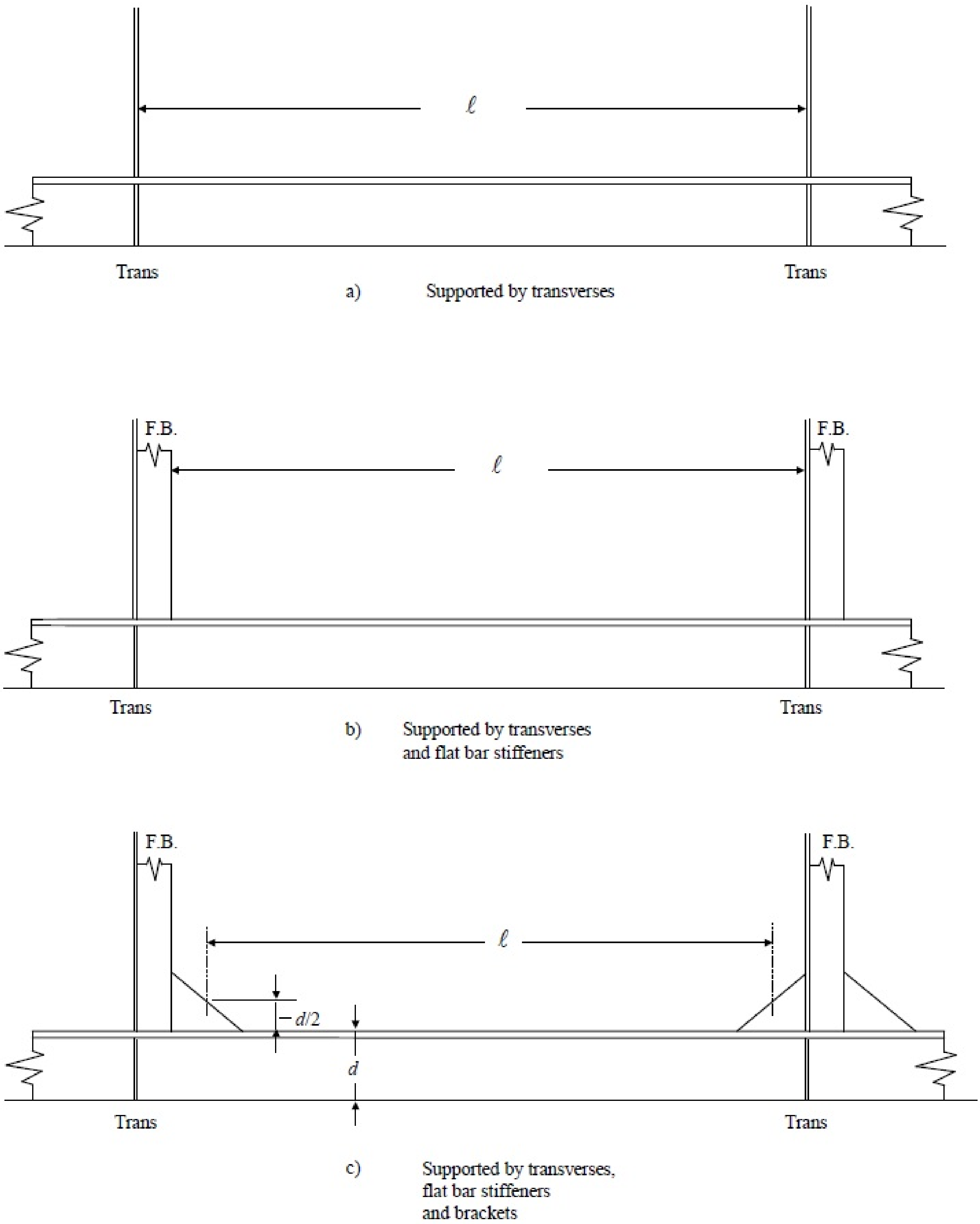
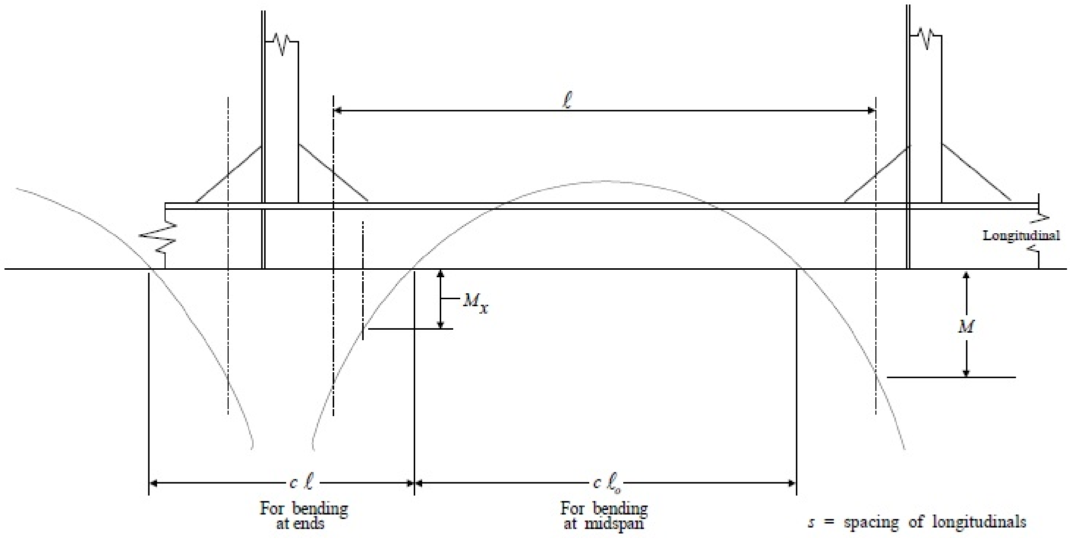


FIGURE 3
Effective Breadth of Plating b_e



a) For bending at midspan

$c\ell_o/s$	1.5	2	2.5	3	3.5	4	4.5 and greater
b_e/s	0.58	0.73	0.83	0.90	0.95	0.98	1.0

b) For bending at ends $\left[b_e/s = (0.124c\ell/s - 0.062)^{1/2}\right]$

$c\ell_o/s$	1	1.5	2	2.5	3	3.5	4.0
b_e/s	0.25	0.35	0.43	0.5	0.55	0.6	0.67

7.23 Bowflare Slamming

When bowflare slamming as specified in 3/13.5 is considered, the side shell structure above the waterline in the region between $0.0125L$ and $0.25L$ from the FP is to be in compliance with the following requirements.

7.23.1 Side Shell Plating

The thickness of the side shell plating between $0.0125L$ and $0.25L$ from the FP is not to be less than t_1 or t_2, whichever is greater, obtained from the following equations:

$$t_1 = 0.73s(k_1 p_s/f_1)^{1/2} + 1.5 \quad \text{in mm}$$

$$t_2 = 0.73s(k_2 p_s/f_2)^{1/2} + 1.5 \quad \text{in mm}$$

where

s = spacing of longitudinal or transverse stiffeners, in mm

k_1 = 0.342 for longitudinally stiffened plating

= $0.5k^2$ for transversely stiffened plating

k_2 = 0.5 for longitudinally stiffened plating

	=	0.342 for transversely stiffened plating
k	=	$\left[3.075(\alpha)^{1/2} - 2.077\right]/(\alpha + 0.272)$ $(1 \le \alpha \le 2)$
	=	1.0 $(\alpha \ge 2)$
α	=	aspect ratio of the panel (longer edge/shorter edge)
p_s	=	design slamming pressure = $k_u p_{ij}$
p_{ij}	=	nominal bowflare slamming pressure, as specified in 3/13.5, at the center of the supported panel under consideration, in kgf/cm^2
k_u	=	slamming load factor = 1.1
f_1	=	0.85 $S_m f_y$ for side shell plating in the region between 0.0125L and 0.125L, from the FP, in kgf/cm^2
	=	0.75 $S_m f_y$ for side shell plating in the region between 0.125L and 0.25L, from the FP, in kgf/cm^2
f_2	=	0.85 $S_m f_y$, in kgf/cm^2

S_m and f_y are as defined in 5/7.21.1.

7.23.2 Side Longitudinals and Stiffeners

The section modulus of the stiffener, including the associated effective plating, is not to be less than that obtained from the following equation:

$SM = M/f_b$ in cm^3

$M = p_s s \ell^2 10^3 / k$ in kgf-cm

where

k	=	16	
ℓ	=	unsupported span of the stiffener, as shown in 5/7.21.3 FIGURE 2,in m	
p_s	=	the maximum slamming pressure, in kgf/cm^2, as defined in 3/13.5, at the midpoint of the span ℓ	
s	=	spacing of longitudinal or transverse stiffeners, in mm	
f_b	=	0.8 $S_m f_y$	for transverse and longitudinal stiffeners in the region between 0.0125L and 0.125L, from the FP
	=	0.7 $S_m f_y$	for longitudinal stiffeners in the region between 0.125L and 0.25L from the FP, in kgf/cm^2

The effective breadth of plating, b_e, is as defined in 5/7.21.1.

S_m and f_y are as defined in 5/7.21.1.

7.23.3 Side Transverses and Stringers

The side transverses and stringers in the forepeak space are to be evaluated using the direct engineering analysis using the slamming pressure specified in 3/13.5.

7.25 Bow Strengthening

When impact loads on the bow, as specified in 3/13.1 are considered, the side shell structure above the waterline in the region forward of the collision bulkhead is to be in compliance with the following requirements.

7.25.1 Side Shell Plating

The thickness of the side shell plating is not to be less than t, obtained from the following equations:

$$t = 0.73sk(k_3 p_b / f_3)^{1/2} + 1.5 \quad \text{in mm}$$

where

s = spacing of longitudinal or transverse stiffeners, in mm

k_3 = 0.5

k = $\left(3.075(\alpha)^{1/2} - 2.077\right)/(\alpha + 0.272)$, $(1 \le \alpha \le 2)$

= 1.0 $(\alpha > 2)$

α = aspect ratio of the panel (longer edge/shorter edge)

p_b = the design bow pressure = $k_u p_{bij}$

p_{bij} = nominal bow pressure, as specified in 3/13.1, at the center of the supported panel under consideration, in kgf/cm^2

k_u = impact load factor = 1.1

f_3 = 0.85 $S_m f_y$, in kgf/cm^2

S_m and f_y are as defined in 5/7.21.1.

7.25.2 Side Longitudinals and Stiffeners

The net section modulus of the stiffener, including the effective plating, is not to be less than that obtained from the following equation:

$$SM = M / f_b \text{ in cm}^3$$

$$M = p_s s \ell^2 10^3 / k \text{ in kgf-cm}$$

where

k = 16

ℓ = unsupported span of the stiffener, as shown in 5/7.21.3 FIGURE 2, in m

p_b = the maximum bow pressure, in kgf/cm^2, as defined in 3/13.1, above at the midpoint of the span ℓ

s = spacing of longitudinal or transverse stiffeners, in mm

f_{bi} = 0.8 $S_m f_y$ for transverse and longitudinal stiffeners

The effective breadth of plating, b_e, is as defined in 5/7.21.3.

9 Independent Cargo Tank Structures

9.1 General

The scantlings of the cargo tank are to comply with the deep tank requirements taking into account the internal pressure as indicated in 5/9.3.2 and any corrosion allowance required by 5/9.3.3.

9.3 Allowable Stresses and Corrosion Allowances

9.3.1 Allowable Stresses *(1 June 2017)*

For the purpose of ultimate strength assessment, the following material parameters apply:

R_e = specified minimum yield stress at room temperature (kgf/cm^2). If the stress-strain curve does not show a defined yield stress, the 0.2% proof stress applies.

R_m = specified minimum tensile strength at room temperature (kgf/cm^2).

For welded connections where under-matched welds, i.e. where the weld metal has lower tensile strength than the parent metal, are unavoidable, such as in some aluminum alloys, the respective R_e or R_m of the welds, after any applied heat treatment, shall be used. In such cases, the transverse weld tensile strength shall not be less than the actual yield strength of the parent metal. If this cannot be achieved, welded structures made from such materials shall not be incorporated in cargo containment systems.

9.3.2 Scantling Requirements *(1 May 2009)*

The scantlings of independent tanks are not to be less than that required by Section 3-2-10 of the Rules (except 3-2-10/5), as modified below:

9.3.2(a) Head.

The value of h used in the various equations is to be derived from 3/11.3.

9.3.2(b) Plating. (1 May 2023)

i) *Steel.* The plating thickness is to be determined from 3-2-10/3.1 of the Rules where Y is the specified minimum yield stress at room temperature. If the stress-strain curve does not show a defined yield stress, the 0.2% proof stress (offset method) applies.

Where the cargo is non-corrosive, the thickness obtained may be reduced by the corrosion allowance (CA) indicated in 5/9.3.2(e) below.

For the tank top plating, the required thickness is to be increased by 1.0 mm.

ii) *Aluminum Alloy.* The plating thickness is to be obtained from the following equation:

$$t_a = [t_s - CA]\left(\frac{E_s}{E_a}\right)^{\frac{1}{3}}$$

where

t_a = required thickness of aluminum, in mm

t_s = required thickness of steel from Section 3-2-10 with Q = 1.0

CA = if cargo is non-corrosive, the value of the corrosion allowance is indicated in 5/9.3.2(e) below

E_s = modulus of elasticity of steel

E_a = modulus of elasticity of aluminum

9.3.2(c) Stiffeners (1 May 2023)

Each of the stiffeners in steel or aluminum alloy in association with the plating to which it is attached is not to have a section modulus less than that required by the following equation

$$SM_R = SMK_1K_2/\sigma_a$$

where

SM_R	=	required section modulus of material proposed, in cm^3
SM	=	required section modulus from 3-2-10/3.3 using c = 1.0 and ℓ is the distance, in m, between supports
σ_a	=	allowable stress not exceeding the lower of R_m/2.66 or R_e/1.33 for steel or aluminum alloy, respectively and R_m and R_e, as defined in 5/9.3.1
K_1	=	0.9 for non-corrosive cargoes 1.0 for corrosive cargoes.
K_2	=	1100 kgf/cm^2

The above section modulus requirements for cargo tank stiffeners in way of vertical supports, anti-pitch chocks and anti-roll chocks are to be increased by 25%.

If the tank spaces on both sides of the longitudinal bulkheads are always loaded to the same level in the seagoing condition and are gas common, the pressure head to be used for initial scantlings calculation of longitudinal bulkhead plating, stiffeners, and main supporting members need not exceed the greatest of the following:

i) *Static Load*

$$\rho * h/1.025 * \beta$$

where

ρ	=	intended cargo density, t/m^3
h	=	vertical distance to the designed maximum cargo filling level, in m
β	=	0.9, when the tank spaces on both sides of the longitudinal bulheads are always loaded to the same level both in the seagoing and harbor conditions
	=	1.0, when the tank spaces on both sides of the longitudinal bulhead are always loaded to the same level only in the seagoing condition

ii) *Tank Testing Load.* The confirmed hydropneumatics or hydrostatic test head of water as required by 5C-8-4/21.5 or 5C-8-4/22.6 of the *Marine Vessel Rules* (excluding the air test pressure for hydropneumatics). For tank testing with fresh water, the above test head should be divided by 1.025.

iii) *Dynamic Load Pressure Head Resulting from the Maximum Transverse Acceleration*

$$\rho * a_y * b_t/1.025$$

where

ρ	=	intended cargo density, t/m^3
a_y	=	maximum dimensionless transverse component of acceleration as defined in 3/Figure 6
b_t	=	maximum breadth from centerline bulkhead to tank side, in m

For such instances, the loading manual is to include the following note as a loading limit:

"Same filling level between port and starboard cargo tanks should be maintained in the seagoing (and harbor, if applicable) condition."

The scantlings of the cargo tank structure are to be verified for compliance with the yielding and buckling requirements in Section 6.

9.3.2(d) Corrugated Bulkheads.

Corrugated bulkheads are not to be used for primary barriers.

9.3.2(e) Corrosion Allowance. (1 May 2023)

Where the cargo is non-corrosive, the thickness of plating may be reduced by 4 mm for nickel steels, carbon-manganese steels and austenitic steels, and 3 mm for aluminum alloy at the tank bottom and 3 mm at the tank top*, except that where the thickness of plating as determined by 3-2-10/3.1 of the Rules is less than 11.5 mm, the reduction is not to be greater than 20% but the required thickness of tank side plating need not be greater than the required adjacent lower plating, adjusted for the spacing. In no case is the thickness to be less than 8.0 mm for cargo tank bottom plating and 6.5 mm for other cargo tank plating.

Note: * The reduction for nickel steels, carbon-manganese steels and austenitic steels may be obtained by linear interpolation for plates located between the tank bottom and top. Uppermost tank side plating is not to be less than the required tank top plating adjusted for the spacing.

9.3.2(f) Webs and Girders. (1 May 2023)

Webs and girders in steel and aluminum alloy in association with the plating to which it is attached are not to have a section modulus less than that required by the following equation:

$$SM_R = SMK_1K_3/\sigma_a$$

where

σ_a	=	allowable stress not exceeding $R_e/1.33$ for nickel steels, carbon manganese steels and austenitic steels or aluminum alloy and R_e as defined in 5/9.3.1
K_3	=	1260 kgf/cm^2

SM_R, SM, K_1 are defined in 5/9.3.2(c) above.

9.3.2(g) Nontight Bulkheads.

Nontight bulkheads in cargo tanks are to be fitted in line with transverse webs or other structures with equivalent rigidity. They are to be suitably stiffened. Openings in the nontight bulkhead are to have generous radii and their aggregate area is not to exceed 33%, nor to be less than 10% of the area of the nontight bulkhead. The thickness of nontight bulkheads is to be not less than 6.5 mm. Section moduli of stiffeners and webs may be half of those required for watertight bulkheads in 3-2-9/5.3 and 3-2-9/5.7 of the Rules.

Alternatively, the opening ratio and scantlings may be determined by an acceptable method of engineering analysis.

9.3.2(h) Buckling.

For higher strength materials and aluminum alloys, calculations are to be submitted to show adequate provision to resist buckling.

9.3.2(i) Fatigue Strength.

Proportions and scantlings of structural members where deemed necessary may have to be investigated to improve the fatigue strength especially in higher strength material and aluminum alloys.

9.3.3 Corrosion Allowances *(1 May 2009)*

No corrosion allowance is generally required in addition to the thickness resulting from the structural analysis. However, where there is no environmental control around the cargo tank, such as inerting, or where the cargo is of a corrosive nature, a suitable corrosion allowance is to be provided.

Note:

Special attention to stress corrosion cracking (SCC) is needed when cargo tanks are to be designed to carry anhydrous ammonia. SCC may cause cracking without visible reduction in plate thickness. See 5C-8-17/12 of the Rules for details of the SCC phenomena and prevention for such cargo tanks.

11 Supports

Independent cargo tanks are to be supported by the hull in a manner which will prevent bodily movement of the tanks under static and dynamic loads while allowing contraction and expansion of the tanks under temperature variations and hull deflections without undue stressing of the tanks and of the hull.

In general, the protruding part of a support (chock) is to be fitted to the cargo tanks to prevent potential problems associated with undue tightness at the contact surfaces due to shrinkage of the cargo tanks under low cargo temperature.

SECTION 6
Acceptance Criteria

1 General

To assess the adequacy of the structural configuration and the initially selected scantlings, the hull and cargo tank structures are to be reviewed for compliance with the strength criteria for yielding, buckling and fatigue. Individual elements are checked for yielding while buckling is verified for individual plate panels supported along four edges by stiffeners or other structural members.

3 Symbols

f_y	minimum specified yield point of the material, in kgf/cm^2
f_u	minimum specified tensile strength of the material, in kgf/cm^2
S_m	strength reduction factor, equal to 1.000, 0.950, 0.908 and 0.875 for mild steel, H32, H36, and H40, respectively
E	modulus of elasticity of the material, may be taken as 2.1×10^6 kgf/cm^2 for steel
v	Poisson ratio of the material and may be taken as 0.3 in this application for steel.

5 Yielding Failure Mode

It is generally expected that finer finite element mesh induces higher resultant stress from a linear elastic analysis. However, the increase in stress is not just a function of finite element mesh size. It may also depend on the relative stiffness of adjoining structural members and the loading pattern. When a flexible member is connected to a stiff member, the increase in stress will be higher than when two flexible members are joined together. The increase in stress is also higher when bending is applied as compared to axial loads. In other words, the increase in stress due to a reduction in mesh size depends mainly on the expected stress gradient in the connection joint.

Given the recommended basic mesh of one longitudinal spacing for hull and cargo tank structures and finer meshing for critical structural areas such as seatings for vertical supports and chocks, openings and bracket toes, the resulting stresses may be categorized into the following three levels of stresses.

5.1 Field Stress

Field stresses are indicative of stress severity sufficiently away from structural details such as hopper knuckles, openings and bracket toes. The recommended basic mesh size for capturing field stresses is one longitudinal spacing. Element stresses directly obtained from 3D finite element models of one longitudinal spacing can be considered as field stresses. For main supporting members, field stresses are primarily due to primary hull girder deformation and secondary bending between watertight boundaries. In practice, mesh size up to $^1/_3$ longitudinal spacing is often used to calculate field stresses in main supporting members.

5.3 Local Stress

Local stresses reflect stress variation due to the presence of structural openings, details and discontinuities. Local stresses can be determined from elements having a mesh size in the range of $^1/_5$ to $^1/_{10}$ longitudinal spacing. This mesh size is finer than that used for determining the field stresses, but is still relatively coarse for determining stress concentration factors.

5.5 Hot-Spot Stress

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 presence of attachments, but excludes the effects of welds. To determine hot-spot stresses, the mesh size needs to be finer than $^1/_{10}$ longitudinal spacing, but not finer than plate thickness.

5.6 Stress Analysis for Tank Structure (*1 June 2017)*

The most unfavorable scenarios for all relevant phases during construction, handling, testing and in service, and conditions shall be considered.

5.6.1

When the static and dynamic stresses are calculated separately and unless other methods of calculation are justified, the total stresses shall be calculated according to:

$$\sigma_x = \sigma_{x.st} \pm \sqrt{\sum\left(\sigma_{x.dyn}\right)^2}$$

$$\sigma_y = \sigma_{y.st} \pm \sqrt{\sum\left(\sigma_{y.dyn}\right)^2}$$

$$\sigma_z = \sigma_{z.st} \pm \sqrt{\sum\left(\sigma_{z.dyn}\right)^2}$$

$$\tau_{xy} = \tau_{xy.st} \pm \sqrt{\sum\left(\tau_{xy.dyn}\right)^2}$$

$$\tau_{xz} = \tau_{xz.st} \pm \sqrt{\sum\left(\tau_{xz.dyn}\right)^2}$$

$$\tau_{yz} = \tau_{yz.st} \pm \sqrt{\sum\left(\tau_{yz.dyn}\right)^2}$$

where

$\sigma_{x.st}, \sigma_{y.st}, \sigma_{z.st}, \tau_{xy.st}, \tau_{xz.st}, \tau_{yz.st}$ *are static stresses; and*

$\sigma_{x.dyn}, \sigma_{y.dyn}, \sigma_{z.dyn}, \tau_{xy.dyn}, \tau_{xz.dyn}, \tau_{yz.dyn}$ *are dynamic stresses*

Each shall be determined separately from acceleration components and hull strain components due to deflection and torsion.

5.6.2

The equivalent stress σ_c(von Mises, Huber) shall be determined by:

$$\sigma_c = \sqrt{\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z + 3\left(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2\right)\right)}$$

where

σ_x = *total normal stress in x-direction;*

σ_y = *total normal stress in y-direction;*

σ_z = *total normal stress in z-direction;*

τ_{xy} = *total shear stress in x-y plane;*

τ_{xz} = *total shear stress in x-z plane; and*

τ_{yz} = *total shear stress in y-z plane;*

The above values shall be calculated as described in 6/5.6.1.

5.7 Allowable Stresses for Watertight Boundaries *(1 June 2017)*

The allowable stresses defined in 6/5.7 TABLE 1 are applicable to plating and longitudinal stiffeners on watertight boundaries. For the recommended basic mesh size of one longitudinal spacing, each allowable stress is defined as a percentage of the minimum specified yield stress f_y times the strength reduction factor S_m. Application of this allowable stress to rod and beam elements is based on axial stress while von-Mises membrane stresses for quadrilateral elements are checked. The stress results of watertight boundaries for accidental load cases LC12 ~ LC15 in 4/5 TABLE 2 need not be checked.

TABLE 1
Allowable Stresses (kgf/cm²) for Watertight Boundaries *(1 May 2009)*

Load Case	*Stress Limit*	*Mild Steel (S_m = 1.000)*	*HT27 (S_m = 0.980)*	*HT32 (S_m = 0.950)*	*HT36 (S_m = 0.908)*
Sea-going Load Cases (LC1~LC10)	$0.80 \times S_m f_y$	1920	2117	2432	2615
Flooded Load Case (LC11)	$1.00 \times S_m f_y$	2400	2646	3040	3269

Notes

1. The allowable stresses are not applicable to accidental load cases LC12 ~ LC15 in 4/5 TABLE 2.
2. *(1 May 2009)* The allowable stresses are not applicable to Type B and Type C independent tank structures.

Alternatively, for watertight boundaries under lateral load, the von-Mises stress may be determined using the tertiary plate bending stress from the applicable Chapter of Part 5C of the Rules. When the tertiary stress is included, the allowable stress for seagoing load cases (LC1~LC10) can be taken as $1.00 \times S_m f_y$.

For Type A independent tanks, primarily constructed of plane surfaces, *the nominal membrane stresses for primary and secondary members (stiffeners, web frames, stringers, girders), when calculated by classical analysis procedures, shall not exceed the lower of $R_m/2.66$ or $R_e/1.33$ for nickel steels, carbon-manganese steels, austenitic steels and aluminum alloys, where R_m and R_e are defined in 5/9.3.1*

For Type B independent tanks, primarily constructed of bodies of revolution, the allowable stresses *shall not exceed*:

$$\sigma_m \leq f$$

$$\sigma_L \leq 1.5f$$

$$\sigma_b \leq 1.5F$$

$$\sigma_L + \sigma_b \leq 1.5F$$

$$\sigma_m + \sigma_b \leq 1.5F$$

$$\sigma_m + \sigma_b + \sigma_g \leq 3.0F$$

$$\sigma_L + \sigma_b + \sigma_g \leq 3.0F$$

where

σ_m = *equivalent primary general membrane stress*

σ_L = *equivalent primary local membrane stress*

σ_b = *equivalent primary bending stress*

σ_g = *equivalent secondary stress*

f = $\text{the lesser of } \frac{R_m}{A} \text{ or } \frac{R_e}{B}$

F = $\text{the lesser of } \frac{R_m}{C} \text{ or } \frac{R_e}{D}$

with R_m and R_e as defined in 5/9.3.1. With regard to the stresses σ_m, σ_L, σ_b and σ_g the definition of stress categories in 5C-8-4/28.3 of the Rules are referred. The values of A and B shall be shown on the International Certificate of Fitness for the Carriage of Liquefied Gases in Bulk and shall have at least the following minimum values:

	Nickel steels and carbon–manganese steels	***Austenitic Steels***	***Aluminum Alloys***
A	3	3.5	4
B	2	1.6	1.5
C	3	3	3
D	1.5	1.5	1.5

For Type B independent tanks, primarily constructed of plane surfaces, the allowable *membrane equivalent stresses applied for the finite element analysis shall not exceed:*

for nickel steels and carbon-manganese steels, the lesser of $R_m/2$ or $R_e/1.2$;

for austenitic steels, the lesser of $R_m/2.5$ or $R_e/1.2$; and

for aluminum alloys, the lesser of $R_m/2.5$ or $R_e/1.2$.

The above figures may be amended, taking into account the locality of the stress, stress analysis methods and design condition considered in acceptance with the Administration.

For Type B independent tanks, the thickness of the skin plate and the size of the stiffener shall not be less than those required for Type A independent tanks

For Type C independent tanks, the allowable stresses *shall not exceed*:

$$\sigma_m \leq f$$

$$\sigma_L \leq 1.5f$$

$$\sigma_b \leq 1.5f$$

$$\sigma_L + \sigma_b \leq 1.5f$$

$$\sigma_m + \sigma_b \leq 1.5f$$
$$\sigma_m + \sigma_b + \sigma_g \leq 3.0f$$
$$\sigma_L + \sigma_b + \sigma_g \leq 3.0f$$

where

σ_m = *equivalent primary general membrane stress*

σ_L = *equivalent primary local membrane stress*

σ_b = *equivalent primary bending stress*

σ_g = *equivalent secondary stress*

f = $the\ lesser\ of\ \frac{R_m}{A}\ or\ \frac{R_e}{B}$

with R_m and R_e as defined in 5/9.3.1. With regard to the stresses σ_m, σ_L, σ_b and σ_g, the definition of stress categories in 5C-8-4/28.3 of the Rules are referred. The values of A *and* B *shall be shown on the International Certificate of Fitness for the Carriage of Liquefied Gases in Bulk and shall have at least the following minimum values:*

	Nickel steels and carbon–manganese steels	*Austenitic Steels*	*Aluminum Alloys*
A	3	3.5	4
B	1.5	1.5	1.5

5.9 Allowable Stresses for Main Supporting Members and Structural Details *(1 May 2009)*

The allowable stresses defined in 6/5.9 TABLE 2 are applicable to main supporting members and structural details except seatings for supports and chocks. The allowable stress for the recommended basic mesh size is defined as a percentage of the minimum specified yield stress f_y times the strength reduction factor S_m. Application of this allowable stress to rod and beam elements is based on axial stress while von-Mises membrane stresses for quadrilateral elements are checked.

To calculate the local stress distribution in a main supporting member, it is often necessary to model openings, details and discontinuities using various mesh sizes. In areas of high stress gradient, the allowable stresses are to be adjusted according to mesh sizes and are listed in 6/5.9 TABLE 2.

TABLE 2
Allowable Stresses (kgf/cm^2) for Various Finite Element Mesh Sizes *(1 May 2009)*

Mesh Size	*Stress Limit*	*Mild Steel (S_m = 1.000)*	*HT27 (S_m = 0.980)*	*HT32 (S_m = 0.950)*	*HT36 (S_m = 0.908)*
1 × LS	$1.00 \times c_f S_m f_y$	$2400 \times c_f$	$2646 \times c_f$	$3040 \times c_f$	$3269 \times c_f$
$^1/_2$ × LS (1)	$1.06 \times c_f S_m f_y$	$2544 \times c_f$	$2805 \times c_f$	$3222 \times c_f$	$3465 \times c_f$
$^1/_3$ × LS (1)	$1.12 \times c_f S_m f_y$	$2688 \times c_f$	$2963 \times c_f$	$3404 \times c_f$	$3661 \times c_f$
$^1/_4$ × LS (1)	$1.18 \times c_f S_m f_y$	$2832 \times c_f$	$3122 \times c_f$	$3587 \times c_f$	$3857 \times c_f$

Mesh Size	*Stress Limit*	*Mild Steel (S_m = 1.000)*	*HT27 (S_m = 0.980)*	*HT32 (S_m = 0.950)*	*HT36 (S_m = 0.908)*
$^1/_5 \times$ LS ~ $^1/_{10} \times$ LS (1)	$1.25 \times c_f S_m f_y$	$3000 \times c_f$	$3308 \times c_f$	$3800 \times c_f$	$4086 \times c_f$
Thickness (1, 2)	$c_f f_u$ or $1.50 \times c_f S_m f_y$	$4100 \times c_f$	$c_f f_u$ or $1.50 \times c_f S_m f_y$	$4500 \times c_f$	$4903 \times c_f$

Notes:

1 Stress limits greater than $1.00 \times c_f S_m f_y$ are to be restricted to small areas in way of structural discontinuities.

2 When the fatigue strength of the detail is found satisfactory, the hot spot stress in the detail may be allowed up to the minimum tensile strength of the material.

3 c_f is to be taken as 0.95 for dynamic sea load cases (LC1 ~ LC 9) in 4/5 TABLE 1
c_f is to be taken as 0.80 for port load case (LC10) in 4/5 TABLE 2
c_f is to be taken as 1.00 for flooded load case (LC11) in 4/5 TABLE 2

4 The allowable stresses are not applicable to accidental load cases LC12 ~ LC15 in 4/5 TABLE 2

5 *(1 May 2009)* The allowable stresses are not applicable to Type B and Type C independent tank structures.

For Type B independent tanks, primarily constructed of bodies of revolution, the allowable stresses for the recommended basic mesh size of one longitudinal spacing are defined as follows:

- Nickel Steels and Carbon-Manganese Steels

  The lesser of $R_m/2.0$ or R_e

- Austenitic Steels

  The lesser of $R_m/2.0$ or R_e

- Aluminum Alloys

  The lesser of $R_m/2.0$ or R_e

For Type B independent tanks, primarily constructed of plane surfaces, the allowable stresses for the recommended basic mesh size of one longitudinal spacing are defined as follows:

- Nickel Steels and Carbon-Manganese Steels

  The lesser of $R_m/2.0$ or $R_e/1.33$

- Austenitic Steels

  The lesser of $R_m/2.5$ or $R_e/1.25$

- Aluminum Alloys

  The lesser of $R_m/2.5$ or $R_e/1.33$

For Type C independent tanks, the allowable stresses for the recommended basic mesh size of one longitudinal spacing are defined as follows:

- Nickel Steels and Carbon-Manganese Steels

  The lesser of $R_m/2.0$ or R_e

  Note:

In way of the supports of the independent cargo tanks made of Carbon-Manganese Steels, the allowable stresses are not to be more than the lesser of $0.57R_m$ or $0.85R_e$.

- Austenitic Steels

  The lesser of $R_m/2.0$ or R_e

- Aluminum Alloys

  The lesser of $R_m/2.0$ or R_e

R_m and R_e are defined in 5/9.3.1. For the mesh size other than the recommended one longitudinal spacing, the allowable stresses defined above for Type B and Type C independent tanks are to be adjusted in the same way as that in 6/5.9 TABLE 2.

5.11 Allowable Stresses for Vertical Supports and Chocks *(1 May 2023)*

The allowable stresses described in this Section are applicable to seatings for supports and chocks. The allowable stress for the recommended basic mesh size is the minimum specified yield stress f_y times the strength reduction factor S_m. Application of this allowable stress to rod and beam elements is based on axial stress while von-Mises membrane stresses for quadrilateral elements are checked.

TABLE 3
Allowable Stresses (kgf/cm²) for Various Finite Element Mesh Sizes
(1 May 2023)

Mesh Size	*Stress Limit*	*Mild Steel (S_m = 1.000)*	*HT27 (S_m = 0.980)*	*HT32 (S_m = 0.950)*	*HT36 (S_m = 0.908)*
1 × LS	$1.00 \times c_f S_m f_y$	$2400 \times c_f$	$2646 \times c_f$	$3040 \times c_f$	$3269 \times c_f$
$^1/_2$× LS (1)	$1.06 \times c_f S_m f_y$	$2544 \times c_f$	$2805 \times c_f$	$3222 \times c_f$	$3465 \times c_f$
$^1/_3$ × LS (1)	$1.12 \times c_f S_m f_y$	$2688 \times c_f$	$2963 \times c_f$	$3404 \times c_f$	$3661 \times c_f$
$^1/_4$ × LS (1)	$1.18 \times c_f S_m f_y$	$2832 \times c_f$	$3122 \times c_f$	$3587 \times c_f$	$3857 \times c_f$
$^1/_5$ × LS ~ $^1/_{10}$ × LS (1)	$1.25 \times c_f S_m f_y$	$3000 \times c_f$	$3308 \times c_f$	$3800 \times c_f$	$4086 \times c_f$
Thickness (1, 2)	$c_f f_u$ or $1.50 \times c_f S_m f_y$	$4100 \times c_f$	$c_f f_u$ or $1.50 \times c_f S_m f_y$	$4500 \times c_f$	$4903 \times c_f$

Alternatively, anti-flotation chocks and surrounding hull structure under LC 12 flooded condition may be verified by nonlinear analysis and the results are to be submitted to ABS for review. The plastic strain zone obtained by nonlinear analysis around the anti-floating support area is not to be extended to upper deck or side shell. For the detailed analysis procedure, the ABS *Guidance Notes on Nonlinear Finite Element Analysis of Marine and Offshore Structures* can be referred to.

Notes:

1 Stress limits greater than $1.00 \times c_f S_m f_y$ are to be restricted to small areas in way of structural discontinuities.

2 When the fatigue strength of the detail is found satisfactory, the hot spot stress in the detail may be allowed up to the minimum tensile strength of the material.

3 c_f is to be taken as 0.95 for dynamic sea load cases (LC1 ~ LC3, LC5 ~ LC6) in 4/5 TABLE 1
c_f is to be taken as 1.00 for accidental load case (LC12 ~ LC15) in 4/5 TABLE 2

4 The allowable stresses are not applicable to LC4, LC7 ~ LC11 in 4/5 TABLE 1 and 4/5 TABLE 2.

Contact surfaces of vertical supports, anti-roll and anti-pitch chocks are usually made of synthetic materials such as resin, plywood and adhesive. The strength of each contact surface is to be verified under the maximum contact force perpendicular to the surface and the associate friction parallel to the surface. Contact forces are to be calculated from global finite element models. The frictional coefficient for strength verification of the contact surface is to be taken as 0.3. Average compressive and shear stresses in each layer of the synthetic contact surface are to be separately checked against the safe working stresses. The strength of the fastening bolts or other effective means is to be evaluated. The following safety factors for vertical supports and chocks under sea-going and accidental load cases are to be complied with:

- Vertical Supports

LC1 ~ LC8 (Dynamic Sea Load Cases):	Safety Factor = 3.0
LC15 (30° Static Heel):	Safety Factor = 3.0
LC13 ~ LC14 (Accidental Load Cases):	Safety Factor = 1.5

- Anti-pitch Chocks

LC5 ~ LC8 (Dynamic Sea Load Cases):	Safety Factor = 3.0
LC13 ~ LC14 (Accidental Load Cases):	Safety Factor = 1.5

- Anti-roll Chocks

LC5 ~ LC8 (Dynamic Sea Load Cases):	Safety Factor = 3.0
LC15 (30° Static Heel):	Safety Factor = 3.0

- Anti-flotation Chocks

LC12 (Anti-floatation Load Cases):	Safety Factor = 3.0

7 Failure Criteria – Buckling and Ultimate Strength

7.1 General

7.1.1 Approach

The strength criteria described in this Section are to be used in conjunction with the predicted stresses for dynamic sea load cases LC1 ~ LC9.

The strength criteria given here correspond to either serviceability (buckling) state limits or ultimate state limits for structural members and panels, according to the intended functions and buckling resistance capability of the structure. For plate panels between stiffeners, buckling in the elastic range is acceptable, provided that the ultimate strength of the structure satisfies the specified design limits. The critical buckling stresses and ultimate strength of structures may be determined based on either well-documented experimental data or a calibrated analytical approach. When a detailed analysis is not available, the equations given in Appendix A2 may be used to assess the buckling strength.

The strength criteria in this section are based on the gross scantlings reduced by nominal design corrosion values. A nominal design corrosion value of 1 mm is to be used for structural members for each surface directly exposed to ballast water. For other surfaces, nominal design corrosion values need not be applied. The applied stress components in the strength criteria are to be adjusted by:-

- The ratio of the gross thickness and net thickness for local stress components in plate panels,
- The ratio of the gross section modulus and net section modulus for bending stress component in stiffeners.

7.1.2 Buckling Control Concepts

The strength criteria in 6/7.3 through 6/7.7 are based on the following assumptions and limitations with respect to buckling control in design.

7.1.2(a)

The buckling strength of longitudinals and stiffeners is generally greater than that of the plate panels they support.

7.1.2(b)

All longitudinals with their associated effective plating are to have moments of inertia not less than i_o given in A2/9.1.

7.1.2(c)

The main supporting members, including transverses, girders and floors, with their associated effective plating are to have the moments of inertia not less than I_s given in A2/9.5.

In addition, tripping (e.g., torsional instability) is to be prevented, as specified in A2/7.5.

7.1.2(d)

Face plates and flanges of girders, longitudinals and stiffeners are proportioned such that local instability is prevented. (See A2/9.7)

7.1.2(e)

Webs of longitudinals and stiffeners are proportioned such that local instability is prevented (see A2/9.9).

7.1.2(f)

Webs of girders, floors and transverses are designed with proper proportions and stiffening systems to prevent local instability. Critical buckling stresses of the webs may be calculated from equations given in A2/3.

For structures which do not satisfy these assumptions, a detailed analysis of buckling strength using an acceptable method is to be submitted for review.

7.3 Plate Panels

7.3.1 Buckling State Limit

The buckling state limit for plate panels between stiffeners is defined by the following equation:

$$(f_{Lb}/f_{cL})^2 + (f_{Tb}/f_{cT})^2 + (f_{LT}/f_{cLT})^2 \leq 1.0$$

where

$f_{Lb} = f_{L1} + f_{L2}$	=	calculated total compressive stress in the longitudinal direction for the plate, in kgf/cm^2, induced by bending of the hull girder and large stiffened panels between bulkheads
$f_{Tb} = f_{T1} + f_{T2}$	=	calculated total compressive stress in the transverse/vertical direction, in kgf/cm^2
f_{LT}	=	calculated total in-plane shear stress, in kgf/cm^2

f_{cL}, f_{cT} and f_{cLT} are the critical buckling stresses corresponding to uniaxial compression in the longitudinal, transverse/vertical directions and edge shear, respectively, in kgf/cm^2, and may be determined from the equations given in A2/3.

f_L, f_T and f_{LT} are to be determined for the plate panel in question under the load cases specified in Section 4. These stress components are to be adjusted for the net plate thickness as described in 6/7.1.1

7.3.2 Effective Width

When the buckling state limit specified in 6/7.3.1 above is not satisfied, the effective width b_{wL} or b_{wT} of the plating given below is to be used instead of the full width between longitudinals, s, for verifying the ultimate strength, as specified in 6/7.3.3 below. When the buckling state limit in 6/7.3.1 above is satisfied, the full width between longitudinals, s, may be used as the effective width, b_{wL}, for verifying the ultimate strength of longitudinals and stiffeners specified in 6/7.5.

7.3.2(a) For long plate:

$$b_{wL}/s = C$$

C	=	$2.25/\beta - 1.25/\beta^2$	for $\beta \geq 1.25$
	=	1.0	for $\beta < 1.25$
β	=	$(f_y/E)^{1/2}s/t_n$	
s	=	longitudinal spacing, in cm	
t_n	=	net thickness of the plate, in cm	

7.3.2(b) For wide plate (compression in transverse direction):

$$b_{wT}/\ell = Cs/\ell + 0.115(1 - s/\ell)\left(1 + 1/\beta^2\right)^2 \leq 1.0$$

where

ℓ = spacing of transverses, in cm

C, β and s are as defined in 6/7.3.2(a) above.

7.3.3 Ultimate Strength

The ultimate strength of a plate panel between stiffeners is to satisfy all of the following equations:

$$(f_{Lb}/f_{uL})^2 + (f_{LT}/f_{uLT})^2 \leq S_m$$

$$(f_{Tb}/f_{uT})^2 + (f_{LT}/f_{uLT})^2 \leq S_m$$

$$(f_{Lb}/f_{uL})^2 + (f_{Tb}/f_{uT})^2 - \eta(f_{Lb}/f_{uL})(f_{Tb}/f_{uT}) + (f_{LT}/f_{uLT})^2 \leq S_m$$

where

f_{Lb}, f_{Tb} and f_{LT} are as defined in 6/7.3.1 above.

η = $1.5 - \beta/2 \geq 0$

β is as defined in 6/7.3.2 above.

f_{uL}, f_{uT} and f_{uLT} are the ultimate strengths with respect to uniaxial compression and edge shear, respectively, and may be obtained from the following equations, except that they need not be taken less than the corresponding critical buckling stresses specified in 6/7.3.1 above.

$$f_{uL} = f_y b_{wL}/s$$

$$f_{uT} = f_y b_{wt}/\ell$$

$$f_{uLT} = f_{cLT} + 0.5\left(f_y - \sqrt{3} f_{cLT}\right)/\left(1 + \alpha + \alpha^2\right)^{1/2}$$

where

α = ℓ/s

b_{wL}, b_{wT}, s, ℓ, and f_{cLT} are as defined in 6/7.3.1 and 6/7.3.2.

7.5 Longitudinals and Stiffeners

7.5.1 Beam-Column Buckling State Limits and Ultimate Strength

The buckling state limits for longitudinals and stiffeners are considered as the ultimate state limits for these members and are to be determined as follows:

$$f_a/(f_{ca}A_e/A) + m f_b/f_y \le S_m$$

where

f_a	=	nominal calculated compressive stress
	=	P/A, kgf/cm^2
P	=	total compressive load, kgf
f_{ca}	=	critical buckling stress, as given in A2/5.1, kgf/cm^2
A	=	total net sectional area, cm^2
	=	$A_s + st_n$
A_s	=	net sectional area of the longitudinal, excluding the associated plating, cm^2
A_e	=	effective net sectional area, cm^2
	=	$A_S + b_{wL}t_n$
b_{wL}	=	effective width, as specified in 6/7.3.2 above
f_b	=	bending stress, kgf/cm^2
	=	M/SM_e
M	=	maximum bending moment induced by lateral loads
	=	$c_m p s \ell^2/12$ kgf-cm
c_m	=	moment adjustment coefficient, and may be taken as 0.75
p	=	lateral pressure for the region considered, kgf/cm^2
s	=	spacing of the longitudinals, cm
SM_e	=	effective section modulus of the longitudinal at flange, accounting for the effective breadth, b_e, cm^3

b_e = effective breadth, which can be taken as the smaller of spacing s and 20% of the unsupported span but not more than the spacing of the longitudinals.

m = amplification factor

= $1/\left[1 - f_a/\pi^2 E(r/\ell)^2\right] \geq 1.0$

ℓ = unsupported span of the longitudinal or stiffener, in cm

r = radius of gyration of area A_e

7.5.2 Torsional-Flexural Buckling State Limit

In general, the torsional-flexural buckling state limit of longitudinals and stiffeners is to satisfy the ultimate state limits given below:

$$f_a/(f_{ct}A_e/A) \leq S_m$$

where

f_a = nominal calculated compressive stress in kgf/cm^2,

f_{ct} = critical torsional-flexural buckling stress in kgf/cm^2, and may be determined by equations given in A2/5.3.

A_e and A are as defined in 6/7.5.1 above.

7.7 Deep Girders and Webs

7.7.1 Buckling Criteria

In general, the stiffness of the web stiffeners along the depth of the web plating is to be in compliance with the requirements of A2/9.3. Web stiffeners which are oriented parallel to and near the face plate, and thus subject to axial compression, are also to satisfy the limits specified in 6/7.5, considering the combined effect of the compressive and bending stresses in the web. In this case, the unsupported span of these parallel stiffeners may be taken between tripping brackets, as applicable.

The buckling strength of the web plate between stiffeners and flange/face plate is to satisfy the limits specified below.

7.7.1(a) For web plate (1 May 2009):

$$(f_{Lb}/f_{cL})^2 + (f_b/f_{cb})^2 + (f_{LT}/f_{cLT})^2 \leq S_m$$

where

f_{Lb} = calculated uniform compressive stress along the length of the girder, kgf/cm^2

f_b = calculated ideal bending stresses, in kgf/cm^2

f_{LT} = calculated total in-plane shear stress, in kgf/cm^2

f_{Lb}, f_b and f_{LT} are to be calculated for the panel in question under the combined load cases specified in Section 4.

For calculating the plate panel stresses, the following equations may be used:

$$f_1 = \frac{E}{1-v^2}\left[\frac{-u_1+u_2}{a} + \frac{v^2(u_1-u_2+u_3-u_4)}{2a} + \frac{v(-v_1-v_2+v_3+v_4)}{2b}\right]$$

$$f_2 = \frac{E}{1-v^2}\left[\frac{u_3-u_4}{a} + \frac{v^2(-u_1+u_2-u_3+u_4)}{2a} + \frac{v(-v_1-v_2+v_3+v_4)}{2b}\right]$$

$$f_{Lb} = \frac{f_1+f_2}{2} \le 0$$

$$f_b = \frac{f_1-f_2}{2} \le 0$$

$$f_{LT} = \frac{E}{4(1+v)}\left[\frac{-u_1-u_2+u_3+u_4}{b} + \frac{-v_1+v_2+v_3-v_4}{a}\right]$$

where

u_i = in-plane x displacement at one corner point in the local x-y coordinate system (i = 1, 2, 3, 4)

v_i = in-plane y displacement at one corner point in the local x-y coordinate system (i = 1, 2, 3, 4)

Corner 1 is assigned to the node located at the bottom left corner of the panel in the local coordinate system. The line joining Corners 1 and 2 is parallel to the x coordinate, and Corners 3 and 4 are numbered counterclockwise (see 6/7.7.2 FIGURE 1). This calculation method is useful when the meshing within the panel is irregular. However, care should be taken when one corner of the panel is located in an area of high stress concentration. The calculated stresses from the above equations tend to be on the conservative side. If the mesh is sufficiently refined, the plate panel stresses may be calculated from the displacements slightly away from the corner point in the said high stress concentration. For a regularly meshed plate panel, f_{Lb}, f_b and f_{LT} may also be directly calculated from the component stresses for the elements in the panel.

f_{cLb} , f_{cb} and f_{cLT} are critical buckling stresses with respect to uniform compression, ideal bending and shear, respectively, and may be determined in accordance with A2/3. In the determination of f_{cL}, f_{cb} and f_{cLT}, the effects of openings are to be accounted for. A practical method for evaluating thin-walled structures is the well established eigenvalue analysis method with suitable edge constraints. If the predicted buckling stresses exceed the proportional linear elastic limit, which may be taken as 0.6 × f_y for steel, plasticity correction is to be made.

In the determination of f_{cL} and f_{cLT}, the effects of openings are to be considered.

For plate panels of bottom girders directly under longitudinal bulkheads and side stringers in way of inner bottom and/or hopper plates, where in-plane support is provided by the surrounding structure, the buckling capacity limits with allowance for redistribution of load specified in 6/7.3.3 may be applied.

7.7.1(b) For face plate and flange.

The breadth to thickness ratio of face plate and flange is to satisfy the limits given in A2/9.7.

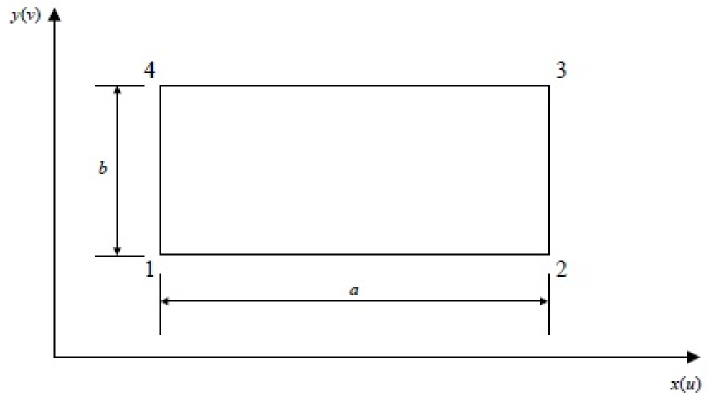
7.7.1(c) For large brackets and sloping webs.

The buckling strength is to satisfy the limits specified in 6/7.7.1(a) above for web plate.

7.7.2 Tripping

Tripping brackets are to be provided in accordance with A2/7.5.

FIGURE 1
Coordinate System for Buckling Strength Evaluation



7.9 Hull Girder Ultimate Strength *(1 January 2010)*

The hull girder ultimate strength can be determined in accordance with Appendix A4, "Hull Girder Ultimate Strength Assessment".

9 Fatigue Damage

9.1 General

An analysis is to be made of the fatigue strength of welded joints and details in highly stressed areas, especially where higher strength steel is used. Special attention is to be given to structural notches, cutouts and bracket toes, and also to abrupt changes of structural sections. A simplified assessment of the fatigue strength of structural details may be accepted when carried out in accordance with Appendix A3.

The following Subparagraphs are intended to emphasize the main points and to outline procedures where refined spectral analysis techniques are used to establish fatigue strength.

9.1.1 Workmanship

As most fatigue data available were experimentally developed under controlled laboratory conditions, consideration is to be given to the workmanship expected during construction.

9.1.2 Fatigue Data

In the selection of S-N curves and the associated stress concentration factors, attention is to be paid to the background of all design data and its validity for the details being considered. In this regard, recognized design data, such as those by AWS (American Welding Society), API (American Petroleum Institute), and DEN (Department of Energy), are to be considered. Sample fatigue data and their applications are shown in Appendix A3 "Rule-based Fatigue Strength Assessment".

If other fatigue data are to be used, the background and supporting data are to be submitted for review.

In this regard, clarification is required whether or not the stress concentration due to the weld profile, certain structural configurations and also the heat effects are accounted for in the proposed S-N curve. Consideration is also to be given to the additional stress concentrations.

9.1.3 Total Stress Range

For determining total stress ranges, the fluctuating stress components resulting from the load combinations specified in A3/7.5 are to be considered.

9.1.4 Design Consideration

In design, consideration is to be given to the minimization of structural notches and stress concentrations. Areas subject to highly concentrated forces are to be properly configured and stiffened to dissipate the concentrated loads.

9.3 Procedures

The analysis of fatigue strength for a welded structural joint/detail may be performed in accordance with the following procedures.

9.3.1 Step 1 – Classification of Various Critical Locations

The class designations and associated load patterns are given in A3/3.3.10 TABLE 1

9.3.2 Step 2 – Simplified Approach

Where deemed appropriate, the accumulative fatigue damage of the structural details classified in Step 1 may be checked in accordance with Appendix A3.

9.3.3 Step 3 – Refined Analysis

Refined analyses are to be performed, as outlined in 6/9.3.3(a) or 6/9.3.3(b) below, for the structural details for which the accumulative fatigue damage exceeds limit, or for which the fatigue characteristics are not covered by the classified details and the associated S-N curves.

The fatigue life of structures is generally not to be less than 20 years, unless otherwise specified.

9.3.3(a) Spectral analysis.

Alternatively, a spectral analysis may be performed, as outlined in 6/9.5 below, to directly calculate fatigue lives for the structural details in question.

9.3.3(b) Refined fatigue data.

For structural details which are not covered by the detail classifications, proposed S-N curves and the associated SCFs, when applicable, may be submitted for consideration. In this regard, sufficient supporting data and background are also to be submitted for review. The refined SCFs may be determined by finite element analyses.

9.5 Spectral Analysis

Where the option in 6/9.3.3(a) is exercised, a spectral analysis is to be performed in accordance with the following guidelines.

9.5.1 Representative Loading Patterns

Several representative loading patterns are to be considered to cover the worst scenarios anticipated for the design service life of the vessel with respect to hull girder local loads.

9.5.2 Environmental Representation *(1 May 2009)*

Instead of the design wave loads specified in Section 3, a wave scatter diagram is to be employed to simulate a representative distribution of all of the wave conditions expected for the design service life of the vessel. In general, the wave data is to cover a time period of not less than 20 years. The probability of occurrence for each combination of significant wave height and mean period of the representative wave scatter diagram is to be weighted, based on the transit time of the vessel at each wave environment within anticipated shipping routes. The representative environment (the wave scatter diagram) is not to be taken less severe than North Atlantic Ocean in terms of fatigue damage.

9.5.3 Calculation of Wave Load RAOs

The wave load RAOs with respect to the wave-induced bending moments, shear forces, motions, accelerations and hydrodynamic pressures can then be predicted by ship motion calculation for a selected representative loading condition.

9.5.4 Generation of Stress Spectrum

The stress spectrum for each critical structural detail (spot) may be generated by performing a structural analysis, accounting for all of the wave loads separately for each individual wave group. For this purpose, a 3D structural model may be used for determining structural responses. The additional secondary and tertiary stresses are also to be considered.

9.5.5 Cumulative Fatigue Damage and Fatigue Life

Based on the stress spectrum and wave scatter diagram established above, the cumulative fatigue damage and the corresponding fatigue life can be estimated by the Palmgren-Miner linear damage rule.

9.7 Fatigue and Fracture Analysis for Type-B Independent Tanks *(1 June 2011)*

IMO IGC requires advanced analyses for type-B independent tanks. Additional analyses are to be conducted for type-B independent tank in accordance with Appendix A5 “Fatigue and Fracture Analysis for Type-B Independent Tanks”:

- Fatigue damage analysis
- Fracture mechanics analysis
- Leakage analysis
- Thermal stress analysis

APPENDIX 1

Structural Modeling and Analysis

1 General

The strength assessment procedure outlined in this Appendix is to be applied to verify the strength adequacy of the following, using a set of standard design load cases:

- Plating and stiffeners of hull and cargo tank structures
- Main supporting members of hull and cargo tank structures, and
- Cargo tank supports and chocks as well as associated seatings in hull and cargo tank structures

The primary concern for the ship structural system is the strength adequacy against external sea, internal liquid pressures, hull girder load effects and other service loads.

It is generally expected that hull girder load effects such as vertical and horizontal bending moments within 0.4*L* amidships are higher than those beyond 0.4*L* amidships. On the other hand, local dynamic loads experienced by hull and cargo tank structures beyond 0.4*L* amidships are more severe than those within 0.4*L* amidships. Furthermore, the fore- and aft-most cargo tanks are generally adjusted to the finer hull geometry beyond 0.4*L* amidships. Therefore, hull and cargo tank structures beyond 0.4*L* amidships are also to be evaluated. The procedure in this Appendix is applicable to hull/cargo tank structures in the forebody, midship and aftbody regions.

3 Overview of Strength Assessment

The standard design load cases given in Section 4 represent combinations of individual design load components defined in Section 3. When warranted, additional design load cases are also to be analyzed to verify the strength of main supporting members against wave impact on bow, bow flare slamming, flat bottom slamming and sloshing. The dynamic load formulae given in Section 3 and Section 4 can be directly applied to the global finite element model using recognized finite element modeling/analysis/post-processing software tools.

This Appendix describes the finite element modeling and analysis techniques generally used for hull/cargo tank structures. These techniques may be substituted by alternative techniques. It is recommended that consultation with ABS on the alternative techniques be made before commencing structural idealization.

The acceptance criteria for the strength assessment procedure are given in Section 6.

Appropriate documentation of the strength assessment described in A1/7 is essential for ABS plan approval. A complete technical report is to be prepared as supporting data of design and submitted together with the relevant plans for ABS review.

5 Structural Idealization

5.1 Structural Modeling Principles

Strength evaluation of hull and cargo tank structures is to follow the structural design process which typically starts with the structural layout and scantlings for the midship region. Therefore a finite element model for the midship region may first be analyzed. To evaluate hull and cargo tank structures with reasonable accuracy, the finite element model is to ideally locate the target cargo tank in the middle and extend approximately one half the length of the adjacent tanks fore and aft.

When the hull and cargo tank structures beyond the 0.4L amidships are sufficiently established, finite element models representing the fore- or aft-most cargo tanks can be constructed. These models are to be used to examine the effects of changes in load characteristics, hull form, cargo tank shape and tank support arrangement on the proposed scantlings.

For the forebody hull and cargo tank structures, it is recommended that the structure forward of the collision bulkhead be included in the finite element model. Otherwise, the model may be terminated at a relatively stiff cross section in the fore end structure. The model is to be extended to the mid of No. 2 cargo tank.

The aft end of the finite element model for the aftbody hull and cargo tank structures may terminate at the aft transverse bulkhead of the slop tanks or engine room bulkhead. The model is to be extended to the mid of the cargo tank forward the aft-most cargo tank.

A1/5.1 FIGURE 1 shows the extents of typical fore, midship and aft cargo tank finite element models.

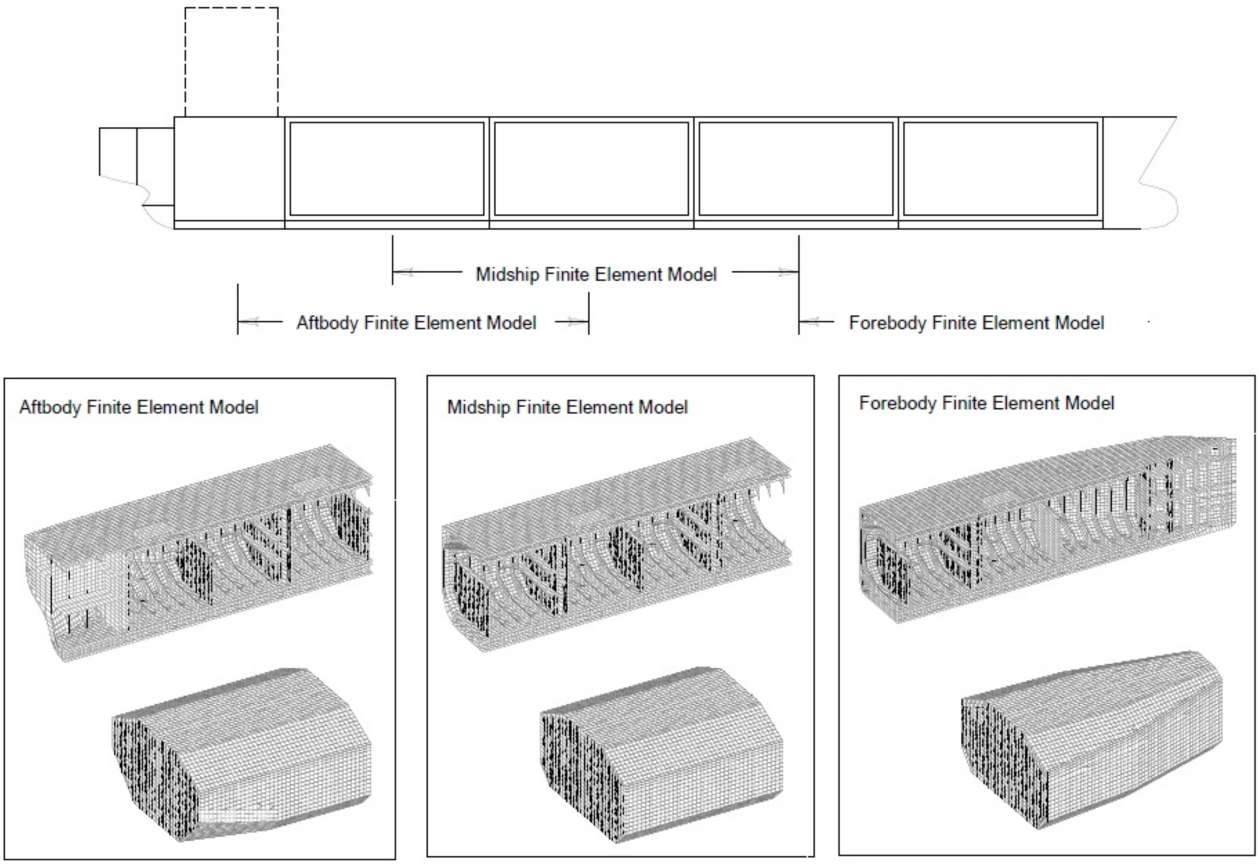
It is recommended that the finite element model cover both port and starboard sides of the vessel for convenience of post-processing and subsequent strength evaluation.

If the extent of a finite element model is shorter than recommended above, the boundary effects may be more significant and the carry-over load effects as a result of the adjacent tanks being loaded may not be suitably represented. In this case, strength assessment of structural members is to be, in principle, carried out based on more conservative acceptance criteria. It is recommended that consultation be made with ABS on the acceptable criteria before commencing the strength evaluation using truncated models.

In general, hull and cargo tank structures are to be evaluated using global finite element models for identification of critical areas. These critical areas are to be further analyzed using fine mesh local models using the boundary conditions derived from a solved global model. For structural connections of high stress gradient which can be identified based on operational experience or from the aforementioned local finite element models, fine mesh models of thickness mesh size are to be developed to establish hot spot stress distribution.

Finite element models are to be constructed using the gross scantlings. Owner’s extra scantlings as included in the vessel’s design specifications are not to be used in the models.

FIGURE 1
Finite Element Models for Typical Fore, Midship and Aft Hull/Cargo Tank Structures



5.3 Global Finite Element Modeling

5.3.1 Modeling of Hull and Cargo Tank Structures

A global finite element model is to be constructed to capture the following structural behaviors:

- Primary hull girder bending
- Secondary bending of main supporting members between watertight boundaries
- Additional secondary bending between main supporting members
- Interaction between the hull structure and cargo tanks through chocks

The model is to adequately represent the overall stiffness distribution in the hull and cargo tank structures. Secondary in-plane bending is to be accurately transmitted to supporting structural members.

Bar elements are commonly used to model longitudinals and stiffeners on watertight boundaries so that local pressures can be proportionally transmitted to main supporting members. If longitudinals and stiffeners are modeled using rod elements (no bending stiffness), local pressures on watertight boundaries are to be directly imposed on the main supporting members. Details of such load shifting are to be submitted for review.

Hull and cargo tank structures may be conveniently modeled using quadrilateral plate bending elements for plating, rod elements for flanges of main supporting members and bar elements for longitudinals/stiffeners. Quadrilateral membrane elements may also be used, provided that local pressure loads do not cause singularities in the finite element model.

The number of triangular elements, or quadrilateral elements with less than ideal proportions, is to be kept to a minimum and only be used to model less critical transitional areas. Critical areas are to be represented by quadrilateral elements of good proportion.

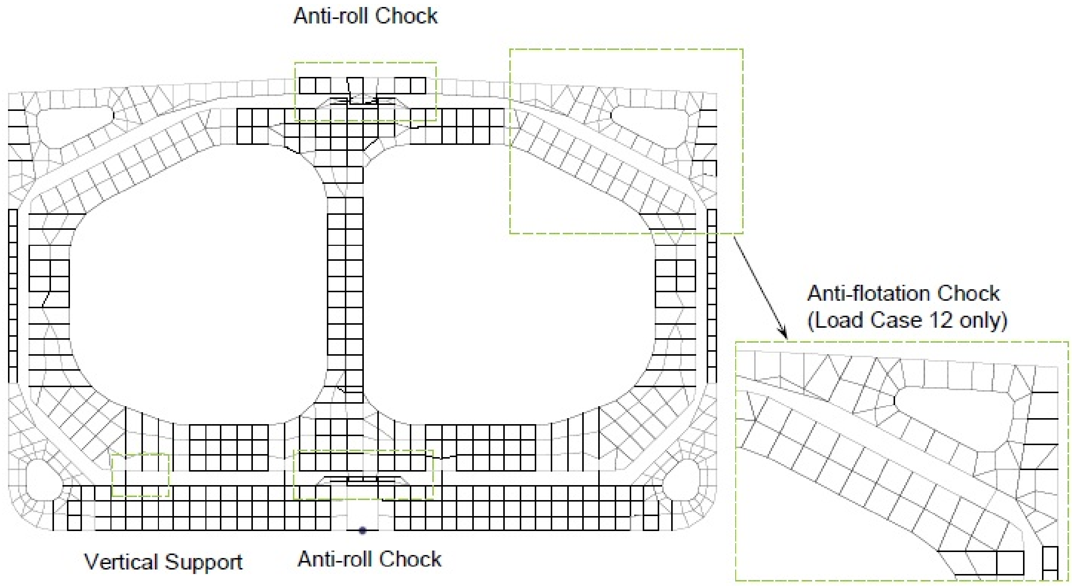
The recommended basic mesh size for capturing field stresses is one longitudinal spacing (see A1/5.3.1 FIGURE 2 for the mesh arrangement). The guidelines for a desirable meshing arrangement are listed below:

- Along the girth of a transverse cross sectional member, one element between two adjacent longitudinals or vertical stiffeners
- Longitudinally, four or more elements between two adjacent web frames fore and aft a transverse bulkhead (aspect ratio approximately equal to 1.0)
- Three or more elements over the depth of double bottom floors, girders, side frames, side stringers, vertical webs and horizontal stringers on transverse bulkheads (aspect ratio approximately equal to 1.0)

It is not recommended to model an opening by deleting elements or having reduced plate thickness as the stresses obtained from such meshing arrangements tend to be unrealistic. If openings are not modeled, the finite element stresses are to be adjusted during post processing for the subsequent strength evaluation to account for reduced effective shear areas.

Rod elements may be used to model the flanges of main supporting members and the first two rows of web stiffeners that are parallel to the flanges. If a web stiffener is sniped at one end, the effective axial area is to be 65% of the cross section area. If both ends are sniped, the effective axial area is to be taken as 30% of the cross section area.

FIGURE 2
Mesh Arrangement for Global Finite Element Model (Main Supporting Members, Supports and Chocks)



5.3.2 Modeling of Supports and Chocks *(1 August 2019)*

Hull and cargo tank structures usually interact through the following supports and chocks which may be represented using rod elements:

- Vertical cargo tank supports,
- Anti-roll chocks,
- Anti-pitch (or collision) chocks,
- Anti-flotation chocks.

These rod elements are intended to represent the overall structural response of the aforementioned supports and chocks. The axial stiffness of each support (or chock) is to be determined from the properties of the layers of special materials such as plywood, resin and adhesive as well as the seatings mounted on the hull and cargo tank structures.

As cargo tank supports and chocks do not physically carry any tensional forces, the final results for some standard load cases are to be obtained by progressively removing those rod elements that are in tension. In some cases, it may take several iterations to reach the final force equilibrium. Iterations do not need to be carried out for load cases 4, 7, 8, 9 and 11 (4/5 TABLE 1 and 4/5 TABLE 2) as applicable for yielding and buckling assessment, and for Ballast Loading Conditions LC1 through LC8 as applicable for the fatigue strength assessment (4/5 TABLE 4) since these are not critical for the tank supports and chocks.

For anti-pitch and anti-roll chocks, there are two contact surfaces on each side of the male key. Rod elements may be introduced to each surface. Those rod elements in tension are to be removed from the subsequent analysis.

For anti-flotation chocks, rod elements may be introduced to each surface for load case 12 only, as shown in A1/5.3.1 FIGURE 2. Those rod elements in tension are to be removed from the subsequent analysis.

The interaction between hull and cargo tank structures in way of supports and chocks may be represented using gap elements or non-linear rod elements with zero stiffness when under tensions.

5.5 Finite Element Modeling for Critical Structural Areas

5.5.1 General

In order to have critical structural areas modeled with the desired accuracy, the mesh size is to be finer than the recommended basic mesh size for global finite element models. For access openings in way of suspected high stress areas, bracket connections, supports and chocks, element sizes of $^{1}/_{5} \sim {}^{1}/_{10}$ longitudinal spacing may be required. Element sizes finer than $^{1}/_{10}$ longitudinal spacing are not recommended unless the stress concentration factor (SCF) at a structural detail is to be established. Any transition from relatively coarse mesh to finer mesh is to be smooth and gradual.

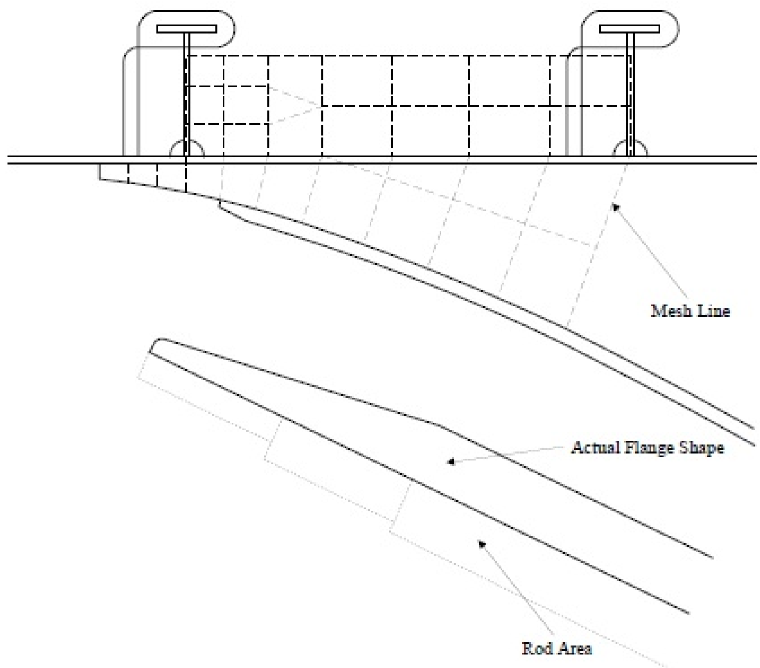
A1/5.5.1 FIGURE 3 shows one acceptable meshing arrangement for a bracket toe for calculating the field or local stress. It is generally not recommended to have the rod or bar element at the tip of the bracket toe directly connected to the attached plating. If the field stress is found approaching the stress limit, a finer mesh model of the bracket may need to be further evaluated.

Materials such as plywood, resin and adhesive are normally fitted to the contacting surfaces of supports or chocks for the purpose of leveling or alignment. The strength of these materials under compressive or frictional contact forces is to be verified in accordance with the requirements in 6/5.11.

The seatings for supports and chocks are to be verified using fine mesh finite element models. Among the supports (or chocks) of the same configuration, a fine mesh finite element model is to be constructed for the one that is subject to the largest contact force.

For each critical structural area, the fine mesh finite element model is to be sufficiently extended to relatively stiff main structural members where the boundary displacements can be properly defined from the global finite element model. Consideration is to be given to the boundary effects on stress distribution in way of the critical structural area.

FIGURE 3
Modeling of Bracket Toe and Tapered Face Plate



5.5.2 Critical Structural Areas *(1 May 2009)*

Critical structural areas are to be identified from a global finite element model and service experience and evaluated using fine mesh finite element models. Upon completion of the global finite element analysis, the following structural areas are to be screened for high stresses. The final list of critical structural areas selected for fine mesh finite element analysis is to be confirmed by ABS.

Hull Structure (See A1/5.5.2 FIGURE 4):

- Dome opening
- Lower and upper brackets of side frame
- Access openings in double bottom floors and girders
- Vertical stiffeners of transverse bulkheads
- Brackets connecting transverse bulkhead vertical stiffeners and deck longitudinals
- Lower brackets of transverse bulkheads

Cargo Tank Structure (See A1/5.5.2 FIGURE 4)

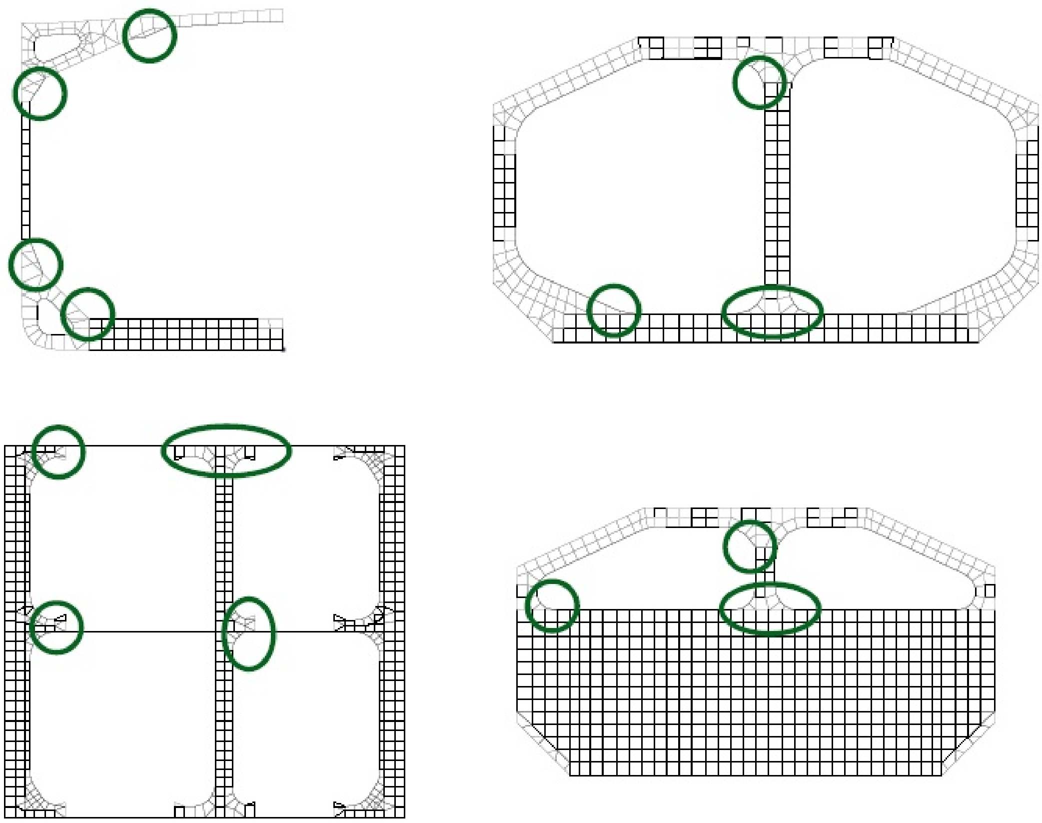
- Bracket connections of transverse web frames
- Bracket connections of swash bulkheads
- Bracket connections of horizontal stringers

Seatings for Cargo Tank Supports and Chocks

- Each type of vertical supports
- Each type of anti-roll chocks
- Each type of anti-pitch chocks
- Each type of anti-flotation chocks

When a relatively flexible structural member is connected to a very stiff main supporting member, the connection bracket is to be evaluated using a fine mesh finite element model. Additional critical areas may be selected for novel structural arrangements and connection details.

FIGURE 4
Critical Areas of Hull and Cargo Tank Structures



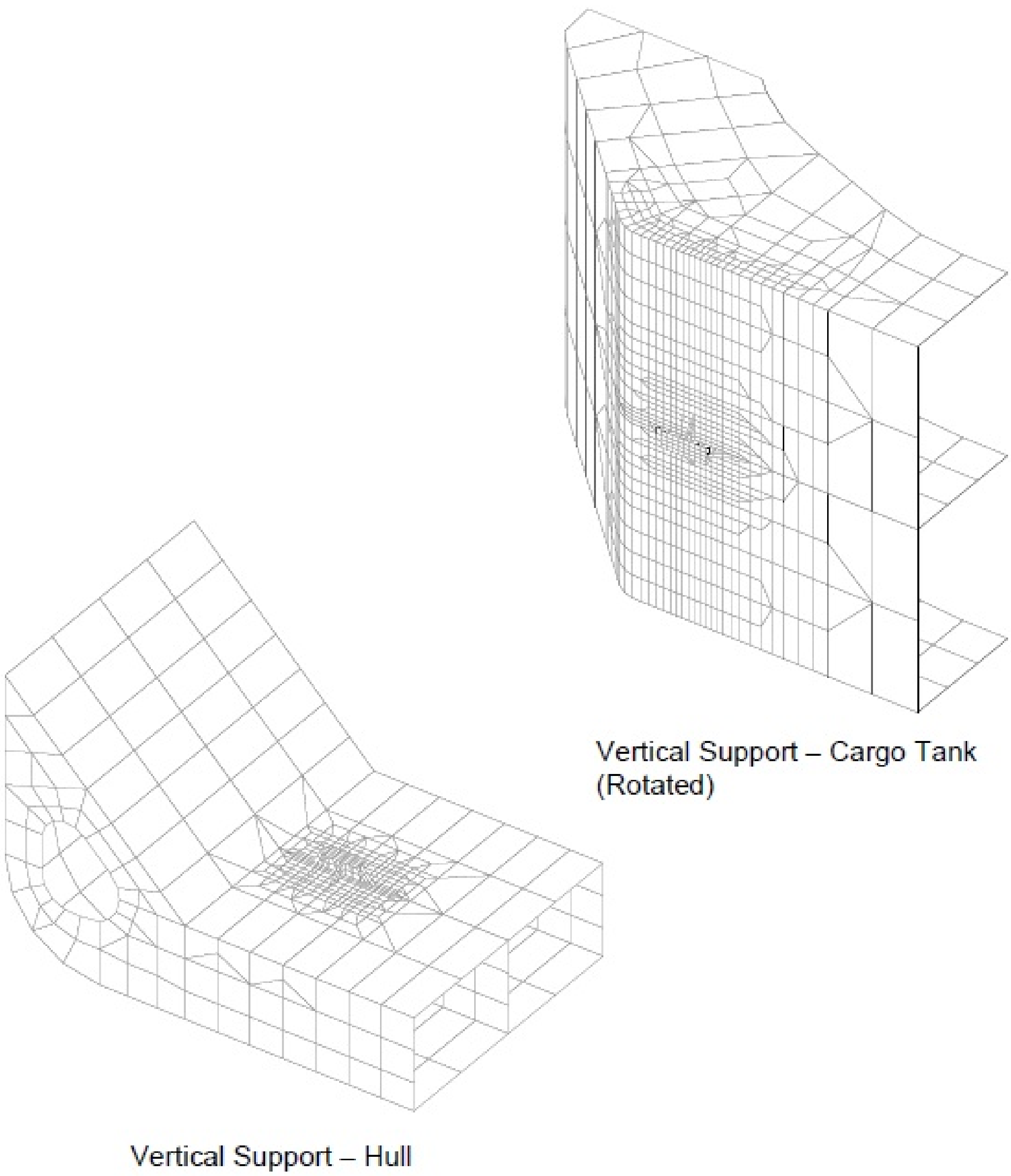
5.5.3 Seatings for Vertical Supports

For each type of vertical supports, two separate fine mesh finite element models are to be analyzed, representing the seatings fitted to the hull and cargo tank structures, respectively. A1/5.5.3 FIGURE 5 shows the two fine mesh models for the most outboard vertical support.

For the seatings fitted to the hull structure, the fine mesh model is to extend, in the longitudinal direction, forward and aft of the vertical support by one floor spacing. In the transverse direction, the model is to terminate at either side girders or other main support members. In the vertical direction, the full depth of the bottom structure including the seatings is to be modeled.

For the seatings fitted to the cargo tank structure, the fine mesh model is to extend, in the longitudinal and transverse directions, in the same way as described above. Vertically, the model is to cover from the bottom plating of the cargo tank including the seatings to the adjacent horizontal stringer.

FIGURE 5
Mesh Arrangement for Critical Structural Areas (Vertical Support)



5.5.4 Seatings for Anti-Roll Chocks

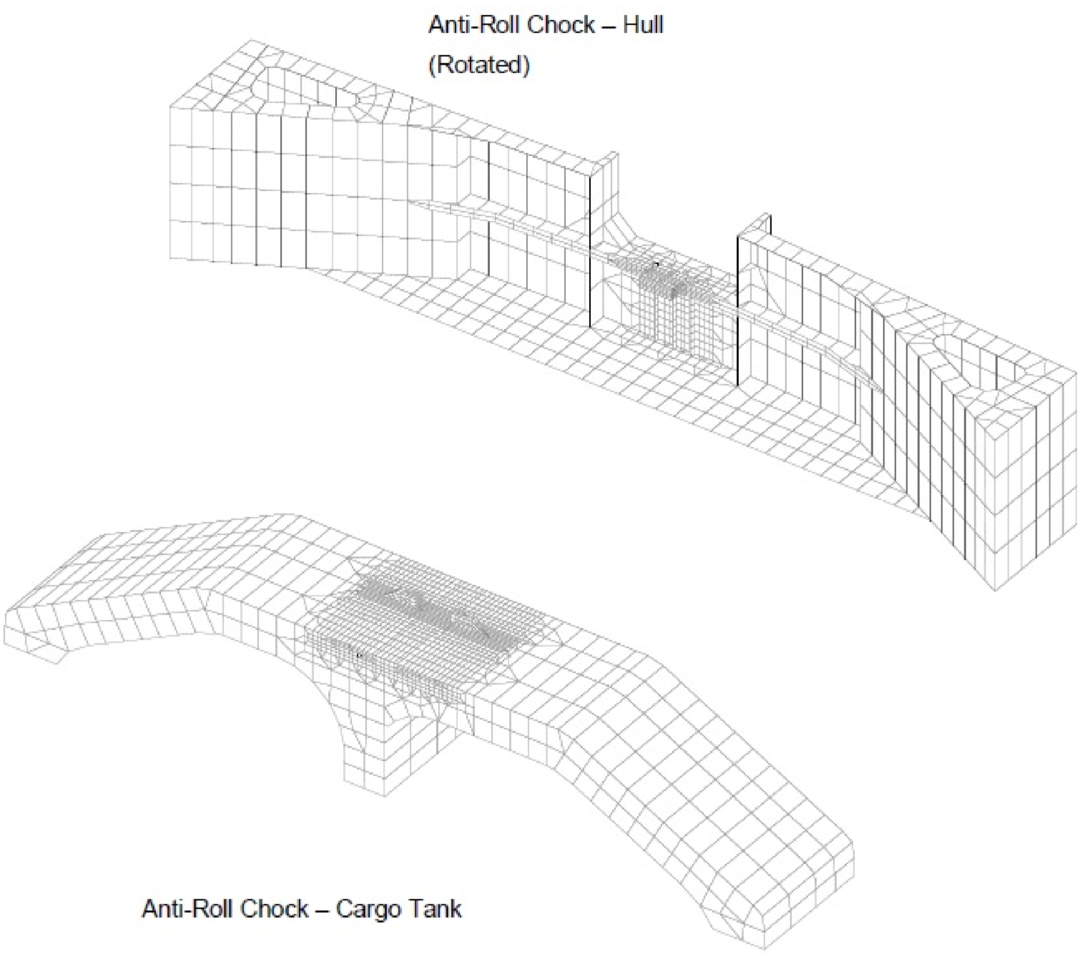
For each type of anti-roll chocks, two separate fine mesh finite element models are to be analyzed, representing the seatings fitted to the hull and cargo tank structures, respectively.

A1/5.5.4 FIGURE 6 shows the two fine mesh models for an anti-roll chock at the deck level.

For the seatings fitted to the hull structure, the fine mesh model is to extend, in the longitudinal direction, forward and aft of the chock by one transverse web frame spacing. In the transverse direction, the model is to terminate at either side girders or other stiff main support members.

For the seatings fitted to the cargo tank structure, the fine mesh model is to extend, in the longitudinal and transverse directions, in the same way as described above. Vertically, the model is to cover from the top plating of the cargo tank including the seatings to the adjacent horizontal stringer.

FIGURE 6
Mesh Arrangement for Critical Structural Areas (Anti-Roll Chock)



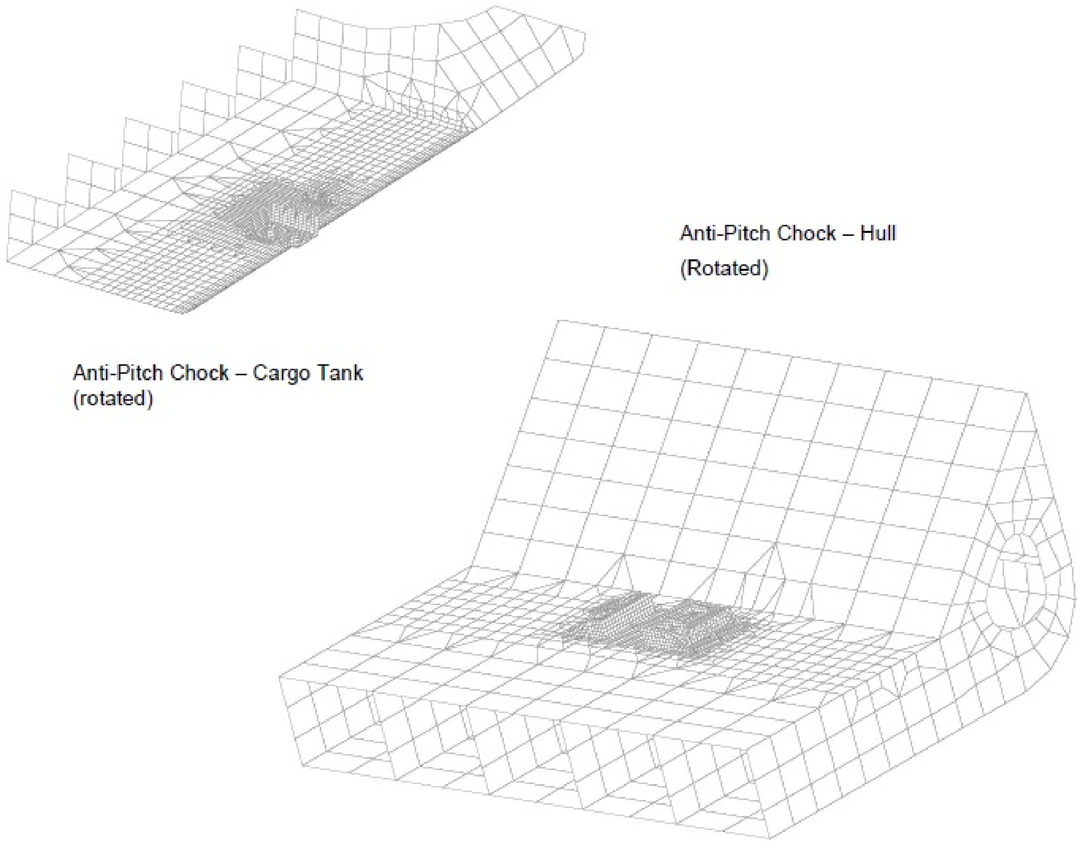
5.5.5 Seatings for Anti-Pitch Chocks

For each type of anti-pitch chocks, two separate fine mesh finite element models are to be analyzed, representing the seatings fitted to the hull and cargo tank structures, respectively.

A1/5.5.5 FIGURE 7 shows the two fine mesh models for an anti-pitch chock at the bottom level.

For the seatings fitted to the hull structure, the fine mesh model is to extend, in the longitudinal direction, forward and aft of the chock by one floor spacing. In the transverse direction, the model is to terminate at either side girders or other main support members. In the vertical direction, the full depth of the double bottom is to be modeled. For the seatings fitted to the cargo tank structure, the fine mesh model is to extend, in the longitudinal and transverse directions, in the same way as described above. Vertically, the model is to extend from one main support members to another main support member.

FIGURE 7
Mesh Arrangement for Critical Structural Areas (Anti-Pitch Chock)

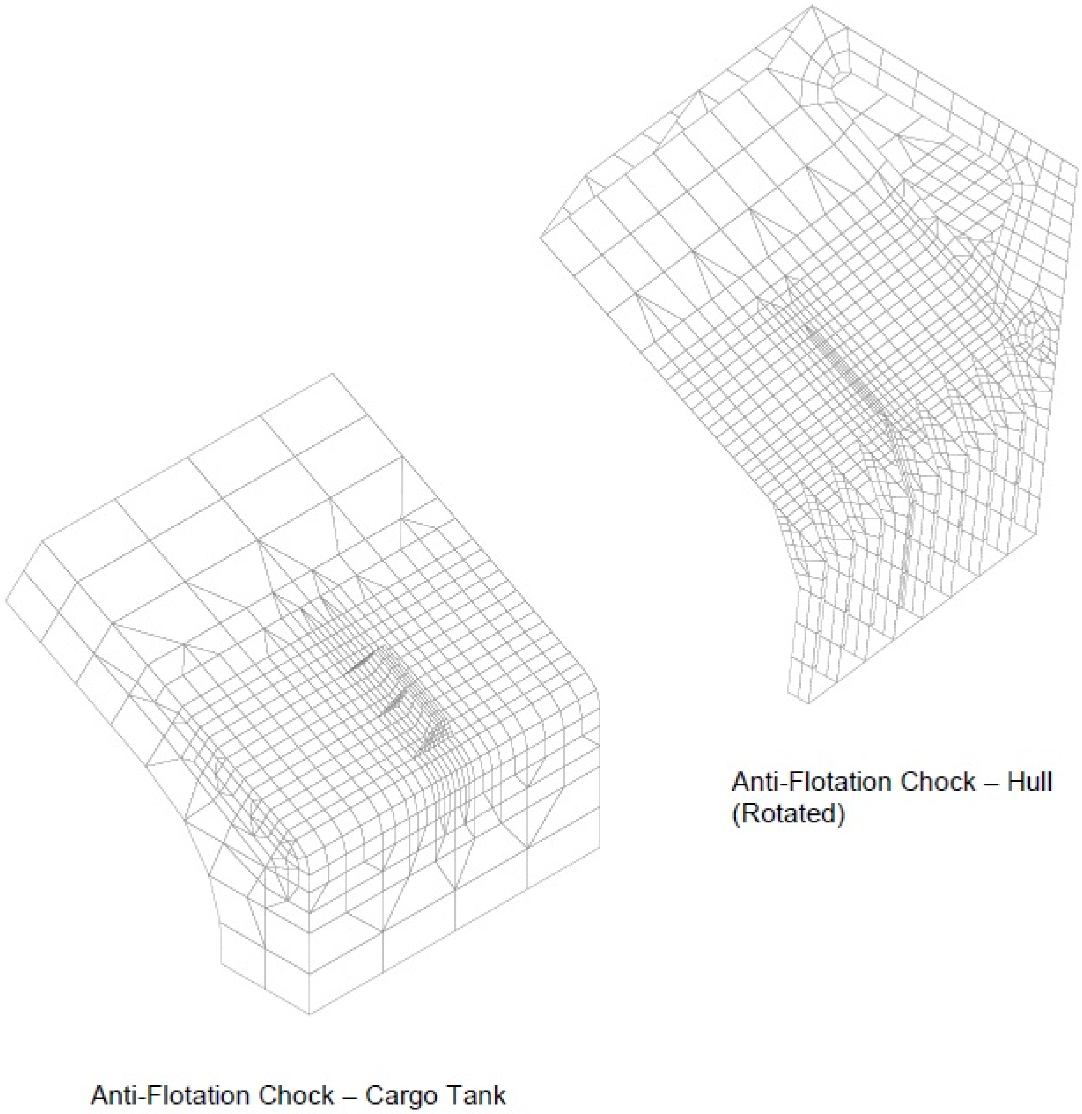


5.5.6 Seatings for Anti-Floatation Chocks

For each type of anti-flotation chocks, two separate fine mesh finite element models are to be analyzed. Typically, the seatings are fitted to the cargo tank structure.

A1/5.5.6 FIGURE 8 shows the two fine mesh models for an anti-flotation chock. For the seatings fitted to the cargo tank structure, the fine mesh model is to extend, in the longitudinal direction, forward and aft of the anti-flotation chock by one web spacing. For the seatings fitted to the hull structure, the fine mesh model is to extend, in the longitudinal direction, forward and aft of the chock by one web spacing.

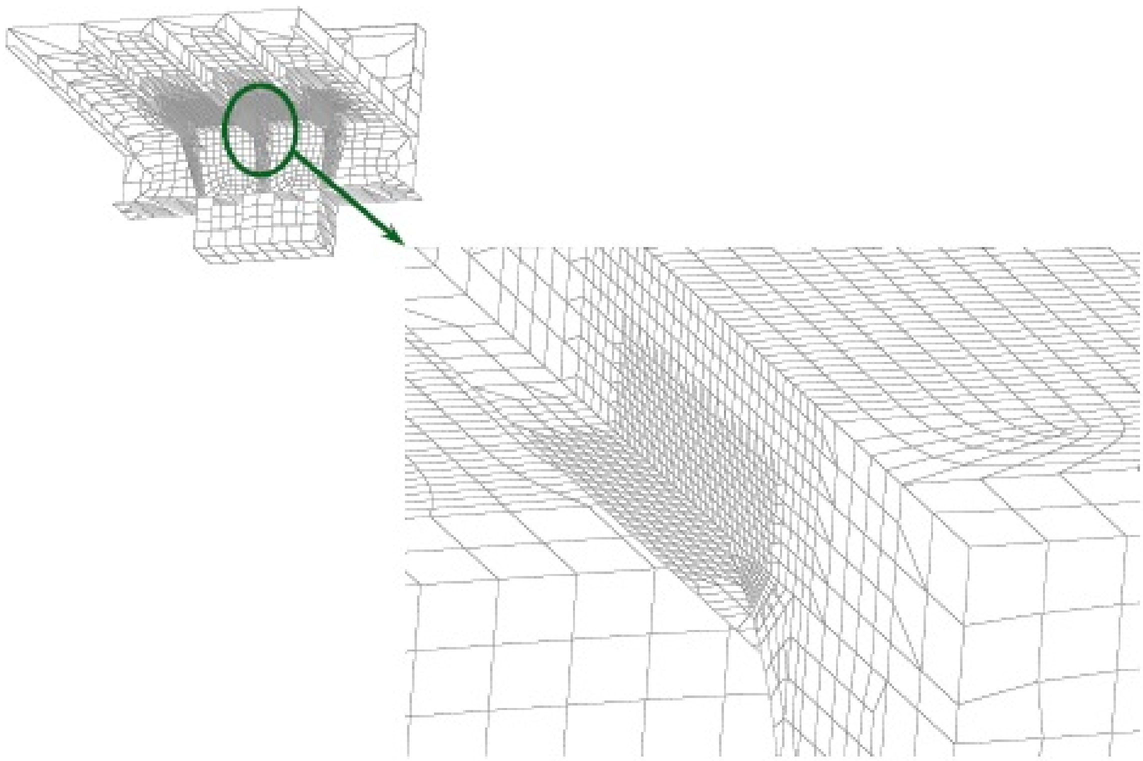
FIGURE 8
Mesh Arrangement for Critical Structural Areas (Anti-Flotation Chock)



5.7 Finite Element Modeling for Critical Structural Details *(1 May 2009)*

Complex structural details that are prone to cracking are to be evaluated in accordance with the fatigue strength requirements in 6/7. For the purpose of fatigue strength verification, hot spot stresses are to be calculated assuming an idealized structural detail with no misalignment. Fine mesh finite element models are to be constructed with a mesh size approximately close to $t \times t$ in way of the target critical detail; the meshing arrangement away from the critical area may be progressively coarser. Quadrilateral elements of good proportion are generally to be used to model the hot spot. A1/5.7 FIGURE 9 shows the fine mesh finite element model for the deck longitudinal connection in way of an anti-roll chock.

FIGURE 9
Fine Mesh Finite Element Analysis for Fatigue Strength Evaluation (Example of Deck Longitudinal Connection in Way of Anti-Roll Chock)



Critical structural details are to be identified from a global finite element model, local fine mesh models, and service experience. Upon completion of the global and local finite element evaluations, the fatigue-prone details in the following structural areas are to be screened for high stress ranges. The final list of critical structural details selected for fatigue strength evaluation is to be confirmed by ABS.

Hull Structure:

- Hatch corners of dome openings
- Lower and upper bracket toes of side frames
- Bracket connections of transverse bulkhead vertical stiffeners at inner bottom and deck levels
- Bracket connections of inner bottom longitudinal in way of vertical supports, anti-roll and anti-pitch chocks
- Bracket connections of side longitudinal close to the ballast waterline
- Bracket toes of deck transverse stiffeners
- Hopper corner connection in way of transverse web frame (mid-tank)

Cargo Tank Structure

- Bracket toes of transverse web frames
- Bracket toes of swash bulkheads
- Bracket toes of horizontal stringers

Seatings for Cargo Tank Supports and Chocks

- Bracket toes of each type of vertical support
- Bracket toes of each type of anti-roll chock
- Bracket toes of each type of anti-pitch chock

7 Boundary Constraints for Local and Hull Girder Sub Load Cases

For each standard design load case listed in Section 4, the load components can be categorized into local and hull girder sub load cases. For each sub load case, the boundary constraints are different. Within a linear, elastic domain, the results for the local and hull girder sub load cases can be combined to obtain the final results of the standard design load cases.

7.1 Local Sub Load Cases *(1 May 2009)*

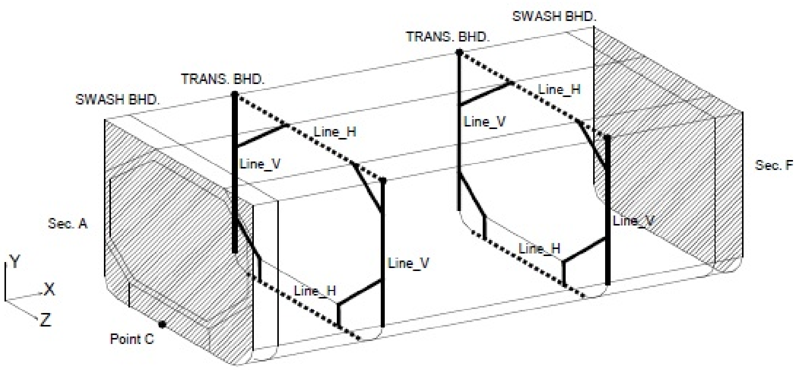
The internal pressure in each ballast or cargo tank can essentially be described by linear pressure distributions in the longitudinal, transverse and vertical directions. It is recommended that these linear pressure distributions are first created as component load cases and repeatedly used to define the local sub load cases for all standard design load cases. This can generally be achieved using appropriate finite element modeling software. A1/7.1 FIGURE 10 illustrates how a global finite element model is constrained and balanced for local sub load cases.

FIGURE 10
Boundary Constraints for Local Sub Load Cases *(1 May 2009)*

Global Midship Finite Element Model

Sec. A and Sec. F	UX = 0, RY = 0, RZ = 0
Point C	UZ = 0
Line_H	UZ = 0* (asymmetric load cases only)
Line_V	UY = 0* (symmetric and asymmetric load cases)

Note: Displacement constraints along Line_H and Line_V are applied initially to the model to calculate unbalanced forces and then removed. Counter forces equal to unbalanced forces are applied along Line_H and Line_V with constraints at the top corners of bulkheads to avoid rigid body motion in the final run.

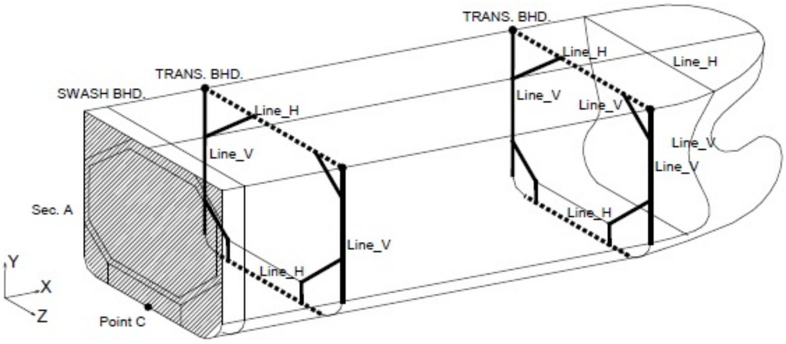


Global Forebody Finite Element Model

Sec. A	UX = 0, RY = 0, RZ = 0

Point C	UZ = 0
Line_H	UZ = 0* (asymmetric load cases only)
Line_V	UY = 0* (symmetric and asymmetric load cases)

Note: Displacement constraints along Line_H and Line_V are applied initially to the model to calculate unbalanced forces and then removed. Counter forces equal to unbalanced forces are applied along Line_H and Line_V with constraints at the top corners of bulkheads to avoid rigid body motion in the final run.



Alternatively, the finite element model may be supported by vertical and horizontal springs to absorb and distribute any unbalanced forces in the vertical and transverse directions. These springs are to be placed along Line_H and Line_V, and may be modeled using rod elements with the cross sectional area defined as follows:

$$A_s = 0.77\frac{A_{shear}\ell_s}{n\ell_t}$$

where

A_s	=	cross sectional area of the spring rod, in cm^2
A_{shear}	=	effective shear area of a hull girder cross section, in cm^2
ℓ_s	=	length of spring rod, in cm
n	=	number of spring rod elements
ℓ_t	=	cargo hold length between transverse bulkheads, in cm

Other methods of constraining and balancing the model may be applied upon ABS review of the details.

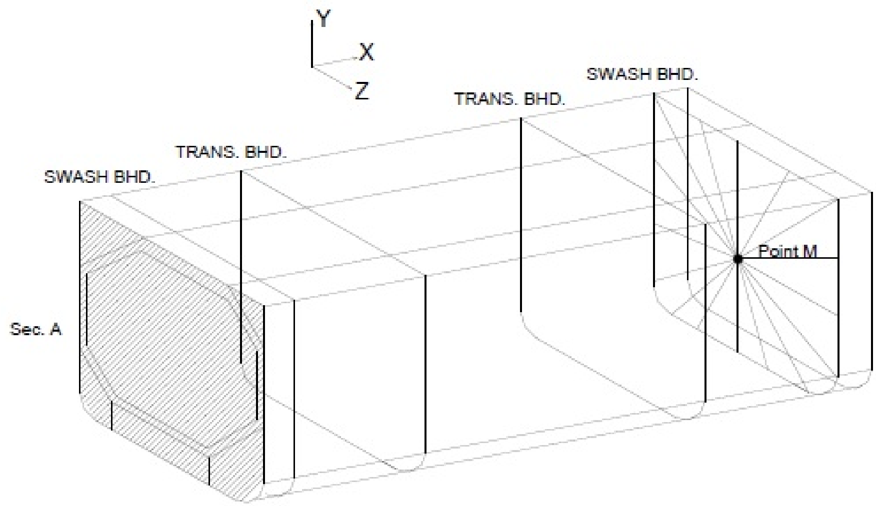
7.3 Hull Girder Sub Load Cases

The boundary constraints for hull girder sub load cases are applied to facilitate the application of the vertical and horizontal bending moments (see A1/7.3 FIGURE 11). As the hull and cargo tank structures extend beyond 0.4*L* amidships, the design vertical and horizontal wave-induced bending moments linearly taper to zero at both ends of the scantling length. The allowable still-water bending moments often follow a linear tapering pattern. The vertical and horizontal bending moments at the middle of the mid cargo tank are to achieve the target values. The aft end of the forebody cargo tank model or the fore end of the aftbody cargo tank model is to be fixed. A relatively stiff cross section such as collision bulkhead or engine room bulkhead is to be selected for application of the target hull girder bending moments.

FIGURE 11
Boundary Constraints for Hull Girder Sub Load Cases

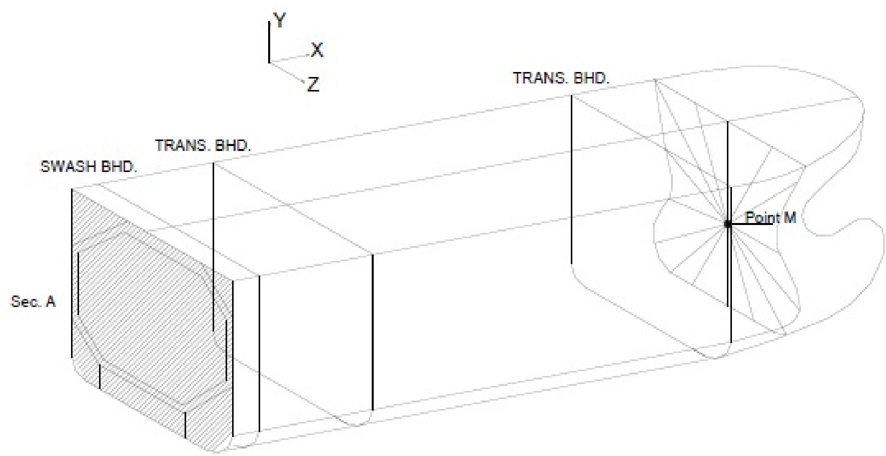
Global Midship Finite Element Model

Sec. A	UX = 0, UY = 0, UZ = 0, RX = 0, RY = 0, RZ = 0
Swash BHD	Rigid Body Element
Point M (Neutral Axis)	Apply Bending Moment



Global Forebody Finite Element Model

Sec. A	UX = 0, UY = 0, UZ = 0, RX = 0 , RY = 0, RZ = 0
Swash BHD	Rigid Body Element
Point M (Neutral Axis)	Apply Bending Moment



9 Overall Check of Finite Element Results

Before proceeding to the strength evaluation in accordance with the acceptance criteria given in Section 6 of this Guide, the finite element results are to be checked for the overall accuracy of the finite element model and the correct transmission of the local and hull girder loads.

The deformed overall finite element model can be visually examined for the expected deformation patterns and the appearance of abnormal nodal displacements due to singularity. Correct deformation patterns are indicative of the adequacy of the boundary constraints. The finite element model can first be analyzed for the local and hull girder sub load cases, and the final results for the standard design load cases are obtained by linear combinations of these sub load cases. Therefore, multi-level visual examination of the deformed overall model can be carried out for the specified load cases.

Visual examination of the deformed main supporting members of cargo or ballast tanks are also to be carried out in the same manner to confirm correct application of local pressures.

In addition to the above visual examination of the deformed global finite element model and element representations of main supporting members and tanks, the stress magnitudes are to be compared with those calculated using simple beam theory. For the hull girder sub load cases, comparison is typically made at the deck at side, sufficiently away from the boundaries and transverse bulkheads. The stress levels of the main supporting members in the local load cases are to be consistent with the applied local pressures.

11 Documentation of Strength Assessment for Classification Review

A technical report is to be prepared to document the essential information used in the strength assessment and submitted to ABS for review. As a minimum, the documentation is to include the following:

- A list of reference structural drawings, including dates and versions
  - General Arrangement
  - Trim, Stability and Longitudinal Strength Calculation
  - Tank Capacity Plan
  - Midship Section
  - Construction Profile and Deck Plan
  - Shell Expansion
  - Arrangement of Cargo Tank Supports and Scantlings
  - Key Sections of Engine Room Structure (required for aftbody finite element model)
  - Key Sections of Fore End Structure (required for forebody finite element model)
  - Key Sections of Cargo Tank (required for fore- and aftbody finite element models)
- Vessel's design load envelope curves, such as still-water bending moment curves
- The particulars of the finite element modeling, analysis and post-processing programs used
- Owner's extra scantlings as defined in vessel's design specifications
- Effective accelerations in longitudinal, transverse and vertical direction for each cargo or ballast tank
- External pressure distribution at the mid-tank cross section for standard design load cases
- Physical parameters and load combination factors defining standard design load cases
- Detailed description of finite element structural modeling and assumptions
- Description of material properties
- Description of load application and boundary constraints for hull girder and local sub load cases

- Plots showing finite element meshing and scantlings
- Vertical and horizontal moments of inertia and neutral axes of the reference section
- Plots showing internal and external pressure distributions of typical cross sections and elevations
- Stress/deformation plots and verification of structural behavior under local and hull girder sub load cases
- Stress/deformation plots of overall structural model and critical areas under standard design load cases to demonstrate the acceptance criteria are not exceeded
- Results for buckling strength assessments of hull and cargo tank boundaries and main supporting members
- Component, von-Mises and principal stress plots of critical structural members/details
- Recommended modifications to the reference drawings and strength assessment results for modified structural members/details

ABS may request detailed results and data files for verification and reference so that any discrepancies can be quickly identified.

APPENDIX 2
Calculation of Critical Buckling Stresses

1 General

The critical buckling stresses for various structural elements and members may be determined in accordance with this Appendix or other recognized design practices. Critical buckling stresses derived from experimental data or analytical studies may be considered, provided that well-documented supporting data are submitted for review.

3 Rectangular Plates

The critical buckling stresses for rectangular plate elements, such as plate panels between stiffeners; web plates of longitudinals, girders, floors and transverses; flanges and face plates, may be obtained from the following equations, with respect to uniaxial compression, bending and edge shear, respectively.

$f_{ci} = f_{Ei}$ for $f_{Ei} \leq P_r f_{yi}$

$f_{ci} = f_{yi}\left[1 - P_r(1 - P_r) f_{yi}/f_{Ei}\right]$ for $f_{Ei} > P_r f_{yi}$

where

f_{ci} = critical buckling stress with respect to uniaxial compression, bending or edge shear, separately, kgf/cm^2

f_{Ei} = $K_i\left[\pi^2 E/12\left(1 - \nu^2\right)\right](t_n/s)^2$, kgf/cm^2

K_i = buckling coefficient, as given in A2/3 TABLE 1

E = modulus of elasticity of the material, may be taken as 2.1×10^6 kgf/cm^2 for steel

ν = Poisson's ratio, may be taken as 0.3 for steel

t_n = net thickness of the plate, in cm

s = spacing of longitudinals/stiffeners, in cm

P_r = proportional linear elastic limit of the structure, may be taken as 0.6 for steel

f_{yi} = f_y, for uniaxial compression and bending

= $f_y/\sqrt{3}$, for edge shear

f_y = specified minimum yield point of the material, in kgf/cm^2

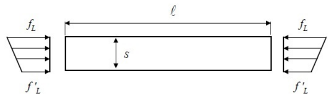
TABLE 1
Buckling Coefficient, K_i

For Critical Buckling Stress Corresponding to f_L, f_T, f_b or F_{LT}

I. Plate panel between stiffeners — K_i

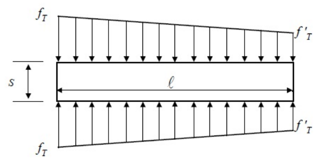
A Uniaxial compression

1. Long plate
$\ell \geq s$



a. For $f'_L, = f_L$: $4C_1$,
b. For $f'_L, = f_L/3$: $5.8C_1$,
(see note)

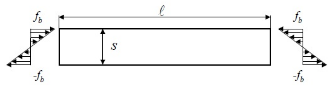
2. Wide plate
$\ell \geq s$



a. For $f'_T, = f_T$: $[1 + (s/\ell)^2]^2 C_2$
b. For $f'_T, = f_T/3$: $1.45[1 + (s/\ell)^2]^2 C_2$
(see note)

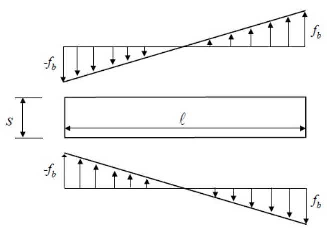
B Ideal Bending

1. Long plate
$\ell \geq s$



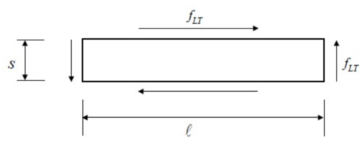
$24C_1$

2. Wide plate
$\ell \geq s$



a. For $1.0 \leq \ell/s \leq 2.0$: $24(s/\ell)^2 C_2$
b. For $2.0 < \ell/s$: $12(s/\ell)C_2$

C Edge Shear



K_i
$[5.34 + 4(s/\ell)^2]C_1$

D Values of C_1 and C_2

1. For plate panels between angles or tee stiffeners

$C_1 = 1.1$

$C_2 = 1.3$ within the double bottom or double side*

$C_2 = 1.2$ elsewhere

2. For plate panels between flat bars or bulb plates

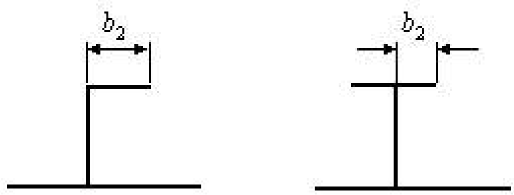
$C_1 = 1.0$

$C_2 = 1.2$ within the double bottom or double side*

$C_2 = 1.1$ elsewhere

* applicable where shorter edges of a panel are supported by rigid structural members, such as bottom, inner bottom, side shell, inner skin bulkhead, double bottom floor/girder and double side web stringer.

II. Web of Longitudinal or Stiffener	K_i
A Axial compression	
Same as I.A.1 by replacing s with depth of the web and ℓ with unsupported span	
a. For $f'_L = f_L$:	$4C$
b. For $f'_L = f_L/2$:	$5.2C$
(see note)	
where	
$C = 1.0$ for angle or tee stiffeners	
$C = 0.33$ for bulb plates	
$C = 0.11$ for flat bars	
B Ideal Bending	
Same as I.B.	$24C$
III. Flange and Face Plate	K_i
Axial Compression	0.44



$s = b_2$

ℓ = unsupported span

Note: In I.A. (II.A), K_i for intermediate values of $f'_L/f_L(f'_T/f_T)$ may be obtained by interpolation between a and b.

5 Longitudinals and Stiffeners

5.1 Axial Compression

The critical buckling stress, f_{ca}, of a beam-column, i.e., the longitudinal and the associated effective plating, with respect to axial compression may be obtained from the following equations:

$$f_{ca} = f_E \qquad \text{for} \quad f_E \le P_r f_y$$

$$f_{ca} = f_y\left[1 - P_r(1 - P_r)f_y/f_E\right], \qquad \text{for} \quad f_E > P_r f_y$$

where

f_E = $\pi^2 E/(\ell/r)^2$ kgf/cm^2

ℓ = unsupported span of the longitudinal or stiffener, in cm

r = radius of gyration of area A_e, in cm

A_e = $A_s + b_{wL} t_n$

A_s = net sectional area of the longitudinals or stiffeners, excluding the associated plating, cm^2

b_{wL} = effective width of the plating as given in 6/7.3.2, in cm

t_n = net thickness of the plating, in cm

f_y = minimum specified yield point of the longitudinal or stiffener under consideration, kgf/cm^2

P_r and E are as defined in A2/3.

5.3 Torsional/Flexural Buckling

The critical torsional/flexural buckling stress with respect to axial compression of a longitudinal, including its associated plating (effective width, b_{wL}), may be obtained from the following equations:

$f_{ct} = f_{ET}$ for $f_{ET} \le P_r \ f_y$

$f_{ct} = f_y[1 - P_r(1 - P_r)f_y/f_{ET}]$ for $f_{ET} > P_r \ f_y$

where

f_{ct} = critical torsional/flexural buckling stress with respect to axial compression, kgf/cm^2

f_{ET} = $E\left[K/2.6 + (n\pi/\ell)^2\Gamma + C_0(\ell/n\pi)^2/E\right]/I_o\left[1 + C_o(n\pi/\ell)^2/I_o f_{cL}\right]$, kgf/cm^2

K = St. Venant torsion constant for the longitudinal's cross section, excluding the associated plating.

= $\left[b_f t_f^3 + d_w t_w^3\right]/3$

I_o = cluding the associated plating, about the toe (intersection of web and plating), in cm^4

= $I_x + mI_y + A_s(x_o^2 + y_o^2)$

I_x, I_y = moment of inertia of the longitudinal about the x-and y-axis, respectively, through the centroid of the longitudinal, excluding the plating (x-axis perpendicular to the web), in cm^4

m = $1.0 - u(0.7 - 0.1d_w/b_f)$

u = unsymmetry factor

= $1 - 2b_1/b_f$

x_o = horizontal distance between centroid of stiffener, A_s, and centerline of the web plate, cm

y_o = vertical distance between the centroid of the longitudinal's cross section and its toe, cm

d_w = depth of the web, cm

t_w = net thickness of the web, cm

b_f = total width of the flange/face plate, cm

b_1 = smaller outstanding dimension of flange with respect to centerline of web (see A2/5.3 FIGURE 1), cm

t_f = net thickness of the flange/face plate, cm

C_o = $Et_n^3/3s$

Γ = warping constant

≅ $mI_{yf}d_w^2 + d_w^3 t_w^3/36$

I_{yf} = $t_f \ b_f^3(1.0 + 3.0u^2 d_w t_w/A_s)/12$, cm^4

f_{cL} = critical buckling stress for the associated plating, corresponding to n-half waves, kgf/cm^2

= $\pi^2 E(n/\alpha + \alpha/n)^2 (t_n/s)^2 / 12(1 - v^2)$

α = ℓ/s

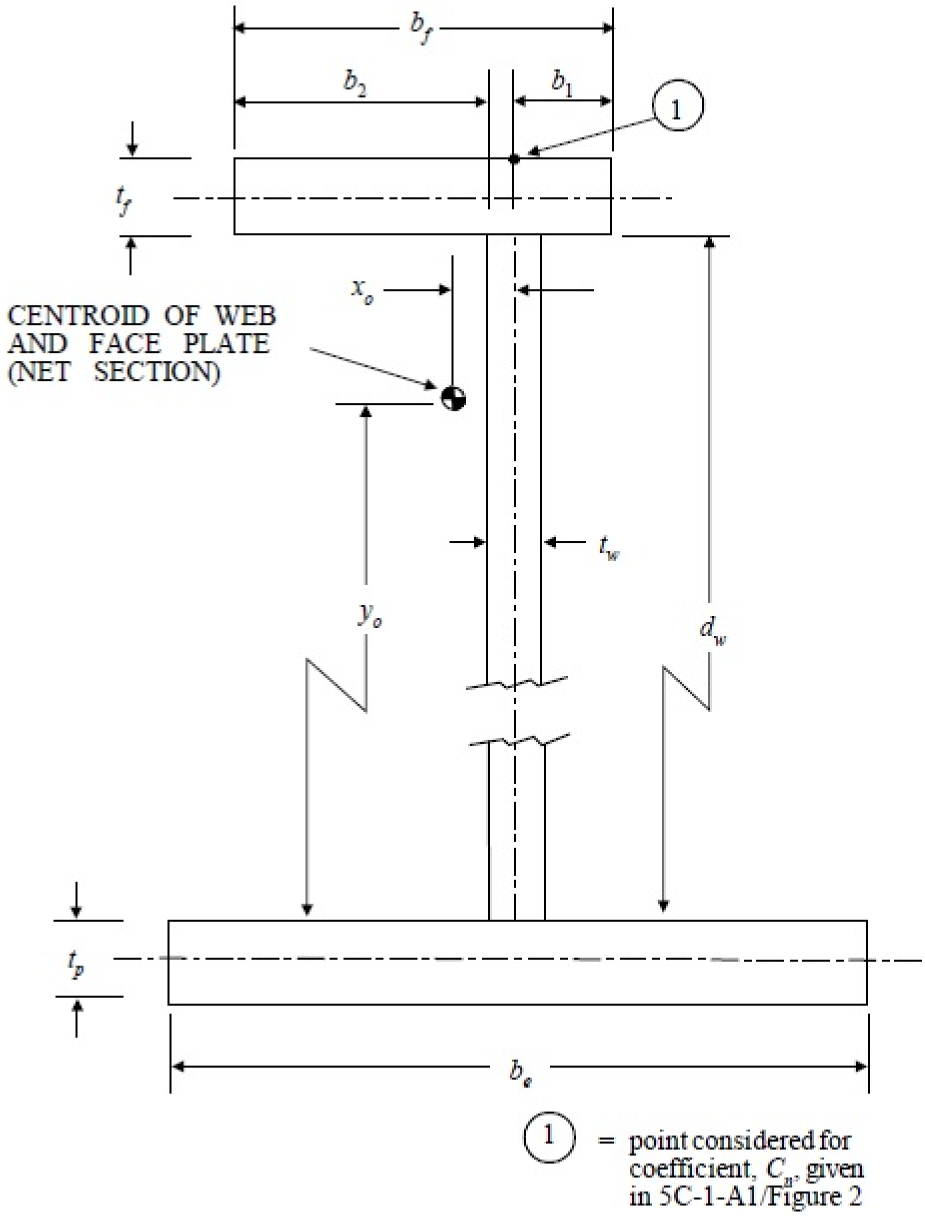
n = number of half-wave which yield a smallest f_{ET}

f_y = minimum specified yield point of the longitudinal or stiffener under consideration, kgf/cm^2

P_r, E, s and v are as defined in A2/3.

A_s, t_n and ℓ are as defined in A2/5.1.

FIGURE 1
Dimensions and Properties of Stiffeners



7 Deep Girders, Webs and Stiffened Brackets

7.1 Critical Buckling Stresses of Web Plates and Large Brackets

The critical buckling stresses of web plates and large brackets between stiffeners may be obtained from the equations given in A2/3 for uniaxial compression, bending and edge shear.

7.3 Effects of Cut-outs

The depth of cut-out, in general, is to be not greater than $d_w/3$, and the stresses in the area calculated are to account for the local increase due to the cut-out.

When cut-outs are present in the web plate, the effects of the cut-outs on reduction of the critical buckling stresses is to be considered, as outlined in the Subparagraphs below.

7.3.1 Reinforced by Stiffeners Around Boundaries of Cut-outs

When reinforcement is made by installing straight stiffeners along boundaries of the cut-outs, the critical buckling stresses of web plate between stiffeners with respect to compression and shear may be obtained from equations given in A2/3.

7.3.2 Reinforced by Face Plates Around Contour of Cut-outs

When reinforcement is made by adding face plates along the contour of the cut-out, the critical buckling stresses with respect to compression, bending and shear may be obtained from equations given in A2/3, without reduction, provided that the net sectional area of the face plate is not less than $8t_w^2$, where t_w is the net thickness of the web plate, and that depth of the cut-out is not greater than $d_w/3$, where d_w is the depth of the web.

7.3.3 No Reinforcement Provided

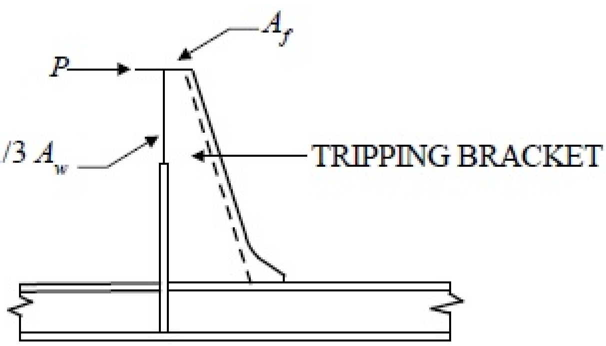
When reinforcement is not provided, the buckling strength of the web plate surrounding the cut-out may be treated as a strip of plate with one edge free and the other edge simply supported.

7.5 Tripping

To prevent tripping of deep girders and webs with wide flanges, tripping brackets are to be installed with a spacing generally not greater than 3 meters.

Design of tripping brackets may be based on the force P acting on the flange, as given by the following equation:

$$P = 0.02 f_{cl}\left(A_f + \tfrac{1}{3}A_w\right)$$



where

f_{cl} = critical lateral buckling stress with respect to axial compression between tripping brackets, kgf/cm²

f_{cl} = f_{ce}, for $f_{ce} \le P_r f_y$

= $f_y[1 - P_r(1 - P_r)f_y/f_{ce}]$, for $f_{ce} > P_r f_y$

f_{ce} = $f_{ce} = 0.6E[(b_f/t_f)(t_w/d_w)^3]^{1/2}$, kgf/cm²

A_f	=	net cross sectional area of the flange/face plate, in cm^2
A_w	=	net cross sectional area of the web, in cm^2

B_f, t_f, d_w, t_w are as defined in A2/5.3.

E, P_r, and f_y are as defined in A2/3.

9 Stiffness and Proportions

To fully develop the intended buckling strength of the assemblies of structural members and panels, supporting elements of plate panels and longitudinals are to satisfy the following requirements for stiffness and proportion in highly stressed regions.

9.1 Stiffness of Longitudinals

The net moment of inertia of the longitudinals, i_o, with effective breadth of net plating, is to be not less than that given by the following equation:

$$i_o = \frac{st_n^3}{12(1-v^2)}\gamma_o \qquad \text{cm}^4$$

where

γ_o	=	$(2.6 + 4.0\delta)\alpha^2 + 12.4\alpha - 13.2\alpha^{1/2}$
δ	=	A/st_n
α	=	ℓ/s
s	=	spacing of longitudinals, cm
t_n	=	net thickness of plating supported by the longitudinal, cm
v	=	Poisson's ratio
	=	0.3 for steel
A	=	net sectional area of the longitudinal (excluding plating), cm^2
ℓ	=	unsupported span of the longitudinal, cm

9.3 Stiffness of Web Stiffeners

The net moment of inertia, i, of the web stiffener, with the effective breadth of net plating not exceeding s or 0.33ℓ, whichever is less, is not to be less than obtained from the following equations:

$$i = 0.17\ell t^3(\ell/s)^3 \qquad \text{cm}^4 \qquad \text{for } \ell/s \le 2.0$$

$$i = 0.34\ell t^3(\ell/s)^2 \qquad \text{cm}^4 \qquad \text{for } \ell/s > 2.0$$

where

ℓ	=	length of stiffener between effective supports, in cm
t	=	required net thickness of web plating, in cm
s	=	spacing of stiffeners, in cm

9.5 Stiffness of Supporting Members

The net moment of inertia of the supporting members, such as transverses and webs, is not to be less than that obtained from the following equation:

$$I_s/i_o \geq 0.2(B_s/\ell)^3(B_s/s)$$

where

I_s = moment of inertia of the supporting member, including the effective plating, cm^4

i_o = moment of inertia of the longitudinals, including the effective plating, cm^4

B_s = unsupported span of the supporting member, cm

ℓ and s are as defined in A2/9.1.

9.7 Proportions of Flanges and Face Plates

The breadth-thickness ratio of flanges and face plates of longitudinals and girders is to satisfy the limits given below:

$$b_2/t_f = 0.4(E/f_y)^{1/2}$$

where

b_2 = larger outstanding dimension of flange, as given in A2/5.3 FIGURE 1, cm

t_f = net thickness of flange/face plate, cm

E and f_y are as defined in A2/3.

9.9 Proportions of Webs of Longitudinals and Stiffeners

The depth-thickness ratio of webs of longitudinals and stiffeners is to satisfy the limits given below.

$$d_w/t_w \leq 1.5(E/f_y)^{1/2}$$ for angles and tee bars

$$d_w/t_w \leq 0.85(E/f_y)^{1/2}$$ for bulb plates

$$d_w/t_w \leq 0.5(E/f_y)^{1/2}$$ for flat bars

where d_w and t_w, are as defined in A2/5.3 and E and f_y are as defined in A2/3.

When these limits are complied with, the assumption on buckling control stated in 6/7.1.2(e) is considered satisfied. If not, the buckling strength of the web is to be further investigated, as per A2/3.

APPENDIX 3

Rule-based Fatigue Strength Assessment

1 General

1.1 Note

This Appendix provides a designer-oriented approach to fatigue strength assessment which may be used for certain structural details in lieu of more elaborate methods such as spectral fatigue analysis. The term "assessment" is used here to distinguish this approach from the more elaborate analysis.

The criteria in this Appendix are developed from various sources, including the Palmgren-Miner linear damage model, S-N curve methodologies, a long-term environment data of the North-Atlantic Ocean (Walden's Data), etc., and assume workmanship of commercial marine quality acceptable to the Surveyor. The capacity of structures to resist the fatigue is given in terms of fatigue damage to allow designers the maximum flexibility possible.

1.3 Applicability

The fatigue strength assessment in this Appendix is to be applied to welded connections of steel with a minimum yield strength less than 4077 kgf/cm^2.

1.5 Loadings

The criteria have been developed for ordinary wave-induced motions and loads. Other cyclic loadings, which may result in significant levels of stress ranges over the expected lifetime of the vessel, are also to be considered by the designer.

Where it is known that a vessel will be engaged in long-term service on a route with a more severe environment (e.g., along the west coast of North America to Alaska), the fatigue strength assessment criteria in this Appendix are to be modified, accordingly.

1.7 Effects of Corrosion

To account for the mean wastage throughout the service life, the total stress range calculated using the gross scantlings is modified by a factor c_f (see A3/9.3).

3 Connections to be Considered for the Fatigue Strength Assessment

3.1 General

These criteria have been developed to allow consideration of a broad variation of structural details and arrangements, so that most of the important structural details anywhere in the vessel can be subjected to an explicit (numerical) fatigue assessment using these criteria. However, where justified by comparison with details proven satisfactory under equal or more severe conditions, an explicit assessment can be exempted.

3.3 Guidance on Locations

As a general guidance for assessing fatigue strength, the following connections and locations are to be considered:

3.3.1 Connections of Longitudinal Stiffeners to Transverse Web/Floor and to Transverse Bulkhead

i) Two (2) to three (3) selected side longitudinals in the region from the 1.1 × draft to about $^1/_3$ × draft in the midship region and also in the region between 0.15*L* and 0.25*L* from F.P., respectively

ii) One (1) to two (2) selected longitudinals from each of the following groups:

Deck longitudinals, bottom longitudinals, inner bottom longitudinals and longitudinals on side longitudinal bulkheads

One longitudinal on each of the longitudinal bulkheads within 0.1D from the deck is to be included

For these structural details, the fatigue assessment is to be first focused on the flange of the longitudinal at the rounded toe welds of attached flat bar stiffeners and brackets, as illustrated for Class F item 2) and Class F_2 item 1) in A3/3.3.10 TABLE 1.

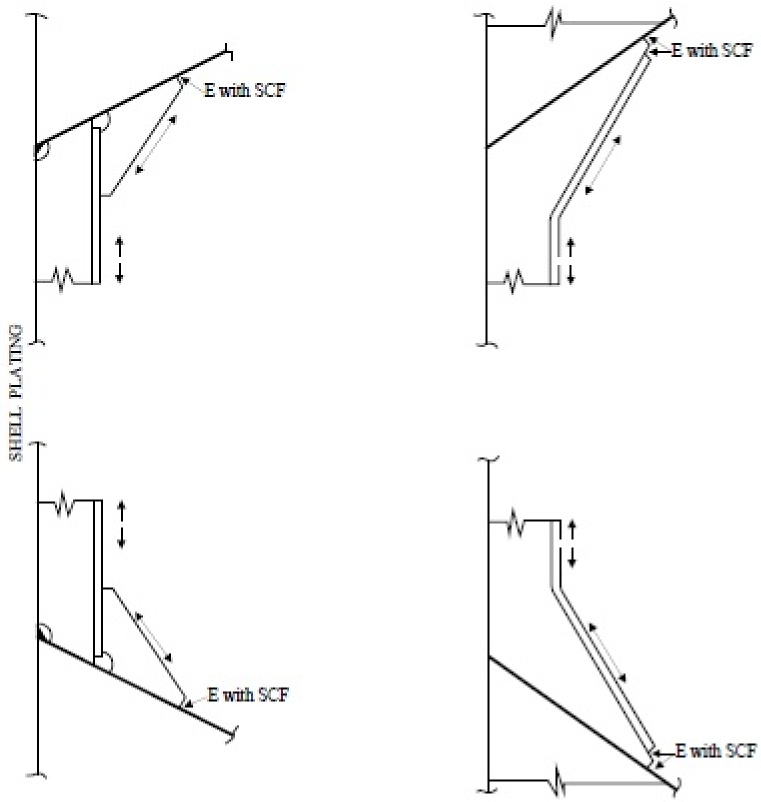
Then, the critical spots on the lower end of the stiffener as well as the weld throat are also to be checked for the selected structural detail.

Where the longitudinal stiffener end bracket arrangements are different on opposing sides of a transverse web, both configurations are to be checked.

3.3.2 Connections of Hold Frame

Typical end connections of hold frames to the upper and lower wing tanks in cargo holds (see A3/3.3.2 FIGURE 1).

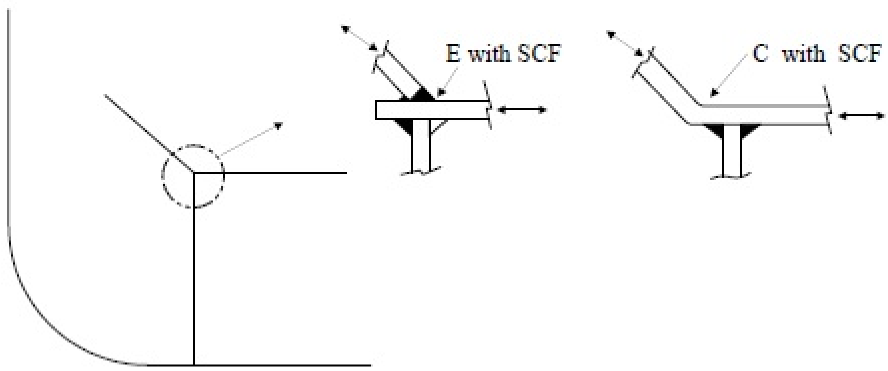
FIGURE 1
Hold Frames



3.3.3 Connections of Slope Plate to Inner Bottom

One selected location amidships at transverse web (see A3/3.3.3 FIGURE 2).

FIGURE 2
Connection between Inner Bottom and Hopper Tank Slope



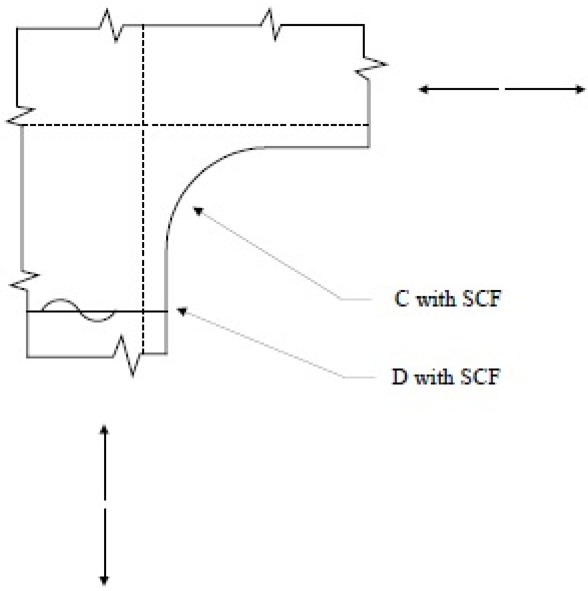
3.3.4 End Bracket Connections for Transverses

One (1) to two (2) selected locations in the midship region for each type of bracket configuration.

3.3.5 Hatch Corners of Dome Openings

Access openings, pipe penetrations and hatch corners of the opening for tank dome (see A3/3.3.5 FIGURE 3).

FIGURE 3
Hatch Corner



3.3.6 Vertical Supports

Representative vertical supports and seatings fitted to hull and cargo tank structures.

3.3.7 Anti-Roll Chocks

Representative anti-roll chocks and seatings fitted to hull and cargo tank structures.

3.3.8 Anti-Pitch Chocks

Representative anti-pitch chocks and seatings fitted to hull and cargo tank structures.

3.3.9 Bracket Toes of Main Supporting Members of Cargo Tank Structures

Bracket toes of transverse web frames, swash bulkheads and horizontal stringers.

3.3.10 Other Regions and Locations

Other regions and locations (e.g., see A3/3.3.10 FIGURE 4), highly stressed by fluctuating loads, as identified from structural analysis.

FIGURE 4
Doublers and Non-load Carrying Members on Deck or Shell Plating

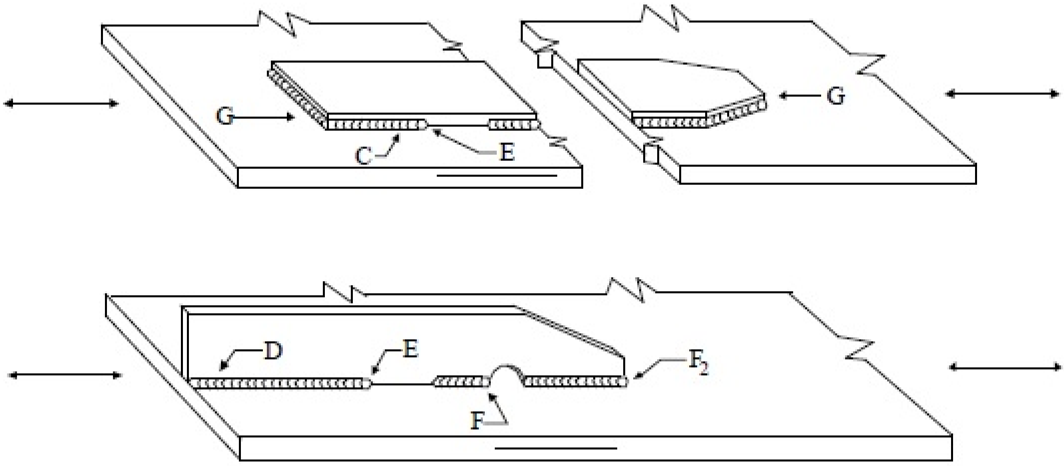
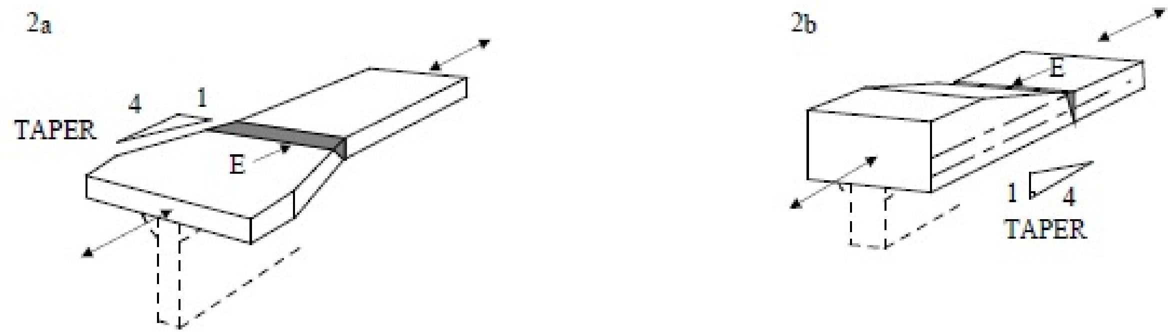
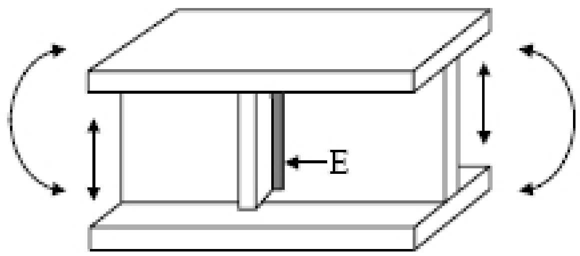


TABLE 1
Fatigue Classification for Structural Details

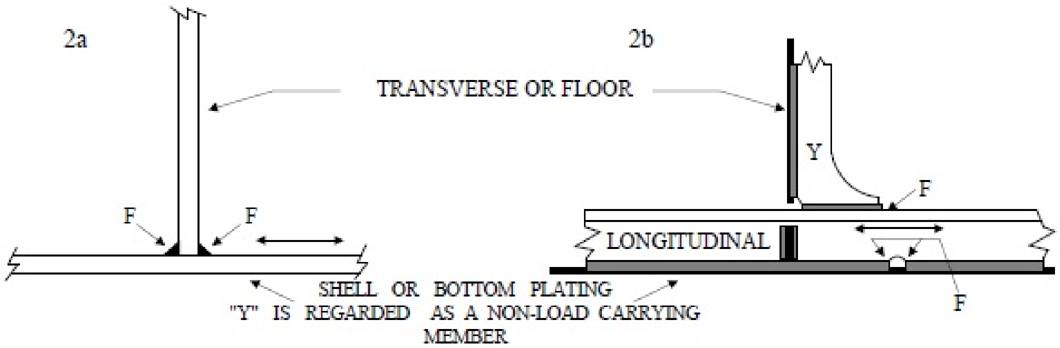
Class Designation	*Description*
B	Parent materials, plates or shapes as-rolled or drawn, with no flame-cut edges. In case with any flame-cut edges, the flame-cut edges are subsequently ground or machined to remove all visible sign of the drag lines
C	1) Parent material with automatic flame-cut edges 2) Full penetration seam welds or longitudinal fillet welds made by an automatic submerged or open arc process, and with no stop-start positions within the length
D	1) Full penetration butt welds between plates of equal width and thickness made either manually or by an automatic process other than submerged arc, from both sides, in downhand position 2) Welds in C-2) with stop-start positions within the length
E	1) Full penetration butt welds made by other processes than those specified under D-1) 2) Full penetration butt welds made from both sides between plates of unequal widths machined to a smooth transition with a slope not more than 1 in 4. Plates of different thickness are to be likewise machined with a slope not more than 1 in 3, unless a transition within the weld bead is approved.



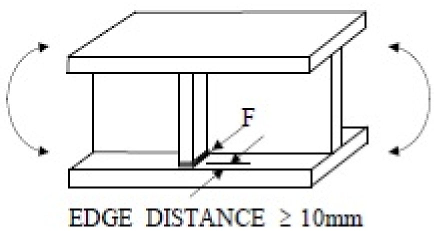
Class Designation		*Description*
	3)	Welds of brackets and stiffeners to web plate of girders



F	1)	Full penetration butt welds made on a permanent backing strip between plates of equal width/thickness or between plates of unequal width/thickness, as specified in E-2.
	2)	Rounded fillet welds as shown below

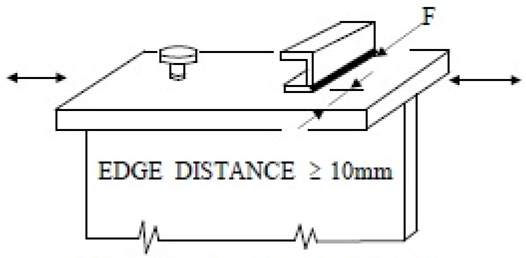


3) Welds of brackets and stiffeners to flanges



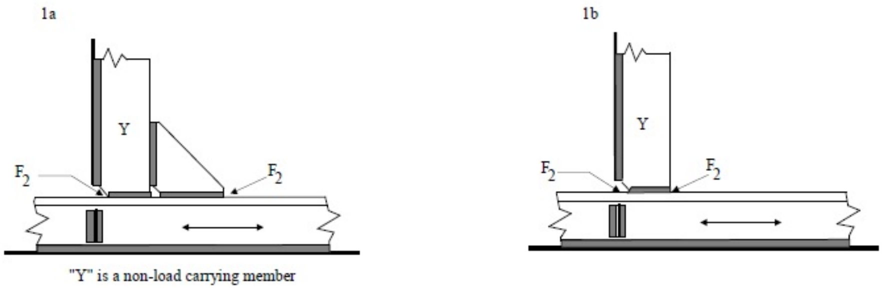
4) Attachments on plate or face plate

Class Designation	*Description*

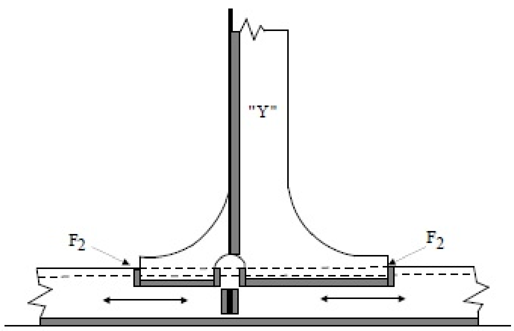


(Class G for edge distance < 10 mm)

F2 1) Fillet welds as shown below with rounded welds and no undercutting

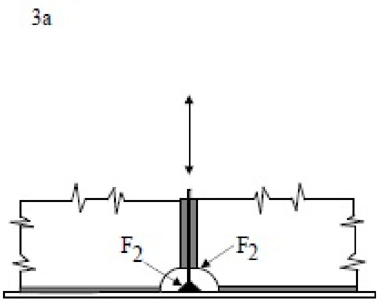


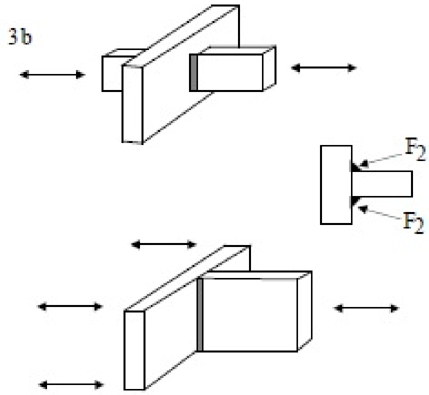
2) Overlapped joints with soft-toe brackets as shown below



3) Fillet welds with any undercutting at the corners dressed out by local grinding

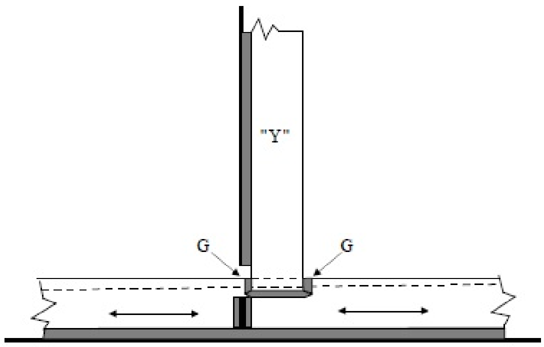
Class Designation	*Description*





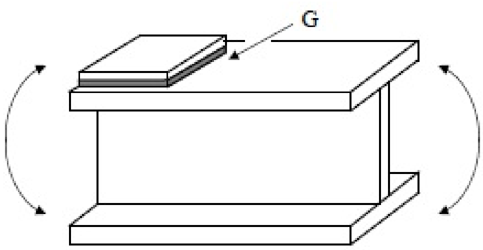
G 1) Fillet welds in F_2 - 1) without rounded toe welds or with limited minor undercutting at corners or bracket toes

2) Overlapped joints as shown below



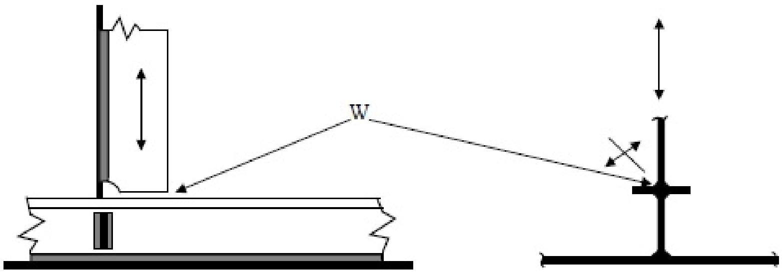
3) Fillet welds in F_2 - 3) with minor undercutting

4) Doubler on face plate or flange



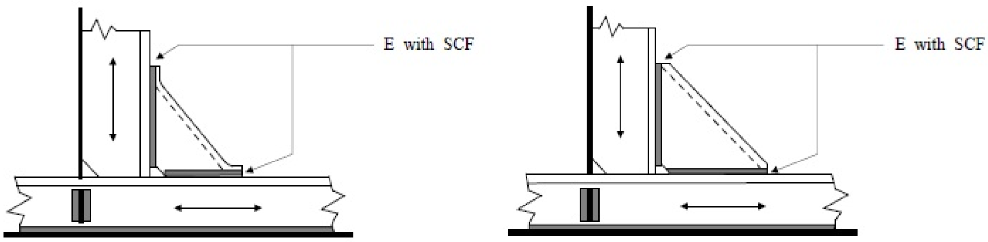
W Fillet welds-weld throat

Class Designation	*Description*



Note:

1 For brackets connecting two or more load carrying members, an appropriate stress concentration factor (SCF) determined from fine mesh 3D or 2D finite element analysis is to be used. In this connection, the fatigue class at bracket toes may be upgraded to class E as shown below.



5 Fatigue Damage Calculation

5.1 Assumptions

The fatigue damage of a structural detail induced by the loads specified here is to be evaluated using the criteria contained in this section. The key assumptions employed are listed below for guidance.

- A linear cumulative damage model (i.e., Palmgren-Miner's Rule) has been used in connection with the S-N data in A3/5.7 FIGURE 5 (extracted from Ref. 1* and the unit for stress range has been converted to kgf/cm^2).
- Cyclic stresses due to the loads in A3/7.3 have been used.
- The target design life of the vessel is taken at 20 years.
- The long-term stress ranges on a detail can be characterized using a modified Weibull probability distribution parameter (γ).
- Structural details are classified and described in A3/3.3.10 TABLE 1, "Fatigue Classification of Structural Details".

Note: * Ref 1: "Offshore Installations: Guidance on Design, Construction and Certification", Department of Energy, U.K., Fourth Edition—1990, London: HMSO

The structural detail classification in A3/3.3.10 TABLE 1 is based on joint geometry and direction of the dominant load. Where the loading or geometry is too complex for a simple classification, a finite element analysis of the details is to be carried out to determine stress concentration factors. A3/11 contains guidance on finite element analysis modeling to determine stress concentration factors for weld toe locations.

5.3 Criteria

The fatigue damage, D_f, obtained using the criteria in A3/5.7, is to be not greater than one (1.0).

5.5 Long Term Stress Distribution Parameter, γ *(1 May 2021)*

The long-term stress distribution parameter, γ, can be determined as below.

$$\gamma = 1.40 - 0.2\alpha L^{0.2} \quad for\ 150 < L < 305m$$
$$= 1.40 - 0.16\alpha L^{0.2} \quad for\ 492 < L < 1000ft$$
$$\gamma = 1.54 - 0.245\alpha^{0.8} L^{0.2} \quad for\ L > 305m$$
$$= 1.54 - 0.19\alpha^{0.8} L^{0.2} \quad for\ L > 1000ft$$

where

α	=	1.0	for deck structures, including side shell and longitudinal bulkhead structures within 0.1D from the deck
	=	0.93	for bottom structures, including inner bottom and side shell, and longitudinal bulkhead structures within 0.1D from the bottom
	=	0.86	for side shell and longitudinal bulkhead structures within the region of 0.25D upward and 0.3D downward from the mid-depth
	=	0.8	for transverse bulkhead structures
	=	0.8	for independent cargo tank structures

α may be linearly interpolated for side shell and longitudinal bulkhead structures between 0.1D and 0.25D (0.2D) from the deck (bottom).

L and D are the vessel's length and depth, as defined in 3/3.

5.7 Fatigue Damage *(1 May 2009)*

The cumulative fatigue damage, D_f, is to be taken as

$$D_f = D_{f1} + D_{f2}$$

where

D_{f1}	=	fatigue damage cumulated under full load condition
D_{f2}	=	fatigue damage cumulated under normal ballast condition

The cumulative fatigue damage for loading condition i can be calculated as

$$D_{f1} = \frac{1}{6}D_{f1\_12} + \frac{1}{6}D_{f1\_34} + \frac{1}{3}D_{f1\_56} + \frac{1}{3}D_{fl\_78}$$

where $D_{fi\_12} + D_{fi\_34} + D_{fi\_56} + D_{fi\_78}$ are the fatigue damage accumulated due to load case pairs 1&2, 3&4, 5&6 and 7&8, respectively (see 4/5 TABLE 3 and 4/5 TABLE 4 for load case pairs).

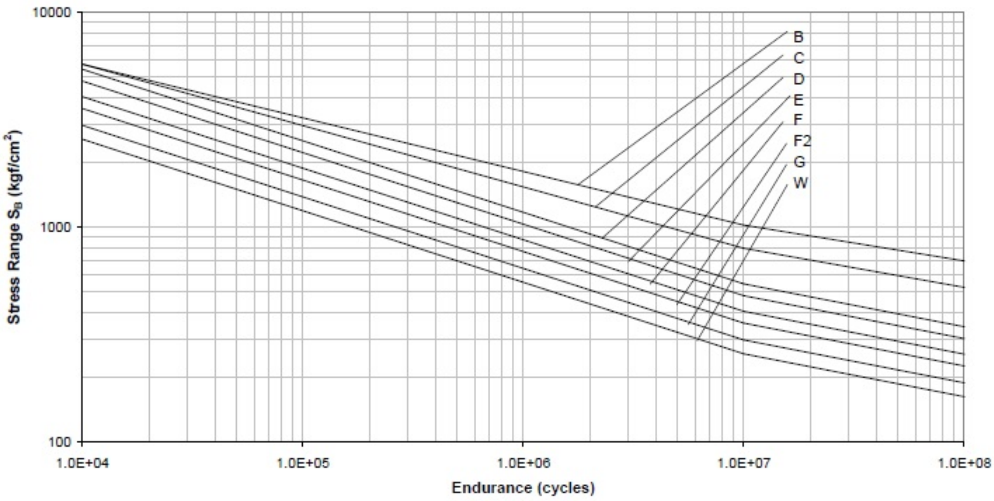
Assuming the long term distribution of stress ranges follow the Weibull distribution, the fatigue damage accumulated due to load pair jk in loading condition i:

$$D_{f1\_jk} = \frac{\alpha_i N_t}{K_2}\frac{f_{Ri\_jk}^m}{(\ln \quad N_R)^{m/\gamma}}\mu_{i\_jk}\Gamma\left(1+\frac{m}{\gamma}\right)$$

where

N_t	=	number of cycles in the design life.
	=	$\frac{f_0 D_L}{4\log L}$
f_0	=	0.85, factor for net time at sea
D_L	=	design life in seconds, 6.31×10^8 for a design life of 20 years
L	=	ship length defined in 3/3
m, K_2	=	S-N curve parameters as defined in A3/5.7 FIGURE 5
α_i	=	proportion of the ship's life α_1= 0.5 for full load condition α_2= 0.5 for normal ballast condition
f_{Ri_jk}	=	stress range of load case pair jk at the representative probability level of 10^{-4}, in kgf/cm^2. For the welded connections with thickness t greater than 22 mm, f_{Ri_jk} is to be adjusted by a factor $(t/22)^{0.25}$. The thickness correction is not applicable to the longitudinal stiffeners which are of flat bars or bulb plates. If it can be conclusively established that the detail under consideration is always subject to a mean stress of σ_m,f_{Ri_jk} is to be adjusted by a factor κ_m
κ_m	=	1.0 for $\sigma_m > f_{Ri\_jk}/2$
	=	$0.85 + 0.3\sigma_m/f_{Ri\_jk}$ for $-f_{Ri\_jk}/2 \le \sigma_m \le f_{Ri\_jk}/2$
	=	0.7 for $\sigma_m < -f_{Ri\_jk}/2$
N_R	=	10000, number of cycles corresponding to the probability level of 10^{-4}
γ	=	long-term stress distribution parameter as defined in A3/5.5
Γ	=	Complete Gamma function
μ_{i_jk}	=	$1-\left(\frac{\Gamma_o\left(1+\frac{m}{\gamma}, \nu_{i\_jk}\right)-\nu_{i\_jk}^{-\Delta m/\gamma}\Gamma_o\left(1+\frac{m+\Delta m}{\gamma}, \nu_{i\_jk}\right)}{\Gamma\left(1+\frac{m}{\gamma}\right)}\right)$
ν_{i_jk}	=	$\left(\frac{f_q}{f_{Ri\_jk}}\right)^{\gamma}\ln \quad N_R$
f_q	=	stress range at the intersection of the two segments of the S-N curve
Δm	=	2, slope change of the upper-lower segment of the S-N curve
$\Gamma_o(\ )$	=	incomplete Gamma function, Legendre form

FIGURE 5
Basic Design S-N Curves



Notes (For A3/5.7 FIGURE 5)

Basic design S-N curves

The basic design curves consist of linear relationships between $\log(S_B)$ and $\log(N)$. They are based upon a statistical analysis of appropriate experimental data and may be taken to represent two standard deviations below the mean line. Thus the basic S-N curves are of the form:

$\log(N) = \log(K_2) - m \log(S_B)$

where

$\log(K_2)$	=	$\log(K_1) - 2\sigma$
N	=	predicted number of cycles to failure under stress range S_B
K_1	=	a constant relating to the mean S-N curve
σ	=	standard deviation of $\log N$
m	=	inverse slope of the S-N curve

The relevant values of these terms are shown in the table below and stress range is in kgf/cm^2. The S-N curves have a change of inverse slope from m to $m + 2$ at $N = 10^7$ cycles.

Class	K_1	$log_{10} K_1$	m	σ	K_2	$log_{10} K_2$
B	2.521×10^{19}	19.4016	4.0	0.1821	1.09×10^{19}	19.0374
C	3.660×10^{17}	17.5635	3.5	0.2041	1.43×10^{17}	17.1553
D	4.225×10^{15}	15.6258	3.0	0.2095	1.61×10^{15}	15.2068
E	3.493×10^{15}	15.5432	3.0	0.2509	1.10×10^{15}	15.0414
F	1.825×10^{15}	15.2614	3.0	0.2183	6.68×10^{14}	14.8248
F_2	1.302×10^{15}	15.1148	3.0	0.2279	4.56×10^{14}	14.6590
G	6.051×10^{14}	14.7818	3.0	0.1793	2.65×10^{14}	14.4232
W	3.978×10^{14}	14.5996	3.0	0.1846	1.70×10^{14}	14.2304

7 Fatigue Inducing Loads and Load Combination Cases

7.1 General

This section provides: 1) the criteria to define the individual load components considered to cause fatigue damage (see A3/7.3); 2) the load combination cases to be considered for the structural detail being evaluated (see A3/7.5).

7.3 Wave-induced Loads – Load Components

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

- Hull girder wave-induced bending moments (both vertical and horizontal), see 3/5 and 3/7.
- External hydrodynamic pressures, see 3/9, and
- Internal tank loads (inertial liquid loads and added static head due to ship's motion, see 3/11).

7.5 Combinations of Load Cases for Fatigue Assessment

Two loading conditions (i.e., full load and normal ballast) are considered in the calculation of stress range. For each loading condition, eight (8) load cases, as shown in 4/5 TABLE 3 and 4/5 TABLE 4, are defined to form four (4) pairs. The combinations of load cases are to be used to find the characteristic stress range corresponding to a probability of exceedance of 10^{-4}, as indicated below.

7.5.1 Standard Load Combination Cases

7.5.1(a)

Calculate dynamic component of stresses for load cases LC1 through LC8, respectively.

7.5.1(b)

Calculate four sets of stress ranges, one each for the following four pairs of combined loading cases.

LC1 and LC2,

LC3 and LC4,

LC5 and LC6, and

LC7 and LC8

7.5.2 Vessels with Either Special Loading Patterns or Special Structural Configuration

For vessels with either special loading patterns or special structural configurations/features, additional load cases may be required for determining the stress range.

9 Nominal Stress Approach

9.1 General

In this approach, the stress range used is nominal stress range and can be evaluated based on beam theory. Structural details are idealized and classified in A3/3.3.10 TABLE 1.

Nominal stress approach can be applied to longitudinal stiffeners (see A3/3.3.1) and their attached flat bars (see A3/9.11), if any, except those on inner bottom. For longitudinal stiffeners on inner bottom the hot spot stress approach described in A3/11 is to be employed to take account of loads from vertical supports.

The procedure to idealize the structural components to obtain the total stress range acting on the detail is described as below.

9.3 Total Stress Range for Longitudinals

The total stress range, f_R, is computed as the sum of the two stress ranges, as follows:

$$f_R = c_f(f_{RG} + f_{RL}) \quad \text{kgf/cm}^2$$

where

f_{RG}	=	global dynamic stress range, in kgf/cm^2
	=	$\lvert(f_{d1vi} - f_{d1vj})\rvert + \lvert(f_{d1hi} - f_{d1hj})\rvert$
f_{RL}	=	ocal dynamic stress range, in kgf/cm^2
	=	$\lvert f_{d2i} - f_{d2j}\rvert$
c_f	=	adjustment factor to reflect a mean wasted condition
	=	1.05
f_{d1vi}, f_{d1vj}	=	wave-induced component of the primary stresses produced by hull girder vertical bending, in kgf/cm^2, for load case *i* and *j* of the selected pairs of combined load cases, respectively
f_{d1hi}, f_{d1hj}	=	wave-induced component of the primary stresses produced by hull girder horizontal bending, in kgf/cm^2, for load case *i* and *j* of the selected pairs of combined load cases, respectively
f_{d2i}, f_{d2j}	=	wave-induced component of the additional secondary stresses produced by the local bending of the longitudinal stiffener between supporting structures (e.g., transverse bulkheads and web frames), in kgf/cm^2, for load case *i* and *j* of the selected pairs of combined load cases, respectively

For calculating the wave-induced stresses, sign convention is to be observed for the respective directions of wave-induced loads, as specified in 4/5 TABLE 3 and 4/5 TABLE 4. The wave-induced local loads are to be calculated with the sign convention for the external and internal loads. However, the total of the external and internal pressures, including both static and dynamic components, need not be taken less than zero.

These wave-induced stresses are to be determined based on the gross ship scantlings. The results of direct calculation, where carried out, may also be considered.

9.5 Hull Girder Bending Stress f_{d1}

f_{d1v} and f_{d1h} may be calculated by a simple beam approach.

9.7 Additional Secondary Stresses f_{d2} *(1 May 2009)*

The additional secondary stresses acting at the flange of a longitudinal stiffener, f_{d2}, may be approximated by

$$f_{d2} = C_t C_\ell \frac{M}{SM} + C_k C_d \frac{4EI\delta}{\ell^2 SM} \quad \text{kgf/cm}^2$$

where

C_k	=	1	for the longitudinal connections at the transverse bulkhead
	=	0	for the longitudinal connections at web frames
C_d	=	$1 - 2\left(\frac{x}{\ell}\right)$	
C_ℓ	=	$1 - 6\left(\frac{x}{\ell}\right) + 6\left(\frac{x}{\ell}\right)^2$	

x = distance from the end of unsupported span to the end of the weld toe.

M = $ps\ell^2/12$

p = wave-induced local net pressure, in kgf/cm^2, for the specified location and load cases at the mid-span of the longitudinal considered

s = spacing of longitudinal stiffener, in cm

ℓ = unsupported span of longitudinal/stiffener, in cm, as shown in 5/7.21.3 FIGURE 2

SM = section modulus of longitudinal with the associated effective plating, in cm^3, at flange or point considered. The effective breadth, b_e, in cm, may be taken as 0.1ℓ

I = moment of inertia of longitudinal with the associated effective plating, in cm^4, at flange or point considered

E = modulus of elasticity of the material, may be taken as 2.1×10^6 kgf/cm^2 for steel

δ = relative deflection between the transverse bulkhead and the adjacent web frame, in cm. This deflection can be obtained from the global finite element model under the local load cases specified in 4/5 TABLE 3 and 4/5 TABLE 4.

C_t = correction factor for the combined bending and torsional stress induced by lateral loads at the welded connection of the flat bar stiffener or bracket to the flange of longitudinal, as shown in A3/9.9.2 FIGURE 7

	=	$1.0 + \alpha_\gamma$	for unsymmetrical sections, fabricated or rolled
	=	1.0	for tee and flat bars

α_γ = $C_n C_p SM/K$

For general applications, α_γ needs not be taken greater than 0.65 for a fabricated angle bar and 0.50 for a rolled section.

C_p = $31.2 d_w (e/\ell)^2$

e = horizontal distance between web centerline and shear center of the cross section, including longitudinal and the effective plating

≈ $d_w b_f^2 t_f u/(2SM)$ cm

K = St. Venant torsion constant for the longitudinal's cross section, excluding the associated plating.

= $\left(b_f t_f^3 + d_w t_w^3\right)/3$ cm^4

C_n = coefficient given in A3/9.7 FIGURE 6, as a function of ψ, for point (1) shown in A2/5.3 FIGURE 1

= $\psi/\tan\psi - 1$ for $\psi \le 3.0$

= $\psi - 1$ for $\psi > 3.0$

u = $1 - 2b_1/b_f$

ψ = $0.31\ell(K/\Gamma)^{1/2}$

Γ = warping constant

= $mI_{yf}d_w^2 + d_w^3t_w^3/36$ cm^6

I_{yf} = $t_f b_f^3(1.0 + 3.0u^2A_w/A_s/)/12$ cm^4

A_w = $d_w t_w$ cm^2

A_s = gross sectional area of the longitudinals, excluding the associated plating,cm^2

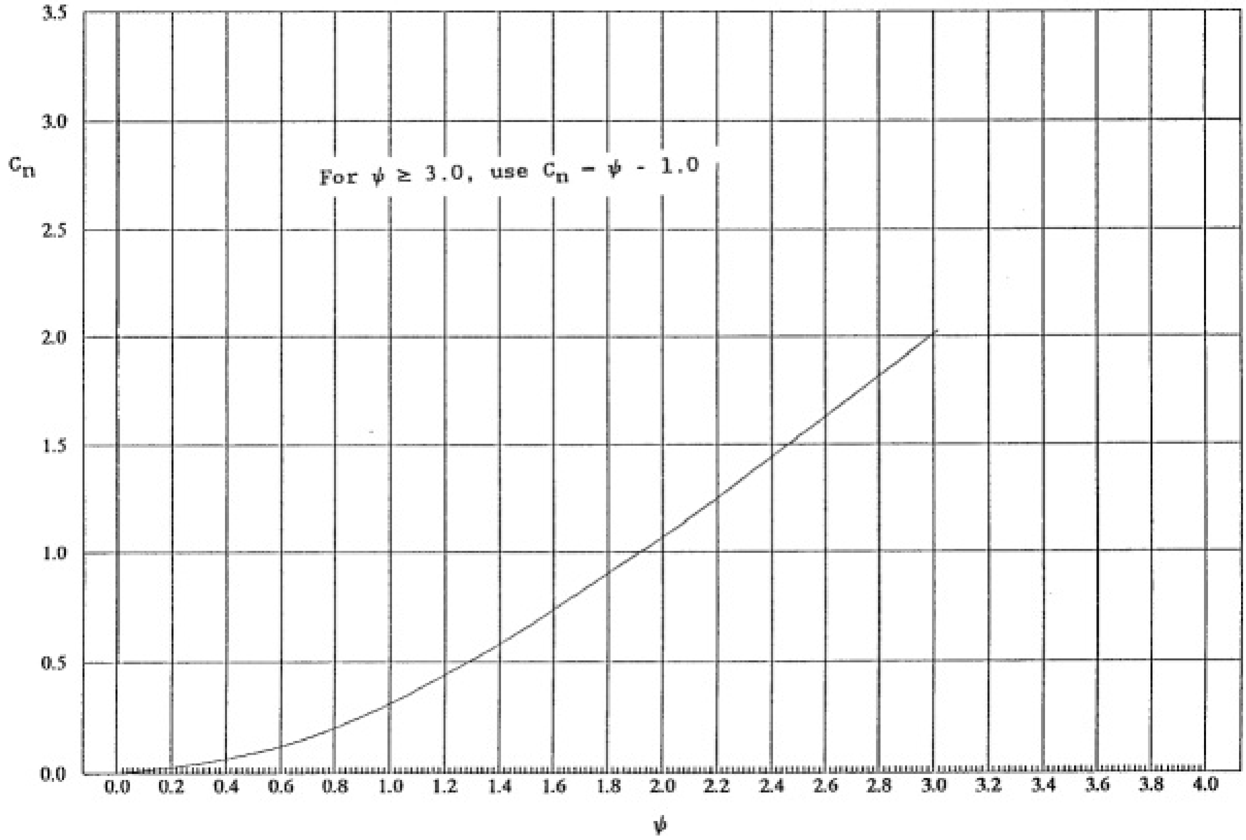
m = $1.0 - u\left(0.7 - 0.1d_w/b_f\right)$

d_w , t_w, b_1, b_f, t_f, all in cm, are as defined in A2/5.3 FIGURE 1.

In absence of the relative deflection, δ, the additional secondary stress f_{d2} may be taken as:

$f_{d2} = 1.3C_tC_\ell\frac{S}{SM}$ kgf/cm^2

FIGURE 6
$C_n = C_n(\psi)$



9.9 Flat Bar Stiffener for Longitudinals

9.9.1 Flat Bar Stiffener or Brackets *(1 May 2009)*

For assessing fatigue life of a flat bar stiffener at location [1] or [2] as shown in A3/9.9.2 FIGURE 7, the peak stress range, f_{Fi}, is to be obtained from the following equation:

$$f_{Ri} = c_f\left[(\alpha_i f_s)^2 + f_{Ri}^2\right]^{1/2} \qquad (i = 1 \text{ or } 2)$$

where

f_{Ri} = stress range in the longitudinal at Location (i = 1 or 2), as specified in A3/9.3

c_f = adjustment factor to reflect a mean wasted condition

= 1.05

α_i = stress concentration factor at Location i (i = 1 or 2) accounting for misalignment and local distortion

- At location [1]

  For flat bar stiffener without brackets

α_1 = 1.50 for double-sided support connection

= 2.00 for single-sided support connection

For flat bar stiffener with brackets

α_1 = 1.00 for double-sided support connection

= 1.25 for single-sided support connection

- At location [2]

For flat bar stiffener without brackets

α_2 = 1.25 for single or double-sided support connection

For flat bar stiffener with brackets

α_2 = 1.00 for single or double-sided support connection

f_s = nominal stress range in the flat bar stiffener

= P/A_s

P = $ps\ell\left(1-\frac{s}{2\ell}\right)\left(\frac{4f_cA_s}{4f_cA_s+A_c}-\frac{s}{\ell}\right)$

s = spacing of longitudinal/stiffener

ℓ = spacing of transverses

p = difference of net lateral pressure of two load cases in a load pair, in kgf/cm^2

A_c = effective shear sectional area of the support or of both supports for double-sided support, in cm^2

= $A_{lc} + A_{ld}$

A_{ld} = shear connection area excluding lug plate, in cm^2

= $\ell_d t_w$

ℓ_d = length of direct connection between longitudinal stiffener and transverse member (see A3/9.9.2 FIGURE 7), in cm

t_{tw} = thickness of transverse member (see 3/13.1 FIGURE 8), in cm

A_{lc} = shear connection area of lug plate, in cm^2

= $f_1\ell_c t_c$

ℓ_c = length of connection between longitudinal stiffener and lug plate (see A3/9.9.2 FIGURE 8), in cm^2

t_c = thickness of lug plate (see A3/9.9.2 FIGURE 8), not to be taken greater than the thickness of adjacent transverse member, in cm

f_1 = shear stiffness coefficient

= 1.0 for stiffener of symmetrical cross section

= $14/w \leq 1.0$ for stiffener of asymmetrical cross section

W = width of the cut-out for an asymmetrical stiffener, measured from the cut-out side of the stiffener web, in cm (see A3/9.9.2 FIGURE 8), in cm

A_s = attached area of the flat bar stiffener, in cm^2

f_c = collar load factor

for intersecting of symmetrical stiffeners

= 1.85 for $A_s \leq 14$

= $1.85 - 0.0441\ (A_s - 14)$ for $14 < A_s \leq 31$

= $1.1 - 0.013\ (A_s - 31)$ for $31 < A_s \leq 58$

= 0.75 for $A_s > 58$

for intersecting of asymmetrical stiffeners

= $0.68 + 0.0172\ell_d/A_s$

If the length of direct and shear connections are different, their mean value is to be used instead of ℓ_d, and in case of a single lug, the value is ℓ_c.

For flat bar stiffener with soft-toed brackets, the brackets may be included in the calculation of A_s.

9.9.2 Weld Throat

For assessing the fatigue life of the weld throat as shown in A3/3.3.10 TABLE 1, Class W, the peak stress range f_R at the weld may be obtained from the following equation:

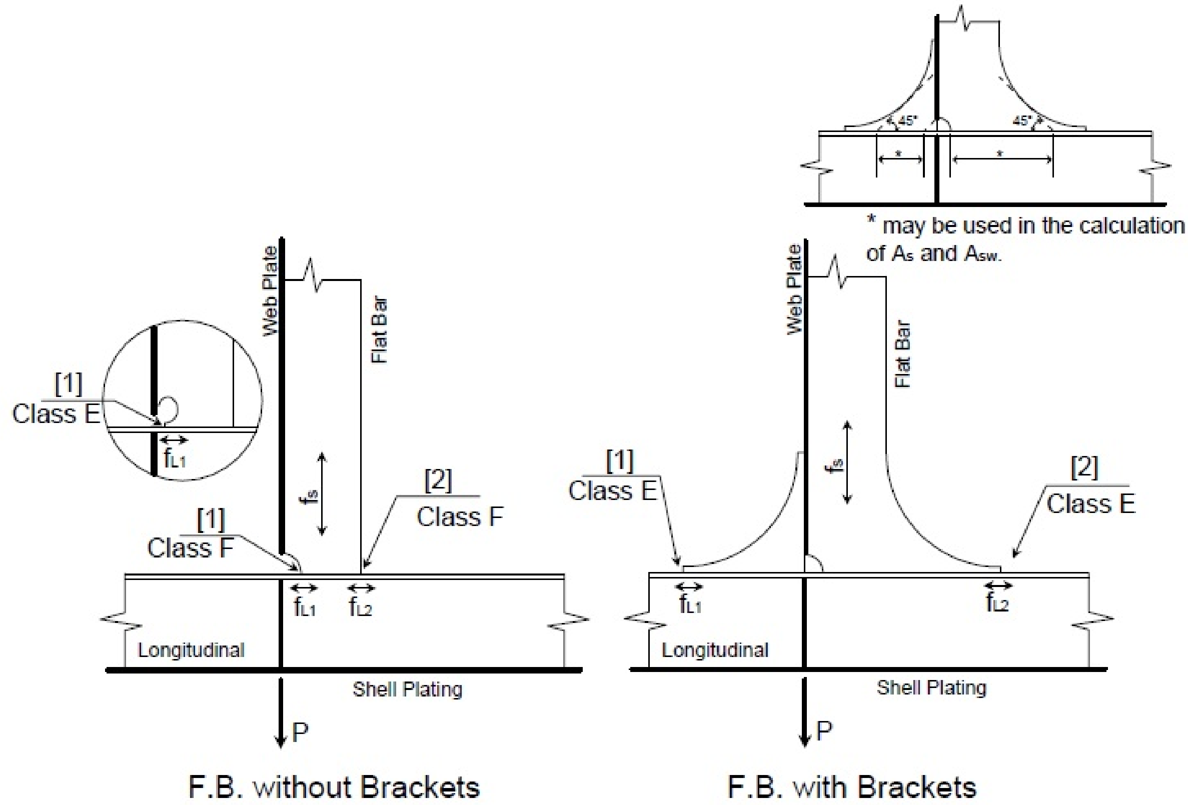
$$f_R = c_f f_s A_s / A_{sw}$$

where

A_{sw} = attached area of the flat bar stiffener, assuming that the flat bar stiffener is connected to the longitudinal stiffener through the weld throat. Brackets may be included in the calculation of A_{sw}, in cm^2 (see A3/9.9.2 FIGURE 7).

c_f,f_s and A_s are as defined in A3/9.9.1 above.

FIGURE 7
Fatigue Classification for Longitudinals in way of Flat Bar Stiffeners *(1 May 2009)*



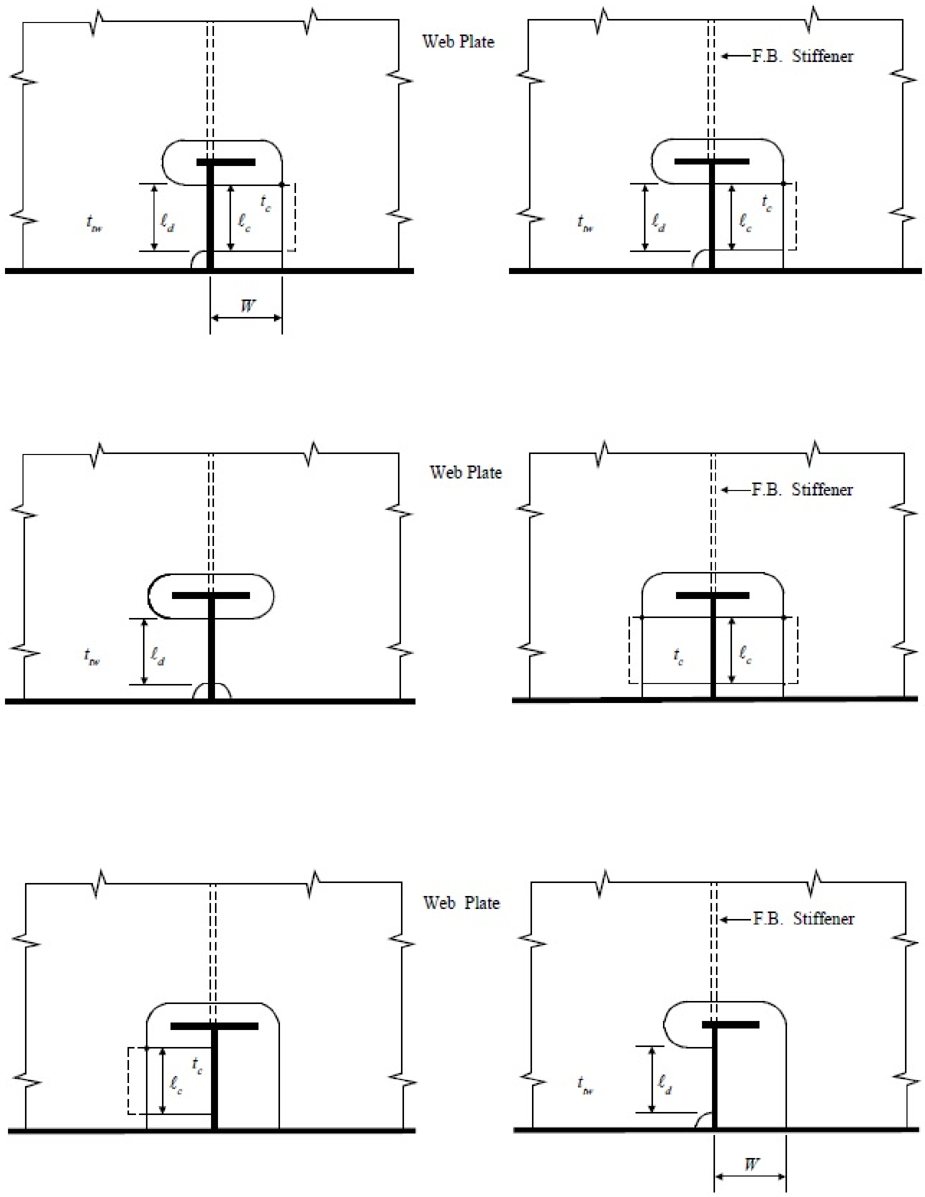
Note:

The basic design curves E' and F' are defined as follows (also see A3/5.7 FIGURE 5):

K_2 = 8.44 × 10^{14} and m = 3.0 for E'

K_2 = 5.51 × 10^{14} and m = 3.0 for F'

FIGURE 8
Cut-outs (Slots) For Longitudinal



9.11 Longitudinally Stiffened Plate Panels *(1 May 2009)*

For welded joints of a stiffened plate panel, the peak plate stress range f_R in the transverse direction is to be obtained from the following equation:

$$f_R = 0.266 c_f^2 C_\ell \ \ p(s/t)^2$$

where

C_ℓ	=	$1 - 6\left(\frac{x}{s}\right) + 6\left(\frac{x}{s}\right)^2$
c_f	=	adjustment factor to reflect a mean wasted condition
	=	1.05

p = difference of net lateral pressure of two load cases in a load pair, in kgf/cm^2

s = spacing of longitudinals, in mm

t = plate thickness, in mm

x = distance from the mid depth of the stiffener web plate to the weld toe

11 Hot Spot Stress Approach with Finite Element Analysis

11.1 Introduction *(1 May 2009)*

In principle, the fatigue strength of all connections can be assessed with the hot spot stress approach described in this section. However, for some details as indicated in A3/9.1, in lieu of the hot spot stress approach, the nominal stress approach can also be employed to evaluate the fatigue strength.

Hot spot stress is defined as the surface stress at the hot spot. Note that the stress change caused by the weld profile is not included in the hot spot stress, but the overall effect of the connection geometry on the nominal stress is represented. Therefore, in hot spot stress approach the selection of an S-N curve depends on: 1) weld profile, i.e., existence of weld and weld type (fillet, partial penetration or full penetration); 2) predominant direction of principal stress; and 3) crack locations (toe, root or weld throat).

There are various adjustments (reductions in capacity) that may be required to account for factors such as a lack of corrosion protection (coating) of structural steel and relatively large plate thickness. The imposition of these adjustments on fatigue capacity will be in accordance with ABS practice for vessels.

There are other adjustments that could be considered to increase fatigue capacity above that portrayed by the cited S-N data. These include adjustments for compressive "mean stress" effects, a high compressive portion of the acting variable stress range and the use of "weld improvement" techniques. The use of a weld improvement technique, such as weld toe grinding or peening to relieve ambient residual stress, can be effective in increasing fatigue life. However, credit is not to be taken of such a weld improvement in the design phase of the structure. Consideration for granting credit for the use of weld improvement techniques is to be reserved for situations arising during construction, operation, or future reconditioning of the structure. An exception may be made if the target design fatigue life cannot be satisfied by other preferred design measures such as refining layout, geometry, scantlings and welding profile to minimize fatigue damage due to high stress concentrations. Grinding or ultrasonic peening can be used to improve fatigue life in such cases. The calculated fatigue life is to be greater than 15 years excluding the effects of life improvement techniques. Where improvement techniques are applied, full details of the improvement technique standard including the extent, profile smoothness particulars, final weld profile, and improvement technique workmanship and quality acceptance criteria are to be clearly shown on the applicable drawings and submitted for review together with supporting calculations indicating the proposed factor on the calculated fatigue life.

Grinding is preferably to be carried out by rotary burr and to extend below the plate surface in order to remove toe defects, and the ground area is to have effective corrosion protection. The treatment is to produce a smooth concave profile at the weld toe with the depth of the depression penetrating into the plate surface to at least 0.5 mm below the bottom of any visible undercut. The depth of groove produced is to be kept to a minimum, and, in general, kept to a maximum of 1 mm. In no circumstances is the grinding depth to exceed 2 mm or 7% of the plate gross thickness, whichever is smaller. Grinding has to extend to areas well outside the highest stress region.

The finished shape of a weld surface treated by ultrasonic peening is to be smooth, and all traces of the weld toe are to be removed. Peening depths below the original surface are to be maintained to at least 0.2 mm. Maximum depth is generally not to exceed 0.5 mm.

Provided these recommendations are followed, an improvement in fatigue life by grinding or ultrasonic peening up to a maximum of 2 times may be granted.

11.3 Calculation of Dynamic Stress Range on an Individual Element

In the hot spot stress approach with finite element analysis, the stress distribution in the vicinity of a hot spot can be obtained by sequentially solving global model, local model and fatigue model (see Appendix A1). This procedure is executed for each load case defined in 4/5 TABLE 3 and 4/5 TABLE 4. Then the dynamic stress range f_R for a load pair can be determined as

$$f_R = c_f(|f_{GV}| + |f_{GH}| + |f_L|)$$

where

f_{GV} = dynamic stress range due to vertical bending moment

f_{GH} = dynamic stress range due to horizontal bending moment

f_L = dynamic stress range due to local pressure

c_f = adjustment factor to reflect a mean wasted condition

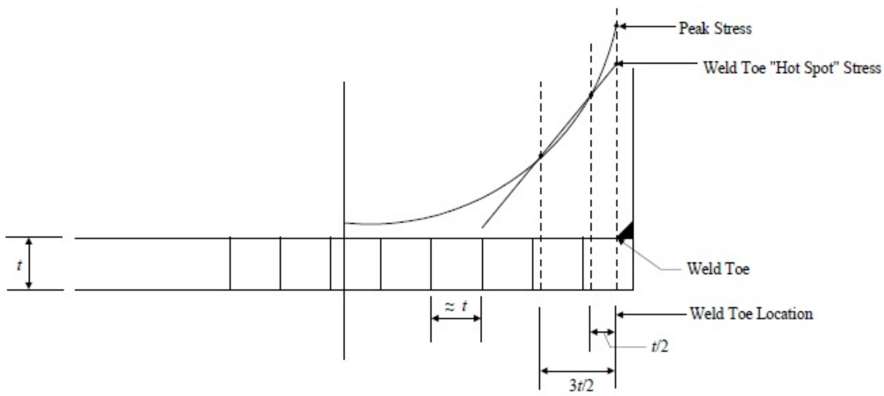
= 1.05

11.5 Calculation of Hot Spot Stress at a Weld Toe

A3/11.5 FIGURE 9 shows an acceptable method which can be used to extract and interpret the "near weld toe" element dynamic stress ranges (refer to as stresses for convenience in the following text in this Subsection) and to obtain a (linearly) extrapolated stress (dynamic stress range) at the weld toe. When plate or shell elements are used in the modeling, it is recommended that each element size is to be equal to the plate thickness.

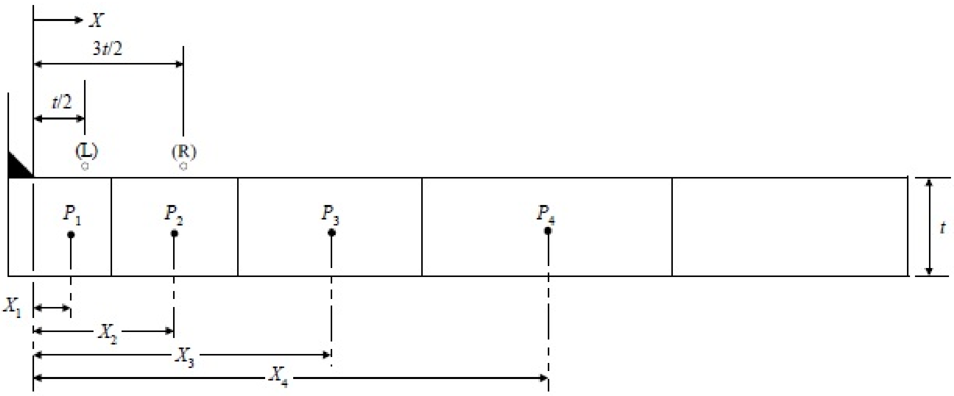
Weld hot spot stress can be determined from linear extrapolation of surface component stresses at $t/2$ and $3t/2$ from weld toe. The principal stresses at hot spot are then calculated based on the extrapolated stresses and used for fatigue evaluation. Description of the numerical procedure is given below.

FIGURE 9
Extrapolation of Dynamic Stress Range at Weld Toe



The algorithm described in the following is applicable to obtain the hot spot stress for the point at the toe of a weld. The weld typically connects either a flat bar member or a bracket to the flange of a longitudinal stiffener, as shown in A3/11.5 FIGURE 10.

FIGURE 10
Determination of Hot Spot Stress at Weld Toe



Consider the four points, P_1 to P_4, measured by the distances X_1 to X_4 from the weld toe, designated as the origin of the coordinate system. These points are the centroids of four neighboring finite elements, the first of which is adjacent to the weld toe. Assuming that the applicable surface component stresses (or dynamic stress ranges), S_i, at P_i have been determined from FEM analysis, the corresponding stresses at "hot spot" (i.e., the stress at the weld toe) can be determined by the following procedure:

11.5.1

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.:

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

where t denotes the thickness of the member to which elements 1 to 4 belong (e.g., the flange of a longitudinal stiffener).

11.5.2

Let $X = X_L$ 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:

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

11.5.3

Let $X = X_R$ and repeat the step in A3/11.5.2 to determine four new coefficients. The stress at Point R can be interpolated likewise, i.e.:

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

11.5.4

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

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

Note:

The algorithm presented in the foregoing involves two types of operations. The first is to utilize the stress values at the centroid of the four elements considered to obtain estimates of stress at Points L and R by way of an interpolation algorithm known as Lagrange interpolation. The second operation is to make use of the stress estimates, S_L and S_R, to obtain the hot spot stress via linear extrapolation.

While the Lagrange interpolation is applicable to any order of polynomial, it is not advisable to go beyond the 3rd order (cubic). Also, the even order polynomials are biased, so that leaves the choice between a linear scheme and a cubic scheme. Therefore, the cubic interpolation, as described in A3/11.5.2, is to be used. It can be observed that the coefficients, C_1 to C_4 are all cubic polynomials. It is also evident that, when $X = X_j$, which is not equal to X_i, all of the C's vanish except C_i, and if $X = X_i$, $C_i = 1$.

11.7 Calculation of Hot Spot Stress at the Edge of Cut-out or Bracket

In order to determine the hot spot stress at the edge of cut-out or bracket, dummy rod elements can be attached to the edge. The sectional area of the dummy rod may be set at 0.01 cm^2. The mesh needs to be fine enough to determine the local stress concentration due to the geometry change. The axial stress range of the dummy rod is to be used to assess the fatigue strength of the cut-out or bracket (edge crack).

APPENDIX 4

Hull Girder Ultimate Strength Assessment *(1 January 2010)*

1 General

The hull structure may be verified for compliance with the hull girder ultimate strength requirements using this Appendix. In general, the requirements are applicable to the hull structure within 0.4L amidships in sea-going conditions. For vessels that are subject to higher bending moment, the hull girder ultimate strength in the forebody and aft body regions is also to be verified.

3 Vertical Hull Girder Ultimate Limit State

The vertical hull girder ultimate bending capacity is to satisfy the following limit state equation:

$$\gamma_S M_{sw} + \gamma_W M_w \leq \frac{M_U}{\gamma_R}$$

where

M_{sw} = still water bending moment, in tf-m, in accordance with 3-2-1/3.3 of the Rules.

M_w = maximum wave-induced bending moment, in tf-m, in accordance with 3/5

M_U = vertical hull girder ultimate bending capacity, in tf-m, as defined in A4/5

γ_S = 1.0 partial safety factor for the still water bending moment

γ_W = 1.20 partial safety factor for the vertical wave bending moment covering environmental and wave load prediction uncertainties

γ_R = 1.10 partial safety factor for the vertical hull girder bending capacity covering material, geometric and strength prediction uncertainties

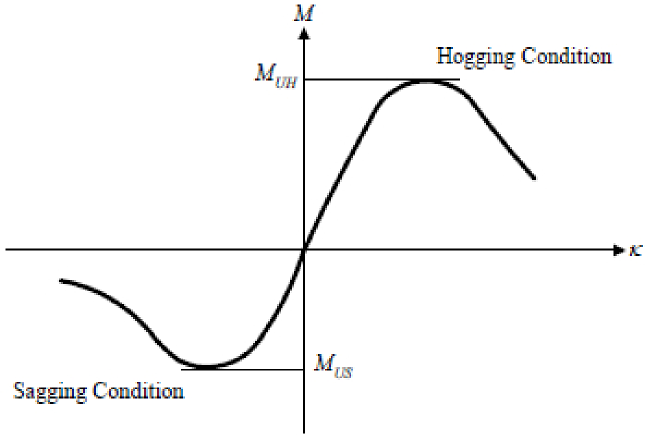
The ultimate strength criteria are based on the gross scantlings reduced by nominal design corrosion values. A nominal design corrosion value of 1 mm is to be used for each surface of an individual member directly exposed to ballast water. For other surfaces, nominal design corrosion values need not be applied.

5 Hull Girder Ultimate Bending Moment Capacity

5.1 General

The ultimate bending moment capacities of a hull girder section, in hogging and sagging conditions, are defined as the maximum values (positive M_{UH}, negative M_{US}) on the static nonlinear bending moment-curvature relationship M-κ. See A4/5.1 FIGURE 1. The curve represents the progressive collapse behavior of the hull girder under vertical bending. Hull girder failure is controlled by buckling, ultimate strength and yielding of longitudinal structural elements.

FIGURE 1
Bending Moment – Curvature Curve *M-κ (1 January 2010)*



The curvature of the critical inter-frame section, κ, is defined as:

$$\kappa = \frac{\theta}{\ell} m^{-1}$$

where

θ = relative angle rotation of the two neighboring cross-sections at transverse frame positions

ℓ = transverse frame spacing in m, i.e., span of longitudinals

The method for calculating the ultimate hull girder capacity is to identify the critical failure modes of all main longitudinal structural elements.

Longitudinal structural members compressed beyond their buckling limit have reduced load carrying capacity. All relevant failure modes for individual structural elements, such as plate buckling, torsional stiffener buckling, stiffener web buckling, lateral or global stiffener buckling, and their interactions, are to be considered in order to identify the weakest inter-frame failure mode.

The effects of shear force, torsional loading, horizontal bending moment and lateral pressure are neglected.

5.3 Physical Parameters

For the purpose of describing the calculation procedure in a concise manner, the physical parameters and units used in the calculation procedure are given below.

5.3.1 Hull Girder Load and Cross Section Properties

M_i = hull girder bending moment, in tf-m

F_i = hull girder longitudinal force, in tf

I_v = hull girder moment of inertia, in m^4

SM = hull girder section modulus, in m^3

SM_{dk} = elastic hull girder section modulus at deck at side, in m^3

SM_{kl} = elastic hull girder section modulus at bottom, in m^3

κ = curvature of the ship cross section, in m^{-1}

z_j = distance from baseline, in m

5.3.2 Material Properties

σ_{yd} = specified minimum yield stress of the material, in kgf/cm^2

E = Young's modulus for steel, 2.1×10^6 kgf/cm^2

ν = Poisson's ratio, may be taken as 0.3 for steel

Φ = edge function as defined in A4/5.9.2

ε = relative strain defined in A4/5.9.2

5.3.3 Stiffener Sectional Properties

The properties of a longitudinal's cross section are shown in A4/5.3.3 FIGURE 2.

A_s = sectional area of the longitudinal or stiffener, excluding the associated plating, in cm^2

b_1 = smaller outstanding dimension of flange with respect to centerline of web, in cm

b_f = total width of the flange/face plate, in cm

d_w = depth of the web, in cm

t_p = net thickness of the plating, in cm

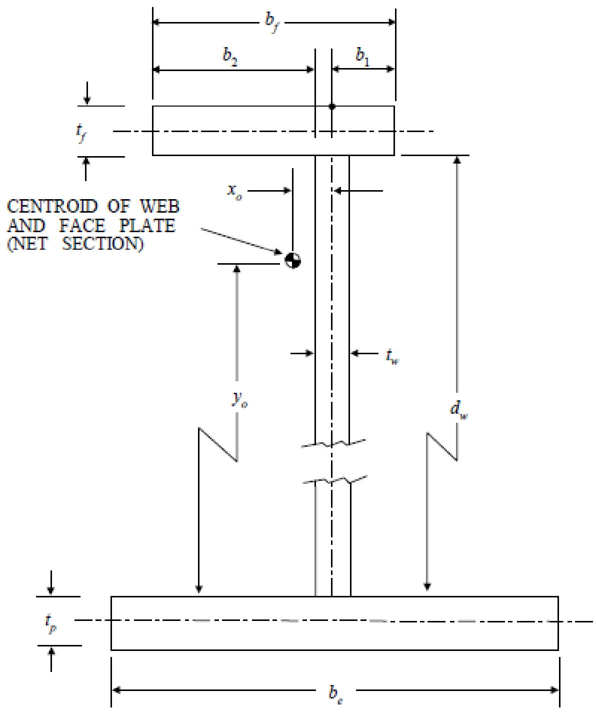
t_f = net thickness of the flange/face plate, in cm

t_w = net thickness of the web, in cm

x_o = distance between centroid of the stiffener and centerline of the web plate, in cm

y_o = distance between the centroid of the stiffener and the attached plate, in cm

FIGURE 2
Dimensions and Properties of Stiffeners *(1 January 2010)*



5.5 Calculation Procedure

The ultimate hull girder bending moment capacity M_U is defined as the peak value of the curve with vertical bending moment M versus the curvature κ of the ship cross section as shown in A4/5.1 FIGURE 1.

The curve M-κ is obtained by means of an incremental-iterative approach. The steps involved in the procedure are given below.

The bending moment M_i which acts on the hull girder transverse section due to the imposed curvature κ_i is calculated for each step of the incremental procedure. This imposed curvature corresponds to an angle of rotation of the hull girder transverse section about its effective horizontal neutral axis, which induces an axial strain ε in each hull structural element.

The stress σ induced in each structural element by the strain ε is obtained from the stress-strain curve σ-ε of the element, which takes into account the behavior of the structural element in the nonlinear elasto-plastic domain.

The force in each structural element is obtained from its area times the stress and these forces are summed to derive the total axial force on the transverse section. Note the element area is taken as the total net area of the structural element. This total force may not be zero as the effective neutral axis may have moved due to the nonlinear response. Hence, it is necessary to adjust the neutral axis position, recalculate the element strains, forces and total sectional force, and iterate until the total force is zero.

Once the position of the new neutral axis is known, then the correct stress distribution in the structural elements is obtained. The bending moment M_i about the new neutral axis due to the imposed curvature κ_i is then obtained by summing the moment contribution given by the force in each structural element.

The main steps of the incremental-iterative approach are summarized as follows:

Step 1 Divide the hull girder transverse section into structural elements (i.e., longitudinal stiffened panels (one stiffener per element), hard corners and transversely stiffened panels), see A4/5.7.

Step 2 Derive the stress-strain curves (also known as the load-end shortening curves) for all structural elements, see A4/5.9.

Step 3 Derive the expected maximum required curvature, κ_F. The curvature step size $\Delta\kappa$ is to be taken as $\kappa_F/300$. The curvature for the first step, κ_1 is to be taken as $\Delta\kappa$.

Derive the neutral axis $z_{NA\text{-}i}$ for the first incremental step (i = 1) with the value of the elastic hull girder section modulus, see 3-2-1/9 of the Rules.

Step 4 For each element (index j), calculate the strain $\varepsilon_{ij} = \kappa_i\left(z_j - z_{NA-i}\right)$ corresponding to κ_i, the corresponding stress σ_j, and hence the force in the element $\sigma_j A_j$. The stress σ_j corresponding to the element strain ε_{ij} is to be taken as the minimum stress value from all applicable stress-strain curves σ-ε for that element.

Step 5 Determine the new neutral axis position $z_{NA\text{-}i}$ by checking the longitudinal force equilibrium over the whole transverse section. Hence, adjust $z_{NA\text{-}i}$ until

$$F_i = 10^{-3}\Delta A_j\sigma_j = 0$$

Note σ_j is positive for elements under compression and negative for elements under tension. Repeat from Step 4 until equilibrium is satisfied. Equilibrium is satisfied when the change in neutral axis position is less than 0.0001 m.

Step 6 Calculate the corresponding moment by summing the force contributions of all elements as follows:

$$M_i = 10^{-3} \sum \sigma_j A_j \left| \left(z_j - z_{NA-i} \right) \right|$$

Step 7 Increase the curvature by $\Delta\kappa$, use the current neutral axis position as the initial value for the next curvature increment and repeat from step 4 until the maximum required curvature is reached. The ultimate capacity is the peak value M_u from the M-κ curve. If the peak does not occur in the curve, then κ_F is to be increased until the peak is reached

The expected maximum required curvature κ_F is to be taken as:

$$\kappa_F = 3 \frac{max\left(SM_{dk}\sigma_{yd}, SM_{kl}\sigma_{yd}\right)}{EI_v}$$

5.7 Assumptions and Modeling of the Hull Girder Cross-section

In applying the procedure described in this Appendix, the following assumptions are to be made:

i) The ultimate strength is calculated at a hull girder transverse section between two adjacent transverse webs.

ii) The hull girder transverse section remains plane during each curvature increment.

iii) The material properties of steel are assumed to be elastic, perfectly plastic.

iv) The hull girder transverse section can be divided into a set of elements which act independently of each other.

v) The elements making up the hull girder transverse section are:

- Longitudinal stiffeners with attached plating, with structural behavior given in A4/5.9.2, A4/5.9.3, A4/5.9.4, A4/5.9.5, and A4/5.9.6
- Transversely stiffened plate panels, with structural behavior given in A4/5.9.7
- Hard corners, as defined below, with structural behavior given in A4/5.9.1

vi) The following structural areas are to be defined as hard corners:

- The plating area adjacent to intersecting plates
- The plating area adjacent to knuckles in the plating with an angle greater than 30 degrees.
- Plating comprising rounded gunwales

An illustration of hard corner definition for girders on longitudinal bulkheads is given in A4/5.7 FIGURE 3.

vii) The size and modeling of hard corner elements is to be as follows:

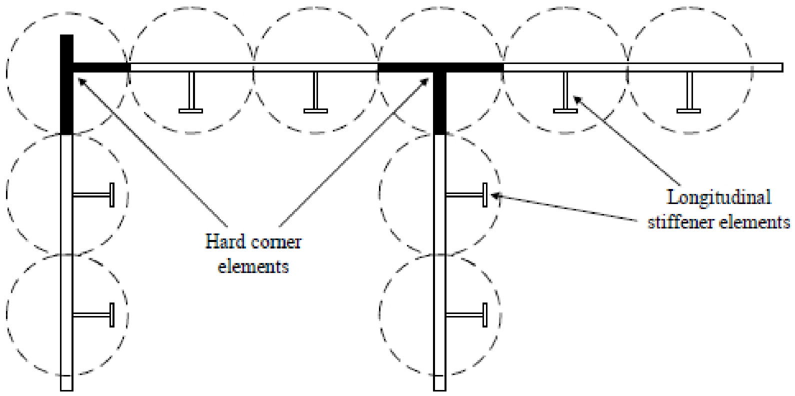
- It is to be assumed that the hard corner extends up to $s/2$ from the plate intersection for longitudinally stiffened plate, where s is the stiffener spacing
- It is to be assumed that the hard corner extends up to $20t_{grs}$ from the plate intersection for transversely stiffened plates, where t_{grs} is the gross plate thickness.

Note:

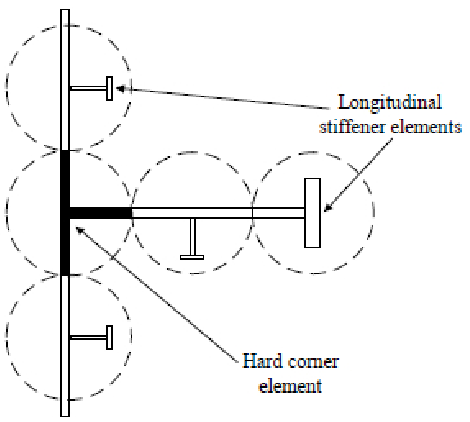
For transversely stiffened plate, the effective breadth of plate for the load shortening portion of the stress-strain curve is to be taken as the full plate breadth, i.e., to the intersection of other plates – not from the end of the hard corner. The area is to be calculated using the breadth between the intersecting plates.

FIGURE 3
Example of Defining Structural Elements *(1 January 2010)*

a) Example showing side shell, inner side and deck



b) Example showing girder on longitudinal bulkhead



5.9 Stress-strain Curves *σ-ε* (or Load-end Shortening Curves)

5.9.1 Hard Corners

Hard corners are sturdier elements which are assumed to buckle and fail in an elastic, perfectly plastic manner. The relevant stress strain curve σ-ε is to be obtained for lengthened and shortened hard corners according to A4/5.9.2.

5.9.2 Elasto-Plastic Failure of Structural Elements

The equation describing the stress-strain curve σ-ε of the elasto-plastic failure of structural elements is to be obtained from the following formula, valid for both positive (compression or shortening) of hard corners and negative (tension or lengthening) strains of all elements (see A4/5.9.2 FIGURE 4):

$$\sigma = \Phi\sigma_{yd} \quad \text{kgf/cm}^2$$

where

Φ = edge function

= -1 for $\varepsilon < -1$

= ε for $-1 < \varepsilon < 1$

= 1 for $\varepsilon > 1$

ε = relative strain

= $\frac{\varepsilon_E}{\varepsilon_{yd}}$

ε_E = element strain

ε_{yd} = strain corresponding to yield stress in the element

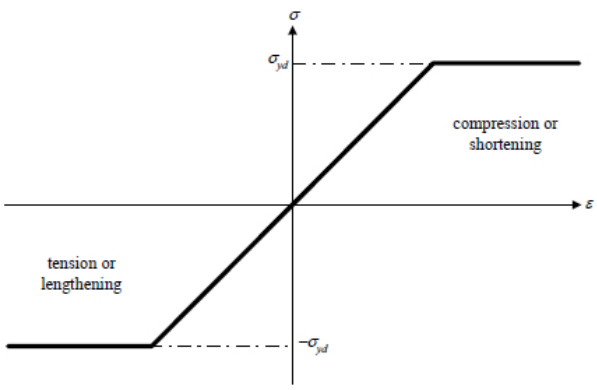
= $\frac{\sigma_{yd}}{E}$

Note:

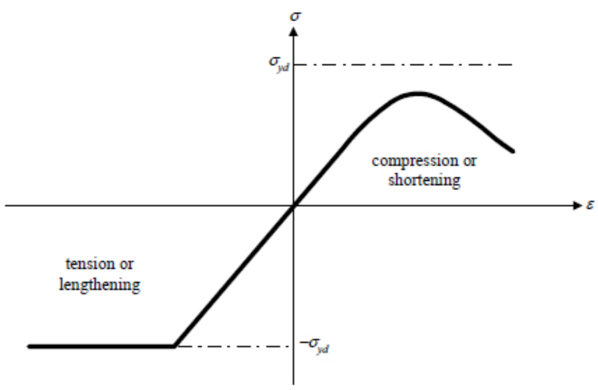
The signs of the stresses and strains in this Appendix are opposite to those in the rest of the Guide.

FIGURE 4
Example of Stress Strain Curves *σ-ε (1 January 2010)*

a) Stress strain curve σ-ε for elastic, perfectly plastic failure of a hard corner



b) Typical stress strain curve σ-ε for elasto-plastic failure of a stiffener



5.9.3 Beam Column Buckling

The equation describing the shortening portion of the stress strain curve σ_{CR1}-ε for the beam column buckling of stiffeners is to be obtained from the following formula:

$$\sigma_{CR1} = \Phi\sigma_{C1}\left(\frac{A_s + b_{eff} - p t_p}{A_s + s t_p}\right) \qquad \text{kgf/cm}^2$$

where

σ_{C1} = critical stress, in kgf/cm²

= $\dfrac{\sigma_{E1}}{\varepsilon}$ for $\sigma_{E1} \le \dfrac{\sigma_{yd}}{2}\varepsilon$

= $\sigma_{yd}\left(1 - \dfrac{\sigma_{yd}\varepsilon}{4\sigma_{E1}}\right)$ for $\sigma_{E1} > \dfrac{\sigma_{yd}}{2}\varepsilon$

σ_{E1} = Euler column buckling stress, in kgf/cm²

= $\pi^2 E \dfrac{I_E}{A_E \ell^2}$

ℓ = unsupported span of the longitudinal, in cm

s = plate breadth taken as the spacing between the stiffeners, in cm

I_E = net moment of inertia of stiffeners, in cm⁴, with attached plating of width $b_{eff\text{-}s}$

$b_{eff\text{-}s}$ = effective width, in cm, of the attached plating for the stiffener

= $\dfrac{s}{\beta_p}$ for $\beta_p > 1.0$

= s for $\beta_p \le 1.0$

β_p = $\dfrac{s}{t_p}\sqrt{\dfrac{\varepsilon\sigma_{yd}}{E}}$

A_E = net area of stiffeners, in cm², with attached plating of width $b_{eff\text{-}p}$

$b_{eff\text{-}p}$ = effective width, in cm, of the plating

= $\left(\dfrac{2.25}{\beta_p} - \dfrac{1.25}{\beta_p^2}\right)s$ for $\beta_p > 1.25$

= s for $\beta_p \le 1.25$

5.9.4 Torsional Buckling of Stiffeners

The equation describing the shortening portion of the stress-strain curve σ_{CR2}-ε for the lateral-flexural buckling of stiffeners is to be obtained according to the following formula:

$$\sigma_{CR2} = \Phi\left(\frac{A_s\sigma_{C2} + s t_p \sigma_{CP}}{A_s + s t_p}\right) \qquad \text{kgf/cm}^2$$

where

σ_{C2} = critical stress

= $\dfrac{\sigma_{E2}}{\varepsilon}$ for $\sigma_{E2} \le \dfrac{\sigma_{yd}}{2}\varepsilon$

= $\sigma_{yd}\left(1 - \dfrac{\sigma_{yd}\varepsilon}{4\sigma_{E2}}\right)$ for $\sigma_{E2} > \dfrac{\sigma_{yd}}{2}\varepsilon$

σ_{CP} = ultimate strength of the attached plating for the stiffener

$= \left(\frac{2.25}{\beta_p} - \frac{1.25}{\beta_p^2}\right)\sigma_{yd}$ for $\beta_p > 1.25$

$= \sigma_{yd}$ for $\beta_p \le 1.25$

β_p = coefficient defined in A4/5.9.3

σ_{E2} = Euler torsional buckling stress, in kgf/cm^2, equal to reference stress for torsional buckling σ_{ET}

σ_{ET} = $E\left[K/2.6 + (n\pi/\ell)^2\Gamma + C_o(\ell/n\pi)^2/E\right]/I_o\left[1 + C_o(\ell/n\pi)^2/I_o f_{cL}\right]$

K = St. Venant torsion constant for the longitudinal's cross section, excluding the associated plating

$= \left[b_f t_f^3 + d_w t_w^3\right]/3$

I_o = polar moment of inertia of the longitudinal, excluding the associated plating, about the toe (intersection of web and plating)

$= I_x + mI_y + A_s\left(x_o^2 + y_o^2\right)$ in cm^4

I_x, I_y = moment of inertia of the longitudinal about the x- and y-axis, respectively, through the centroid of the longitudinal, excluding the plating (x-axis perpendicular to the web), in cm^4

m = $1.0 - u(0.7 - 0.1d_w/b_f)$

u = unsymmetry factor

$= 1 - 2b_1/b_f$

C_o = $Et_p^3/3s$

Γ = warping constant

$\cong mI_{tf}d_w^2 + d_w^3 t_w^3/36$

I_{yf} = $t_f b_f^3\left(1.0 + 3.0u^2 d_w t_w/A_s\right)/12$

f_{cL} = critical buckling stress for the associated plating, corresponding to n-half waves

$= \pi^2 E(n/\alpha + \alpha/n)^2\left(t_p/s\right)^2/12\left(1 - \nu^2\right)$

α = ℓ/s

ℓ = unsupported span of the longitudinal, in cm

s = plate breadth taken as the spacing between the stiffeners, in cm

n = number of half-wave which yield a smallest σ_{ET}

5.9.5 Web Local Buckling of Stiffeners with Flanged Profiles

The equation describing the shortening portion of the stress strain curve σ_{CR3}-ε for the web local buckling of flanged stiffeners is to be obtained from the following formula:

$$\sigma_{CR3} = \Phi\sigma_{yd}\left(\frac{b_{eff-p}t_p + d_{w-eff}t_w + b_f t_f}{st_p + d_w t_w + b_f t_f}\right) \qquad \text{kgf/cm}^2$$

where

s = plate breadth taken as the spacing between the stiffeners, in cm

$b_{eff\text{-}p}$ = effective width of the attached plating in cm, defined in A4/5.9.3

$d_{w\text{-}eff}$ = effective depth of the web, in cm

$= \left(\frac{2.25}{\beta_w} - \frac{1.25}{\beta_w^2}\right)d_w$ for $\beta_w > 1.25$

$= d_w$ for $\beta_w \le 1.25$

$\beta_w = \frac{d_w}{t_w}\sqrt{\frac{\varepsilon\sigma_{yd}}{E}}$

5.9.6 Local Buckling of Flat Bar Stiffeners

The equation describing the shortening portion of the stress-strain curve σ_{CR4}-ε for the web local buckling of flat bar stiffeners is to be obtained from the following formula:

$$\sigma_{CR4} = \Phi\left(\frac{A_s\sigma_{C4} + st_p\sigma_{CP}}{A_s + st_p}\right) \quad \text{kgf/cm}^2$$

where

σ_{CP} = ultimate strength of the attached plating, in kgf/cm^2

σ_{C4} = critical stress, in kgf/cm^2

$= \frac{\sigma_{E4}}{\varepsilon}$ for $\sigma_{Er} \le \frac{\sigma_{yd}}{2}\varepsilon$

$= \sigma_{yd}\left(1 - \frac{\sigma_{yd}\varepsilon}{4\sigma_{E4}}\right)$ for $\sigma_{Er} \le \frac{\sigma_{yd}}{2}\varepsilon$

σ_{E4} = Euler buckling stress

$= \frac{0.44\pi^2 E}{12\left(1-v^2\right)}\left(\frac{t_w}{d_w}\right)^2$

5.9.7 Buckling of Transversely Stiffened Plate Panels

The equation describing the shortening portion of the stress-strain curve σ_{CR5}-ε for the buckling of transversely stiffened panels is to be obtained from the following formula:

$$\sigma_{CR5} = min\begin{cases}\sigma_{yd} \\ \sigma_{yd}\Phi\left[\frac{s}{\ell_{stf}}\left(\frac{2.25}{\beta_p} - \frac{1.25}{\beta_p^2}\right) + 0.115\left(1 - \frac{s}{\ell_{stf}}\right)\left(1 + \frac{1}{\beta_p^2}\right)^2\right]\end{cases} \quad \text{kgf/cm}^2$$

where

β_p = coefficient defined in A4/5.9.3

s = plate breadth taken as the spacing between the stiffeners, in cm

ℓ_{stf} = span of stiffener equal to spacing between primary support members, in cm

APPENDIX **5**

Fatigue and Fracture Analysis for Type-B Independent Tanks *(1 June 2011)*

1 General

IMO requires additional fatigue and fracture mechanics based analysis for type B independent tank. Structural members in independent cargo tanks are affected by dynamic loads from internal pressure caused by ship motion. The strength and safety of type B independent cargo tank are to be verified against dynamic loads through fatigue and fracture mechanics based analysis.

This appendix provides procedure and acceptance criteria for fatigue and fracture analysis of a cargo tank to verify compliance with IMO type B independent tank requirements. Fatigue and fracture analysis are to be carried out for a tank to verify adequate fatigue and crack propagation characteristics. Integrity of the structural member of an independent tank against fatigue and fracture is to be verified by:

- Fatigue damage analysis for high cycle and low cycle fatigue load
- Fracture mechanics based analysis for an initial crack
- Leakage of cargo analysis in case of a penetrating crack

The general procedure for fatigue and fracture analysis is shown in A5/1.5 FIGURE 1.

1.1 Selection of a Tank for the Analysis

The internal pressure on an independent tank due to the acceleration of the center of gravity of liquid cargo can be estimated following the procedure in Subsection 3/11. The tank under the most severe internal pressure is to be selected for the fatigue and fracture analysis. The forward most cargo tank is normally selected as a target cargo tank for the analysis if the shape and size is similar to other tanks.

1.3 FEA Model

The global FEA model including hull, cargo tank, and supporting structure is to be used for the fatigue and fracture analysis. Global finite element modeling is described in Appendix A1. In the FEA model the target cargo tank is to be located in the middle of the model as shown in A1/5.1 FIGURE 1.

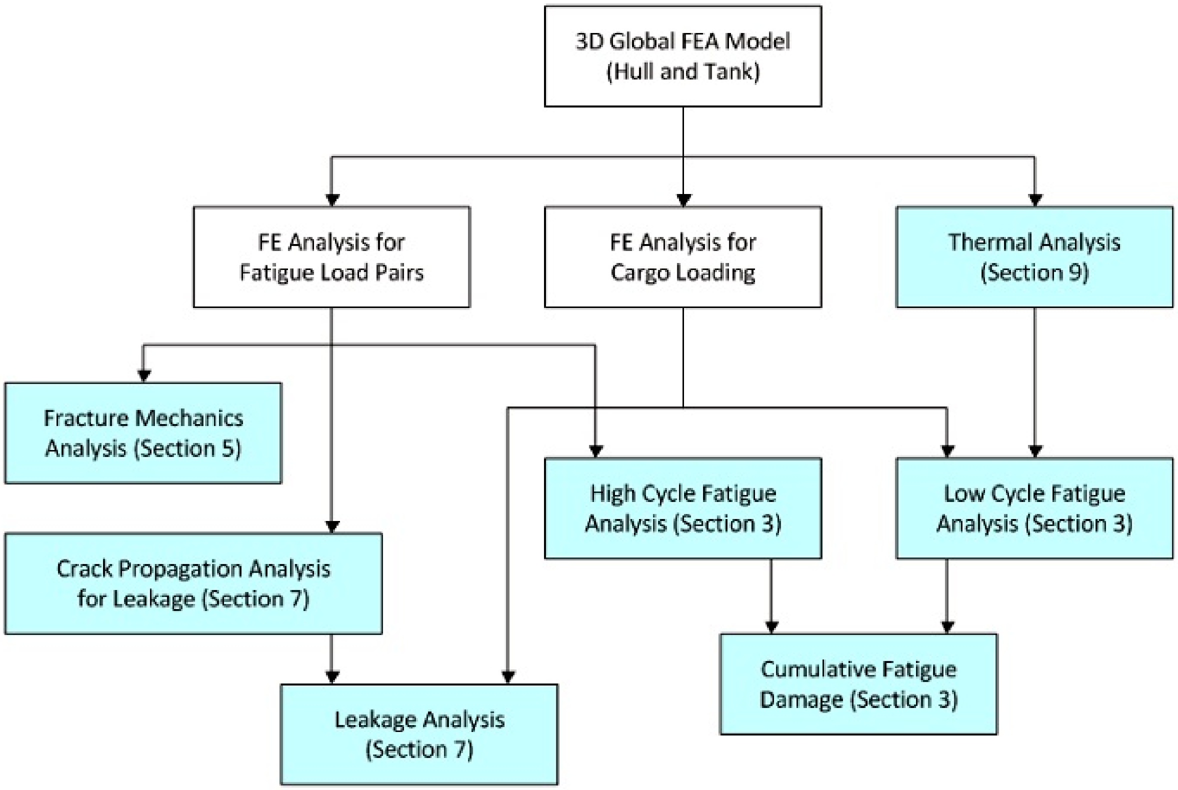
1.5 Critical Locations

Fatigue damage assessment and fracture mechanics analysis are to be carried out for areas of the tank with high stress concentrations. Critical locations with high stress include;

- Tank skin including bottom, top, side, front, and rear plates
- Bracket connections of transverse web frames
- Bracket connections of swash bulkheads
- Bracket connections of horizontal stringers

- Brackets attached to tank at vertical supports and chocks

FIGURE 1
Analysis Procedure *(1 June 2011)*



1.7 Hot Spot Stress with Global Course Mesh

Generally, it is recommended to use hot spot stress as a local stress for fatigue and fracture analysis in this appendix. For an initial screening purpose of critical areas, global coarse FEA model is to be used. When the stress result from global coarse FEA model is used for the analysis, hot spot stress can be estimated from nominal stress with appropriate stress concentration factors for stiffener attachments and skin plates with fillet welds.

The bending stress of a plate between stiffeners from internal pressure is to be considered for fatigue and fracture analysis of tank skin plates. The total stress amplitude is the sum of the membrane stresses from FEA results and local stresses caused by panel bending. Bending stress of a panel between stiffeners is to be calculated from 5C-1-5/3.5 of the *Marine Vessel Rules*.

1.9 Hot Spot Stress with a Local Fine Mesh

For a critical areas identified from the global course mesh, additional fatigue and fracture analysis are to be carried out with local fine mesh FEA models. The hot spot stress is to be calculated from the FEA results with a refined mesh. The mesh size of local area is to be small enough to detect the stress concentration and the element size at the critical location is to be equal to the plate thickness. The procedure to estimate the hot spot stress at a weld toe with refined mesh is specified in A3/11.5.

1.11 Plate Thickness Effect

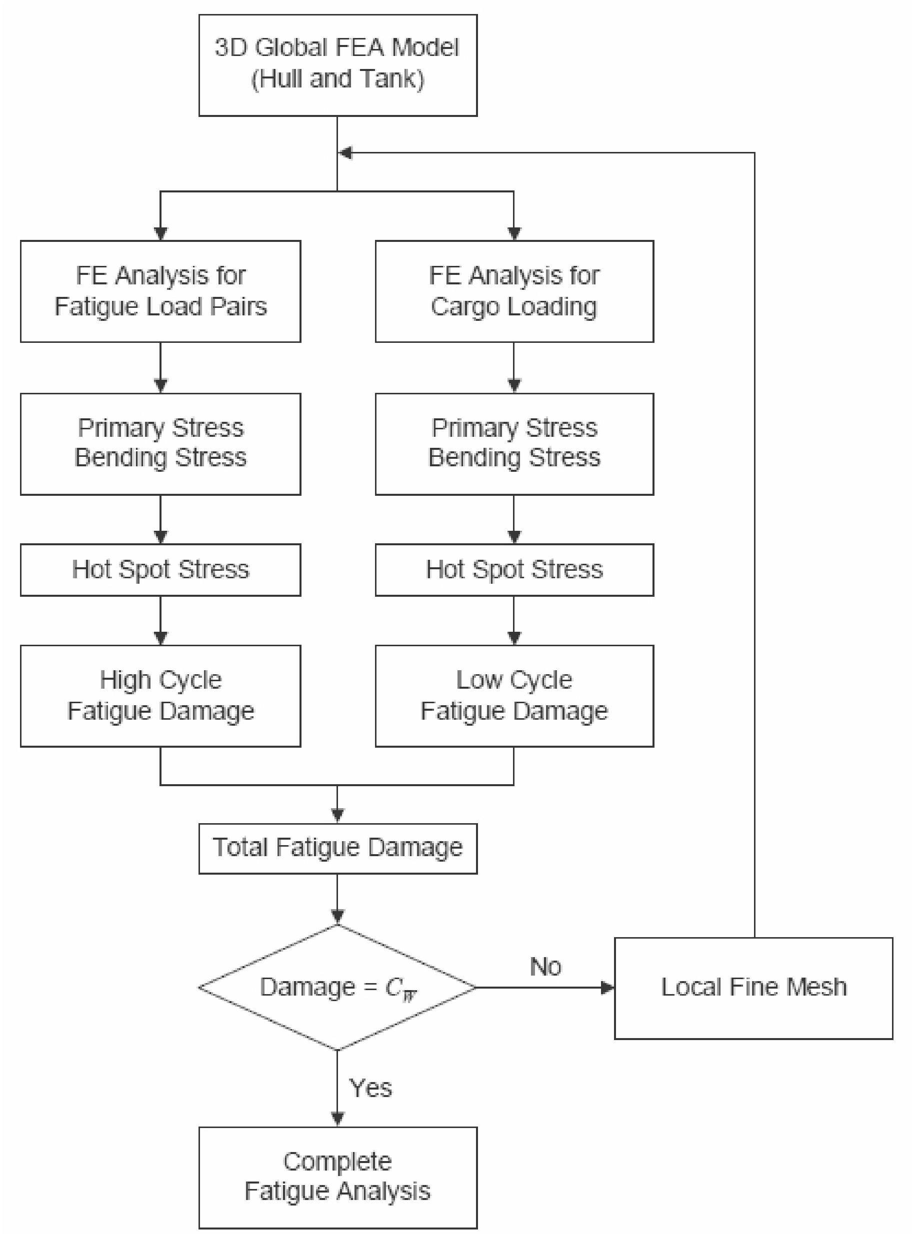
For the welded connections with thickness greater than 22 mm, stress range is to be adjusted by a factor $(t/22)^{0.25}$ as described in A3/5.7.

3 Fatigue Damage Assessment

Accumulated fatigue damage is to be assessed for high cycle and low cycle fatigue loading. High cycle fatigue damage is due to the internal pressure caused by the motion of a ship. For long term prediction of wave loads, wave spectra covering North Atlantic Ocean and a probability level of 10^{-8} are to be employed. Low cycle fatigue damage is caused by loading and unloading of a liquid cargo to the tank.

Fatigue damage is to be calculated based on the appropriate S-N curve with the assumption of linear cumulative damage (Palmgren-Miner rule). Highly stressed areas are to be selected from FEA results considering all fatigue loading cases. The hot spot stress can be calculated as described in A5/1.7 and A5/1.9. Fatigue damage estimation procedure is shown in A5/3 FIGURE 2.

FIGURE 2
Fatigue Damage Assessment Procedure *(1 June 2011)*



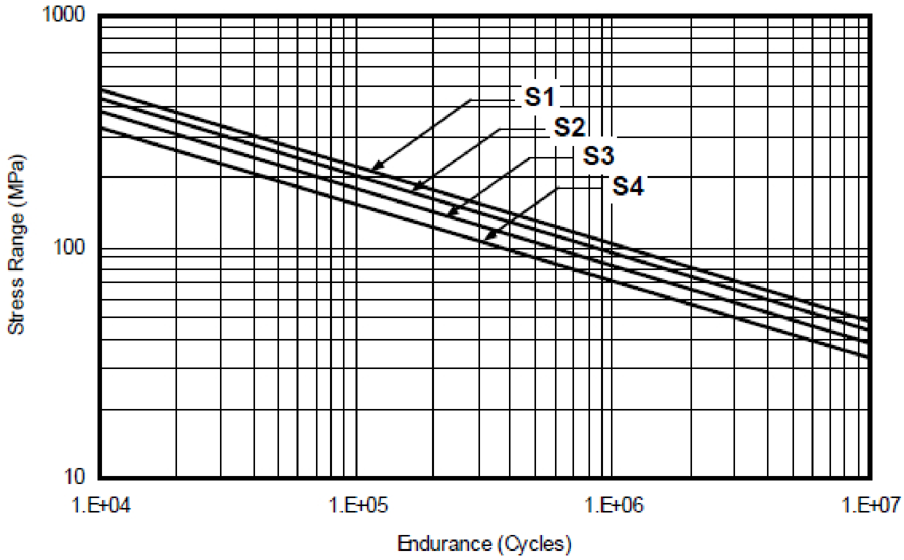
3.1 S-N Curves

Stress results from the global FEA model are to be used for high cycle and low cycle fatigue damage estimation. The maximum principal stress range is to be used for the analysis.

Appropriate S-N curves are to be used for the fatigue damage analysis. The selection of S-N curve depends on weld type, such as butt weld, transverse fillet weld, or longitudinal fillet weld.

S-N curves for stainless steel are shown in A5/3.1 FIGURE 3. Formulation of S-N curve is given in A3/5.7 FIGURE 5. Application of each S-N curve is to follow equivalent S-N curves for steel as shown in A3/3.3.10 TABLE 1.

FIGURE 3
Design S-N Curves for Stainless Steel *(1 June 2011)*

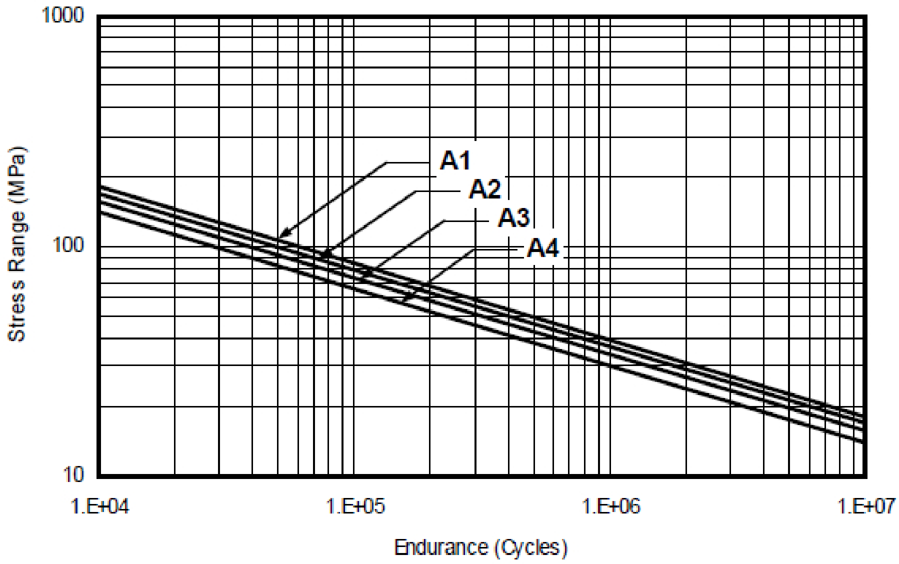


Details of S-N Curves

Class	*m*	*Log(K2)*	*Equivalent S-N curve for steel*
S1	3.0	12.05	D
S2	3.0	11.92	E
S3	3.0	11.75	F
S4	3.0	11.55	F2

S-N curves for aluminum are shown in A5/3.1 FIGURE 4. Application of each S-N curve is to follow equivalent S-N curves for steel as shown in A3/3.3.10 TABLE 1.

FIGURE 4
Design S-N Curves for Aluminum *(1 June 2011)*

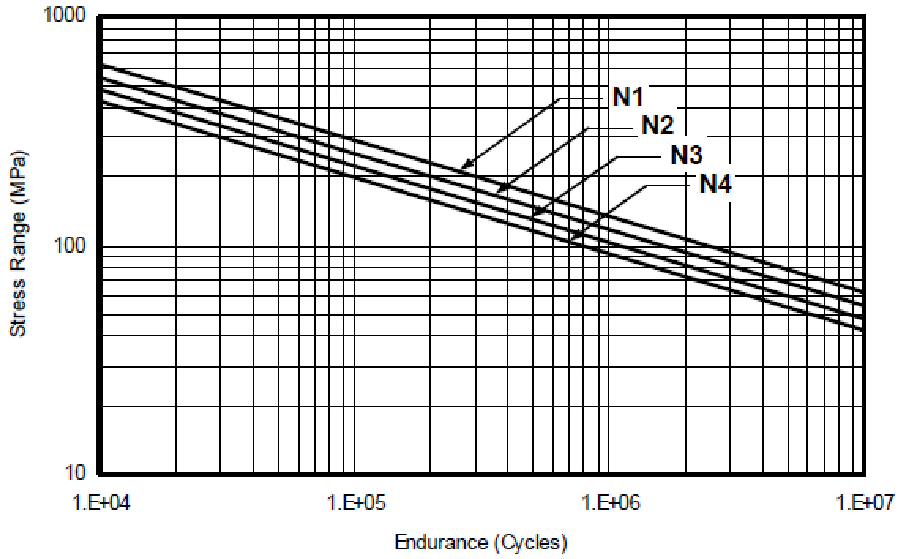


Details of S-N Curves

Class	*m*	*Log(K2)*	*Equivalent S-N curve for steel*
A1	3.0	10.78	D
A2	3.0	10.69	E
A3	3.0	10.59	F
A4	3.0	10.46	F2

S-N curves for 9% Ni are shown in A5/3.1 FIGURE 5. Application of each S-N curve is to follow equivalent S-N curves for steel as shown in A3/3.3.10 TABLE 1.

FIGURE 5
Design S-N Curves for 9% Ni *(1 June 2011)*



Details of S-N Curves

Class	*m*	*Log(K2)*	*Equivalent S-N curve for steel*
N1	3.0	12.37	D
N2	3.0	12.18	E
N3	3.0	12.03	F
N4	3.0	11.89	F2

3.3 High Cycle Fatigue Damage

High cycle fatigue damage is to be calculated for the critical areas from the wave loading by the ship motion. The stress result form integrated hull and tank FEA model is to be used for the analysis. Standard design load cases for fatigue strength assessment is shown in 4/5 TABLE 3 and 4/5 TABLE 4. Four load case pairs for full load and ballast conditions were considered in the tables. The stress amplitude is to be calculated from each load case pair. Each dynamic load case corresponds to a probability level of 10^{-4}.

Fatigue damage is to be calculated following the procedure in A3/5:

$$D_{fi} = \frac{1}{6}D_{fi\_12} + \frac{1}{6}D_{fi\_34} + \frac{1}{3}D_{fi\_56} + \frac{1}{3}D_{fi\_78}$$

where

D_{fi_jk} = fatigue damage due to the stress range from load case pairs jk

The long term stress ranges can be characterized using a modified Weibull probability distribution parameter as described in A3/5.5. Design life of 20 years is to be used to assess the high cycle damage of the structure.

3.5 Low Cycle Fatigue Damage

Low cycle fatigue damage is due to the cyclic stress from loading and unloading of liquid cargo to the tank. Pressure levels for the tank are to be calculated from the sum of liquid cargo and gas pressure. The densities of liquefied gas cargos are listed in 1/1.23 TABLE 2. The pressure envelope of the tank is to be applied to the global hull and tank FEA model to determine the stress at each critical location.

The bending stress of a panel between stiffeners is to be added to the membrane stress from the FEA model for skin plates. The total number of fatigue cycles from the loading and unloading of cargo is to be assumed as 1,000 for the design life (e.g., 20 years) of a vessel.

3.7 Total Fatigue Damage *(1 June 2017)*

Total accumulated fatigue damage is to be assessed as the sum of high cycle and low cycle damage. Total cumulative fatigue damage factor is to be calculated by:

$$D_T = \sum \frac{n_i}{N_i} + \frac{n_{Loading}}{N_{Loading}} = D_F + \frac{n_{Loading}}{N_{Loading}}$$

where

D_T	=	total fatigue damage
D_F	=	high cycle fatigue damage calculated from A3/5.7
n_i	=	*number of stress cycles at each stress level during the life of the tank*
N_i	=	*number of cycles to fracture for the respective stress level according to the Wöhler (S-N) curve*
$n_{Loading}$	=	*number of loading and unloading cycles during the life of the tank, not to be less than 1000. Loading and unloading cycles include a complete pressure and thermal cycle Note: 1,000 cycles normally corresponds to 20 years of operation.*
$N_{Loading}$	=	*number of cycles to fracture for the fatigue loads due to loading and unloading of liquid cargo*

Total fatigue damage shall be based on the design life of the tank but not less than 10^8 wave encounters.

3.9 Acceptance Criteria *(1 June 2017)*

The total fatigue damage is to be less than the allowable damage factor:

$$D_T \leq C_W$$

where

C_W = maximum allowable cumulative fatigue damage ratio

For failures that can be reliably detected by means of leakage detection:

C_W is to be less than or equal to 0.5.

Predicted remaining failure development time, from the point of detection of leakage until reaching a critical state, shall not be less than 15 days, unless different requirements apply for ships engaged in particular voyages.

For failures that cannot be detected by leakage but that can be reliably detected at the time of in-service inspections:

C_w is to be less than or equal to 0.5.

Predicted remaining failure development time, from the largest crack not detectable by in-service inspection methods until reaching a critical state, shall not be less than three times the inspection interval.

In locations of the tank where effective defect or crack development detection cannot be confirmed, the following more stringent fatigue acceptance criteria shall be applied as a minimum:

C_w is to be less than or equal to 0.1.

Predicted failure development time from the assumed initial defect until reaching a critical state shall not be less than three times the lifetime of the tank.

3.11 FEA with Refined Mesh

A detailed fine mesh FEA is required for the critical areas that do not meet the acceptance criteria. The hot spot stress is to be calculated from the FEA model with a refined mesh for the critical areas as described in A5/1.9.

5 Fracture Mechanics Analysis

A fracture mechanics based analysis is to be carried out for the critical locations of the tank structure with high dynamic stresses. A fracture mechanics approach assumes that an idealized crack propagates in relation to the stress intensity factor range.

A fatigue crack propagation analysis is to be conducted for tank skin plates to verify the integrity of a cargo tank. Fatigue crack propagation is to be assessed from the growth of an initial existing crack to a critical size. High stress concentration areas or large fatigue damage locations identified in A5/3 are to be selected for the crack propagation analysis.

5.1 Load Distribution *(1 June 2017)*

5.1.1 Load Distribution Spectrum for Design Life

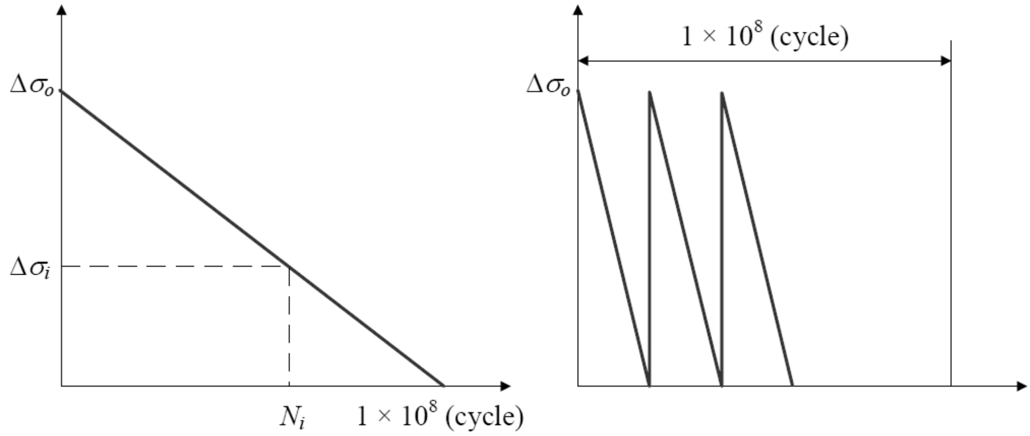
The dynamic load spectrum is to be determined by long term distribution based on the design life of the ship corresponding to realistic wave spectra covering the North Atlantic and a probability level of 10^{-8}. The long term stress ranges can be characterized using a modified Weibull probability distribution parameter. Simplified linear load spectrum can be used for the load distribution. The simplified linear relation is assumed as:

$$\log_{10} N_i = 8 \times \left(1.0 - \frac{\Delta\sigma_i}{\Delta\sigma_o}\right)$$

where $\Delta\sigma_o$ is the most probable maximum stress range over the life of the ship.

The total load spectrum is to be divided into more than 10 groups to remove the effect of loading sequence to crack propagation life as shown in A5/5.1.1 FIGURE 6. $\Delta\sigma_o$ in the figure is the most probable maximum stress range over the life of the ship. Two times of the FEA results from the high cycle fatigue analysis in A5/3.3 (based on 10^{-4} probability level) can be used as the maximum stress range for fracture analysis. The hot spot stress can be calculated from the nominal stress obtained from the FEA results with geometric stress concentration factor as described in A5/1.7.

FIGURE 6
Load Distribution for Crack Propagation Analysis *(1 June 2017)*



5.1.2 Load Distribution Spectrum for 15 Days

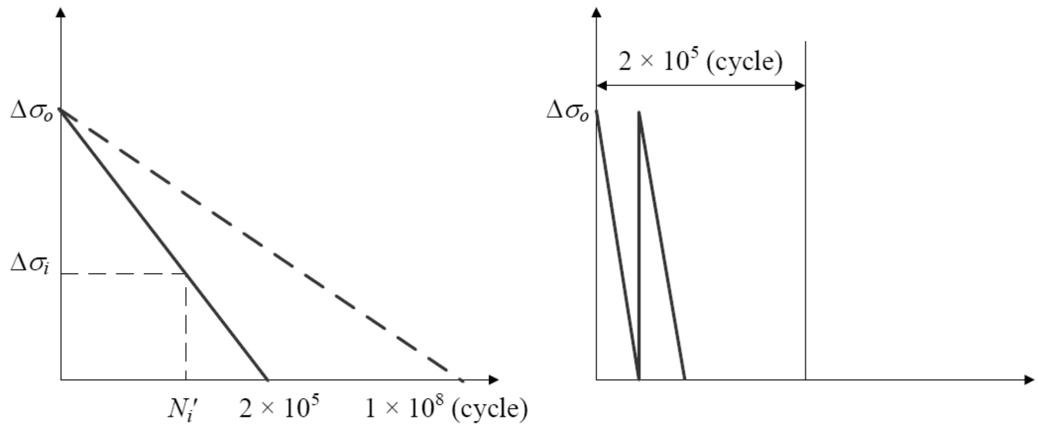
The partial secondary barrier of an independent tank is to be designed to contain any envisaged leakage of liquid cargo for a period of 15 days after the detection of initial leakage. The load spectrum is to be assumed to represent the worst 15 day period from the spectrum the ship will experience (i.e., 15 days of most severe storm during the service life of the ship). Simplified linear distribution over a period of 15 days may be used for crack propagation analysis:

$$\log_{10} N_i = \log_{10}\left(2.0 \times 10^5\right) \times \left(1.0 - \frac{\Delta\sigma_i}{\Delta\sigma_o}\right)$$

where $\Delta\sigma_o$ is the most probable maximum stress range over the life of the ship as specified in A5/5.1.1, shown in A5/5.1.2 FIGURE 7.

The total cycle is to be divided into several groups to remove the effect of loading sequence as described in A5/5.1.1.

FIGURE 7
Load Distribution for 15 Days Crack Propagation *(1 June 2017)*



5.3 Initial Crack

The size of an initial crack is one of the main parameters for the crack propagation analysis. An initial surface crack is to be assumed in a fillet or butt weld areas of the tank structure. The dimension of the surface crack is to be assumed as 0.5 mm depth and 5 mm length.

5.5 Stress Intensity Factor *(1 June 2017)*

The stress intensity factor range is to be calculated from stress range, crack shape and size, and geometry. BS 7910:2005 or the equivalent standard is to be used to assess the stress intensity factor for a surface crack. The stress range is to be based on the maximum principal stress. The stress intensity factor range can be calculated by:

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

where

$Y\Delta\sigma$	=	$Mf_w(M_m\Delta\sigma_m + M_b\Delta\sigma_b)$
M	=	bulging correction factor
f_w	=	finite width correction factor
M_m, M_b	=	stress intensity magnification factors
$\Delta\sigma_m$	=	remote uniform tensile stress
$\Delta\sigma_b$	=	remote bending stress

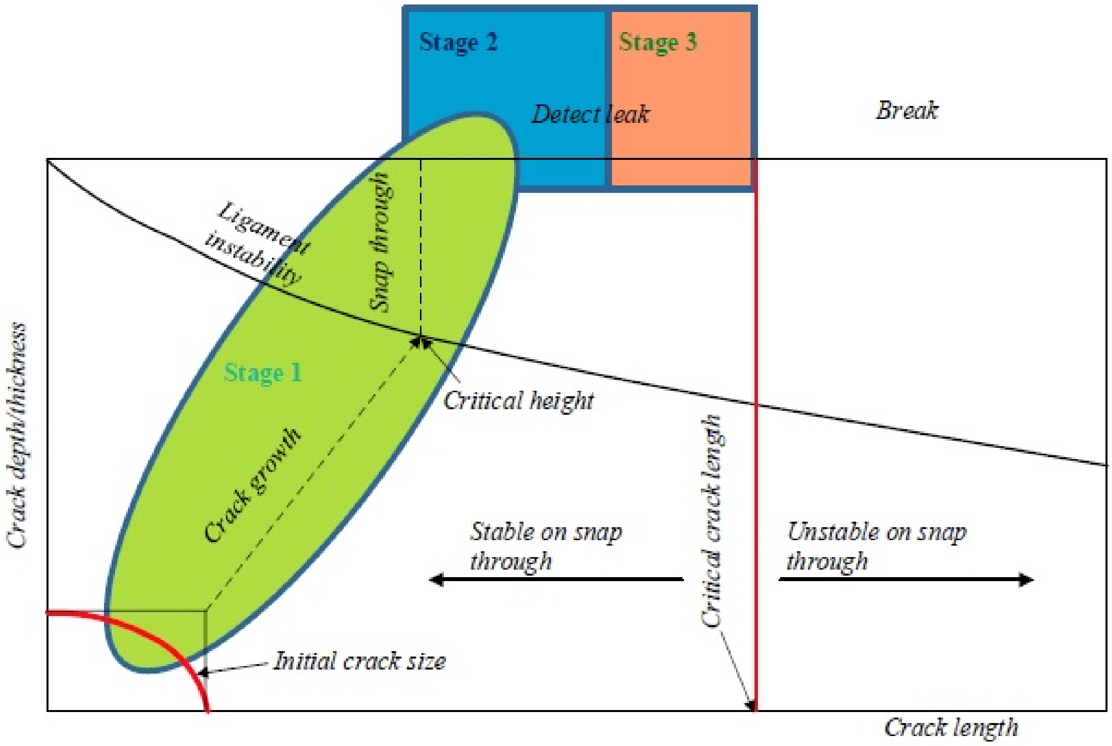
The expressions of these parameters herein can be found in BS 7910:2005. For a semi-elliptical surface crack, stress intensity factor ranges at the deepest point on the crack front and at the ends of the crack, ΔK_a and ΔK_c, can also be calculated according to BS 7910:2005. The residual stress and welding effects at the critical location need to be considered for the calculation of stress intensity factors of semi-elliptical surface crack referring to BS 7910:2005.

5.7 Crack Propagation Analysis *(1 June 2017)*

The process of crack propagation can be classified as three stages, shown in Appendix 5, Figure 8. At stage 1, the crack initiates and propagates as a semi-elliptical surface crack in both thickness and length directions. After penetrating through the thickness, stage 2 starts so that the crack grows as a partly through-thickness crack until there is sufficient opening to cause a detectable leak. At stage 3, the crack grows as a fully through-thickness crack until the final failure occurs. The detailed process is as follows:

- *Stage 1:* A surface crack initiates from the initiation side of plate and propagates in both in-plane and thickness directions until penetrating the thickness to the penetration side of plate. Another possibility is that the ligament instability occurs as the crack grows to a critical height (e.g., t_0) since the stress intensity factor exceeds the critical value defined by fracture toughness according to BS 7910. In this case, the crack is assumed to penetrate through the thickness although the crack depth t_0 is less than the thickness t. At this point, the length of semi-elliptical surface crack at the initiation side is calculated using fracture mechanics analysis and the depth of semi-elliptical surface crack is equal to the thickness.
- *Stage 2 & Stage 3:* The crack grows as a through thickness crack to determine the crack length at initiation side. The crack length at penetration side can be calculated assuming that it keeps the same ratio of short to long half axes during crack propagation.

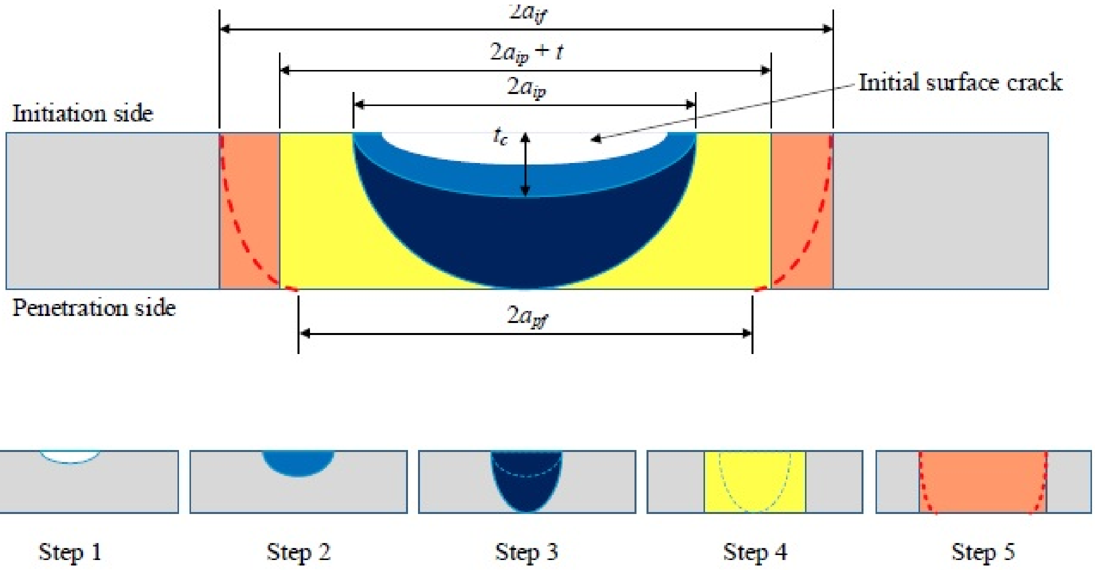
FIGURE 8
Crack Propagation Stages *(1 June 2017)*



Based on the above description, crack propagation calculation procedure, shown in Appendix 5, Figure 9, will be as follows:

- Step 1: Specify an initial surface crack with length, $2a_{i0}$, and depth, t_0.
- Step 2: Perform crack propagation analysis on a surface crack using the Paris' law until the ligament instability occurs. Thus, at ligament failure, the length, $2a_{ip}$, and depth, t_c, of the surface crack are determined.
- Step 3: Extend the surface crack to $2a_{ip}$ and t, and then re-characterize the surface flaw into a through thickness flaw with the crack length of $2a_{ip} + t$.
- Step 4: Perform crack propagation analysis on a through thickness crack using Paris' law until the final crack size is reached. The length $2a_{if}$ of the crack is determined and must be less than the critical length determined by fracture toughness in order to satisfy the leak-before-break criterion. The length $2a_{if}$ is then assumed as the length of the crack at the initiation side.
- Step 5: Determine the crack length at penetration side following the same aspect ratio as that before re-characterization in Step 3. The length of the crack at penetration side is calculated by $a_{Rf} = \sqrt{a_{if}^2 a_{ip}^2}$.

FIGURE 9
Crack Propagation Calculation Procedure *(1 June 2017)*



For a through thickness crack, crack propagation at the critical location is to be calculated with the Paris Equation as follows:

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

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

where

da/dN	=	crack propagation rate
C, m	=	Paris constants
ΔK	=	stress intensity factor range
ΔK_{th}	=	threshold value of stress intensity factor range

For a semi-elliptical surface crack, it follows:

$$\frac{da}{dN} = C(\Delta K_a)^m$$

$$\frac{dc}{dN} = C(\Delta K_c)^m$$

where a and c are long and short half-axial lengths for a semi-elliptical surface crack. ΔK_a and ΔK_c are stress intensity factor ranges at the deepest point on the crack front and at the ends of the crack, respectively, which can be calculated according to BS 7910:2005.

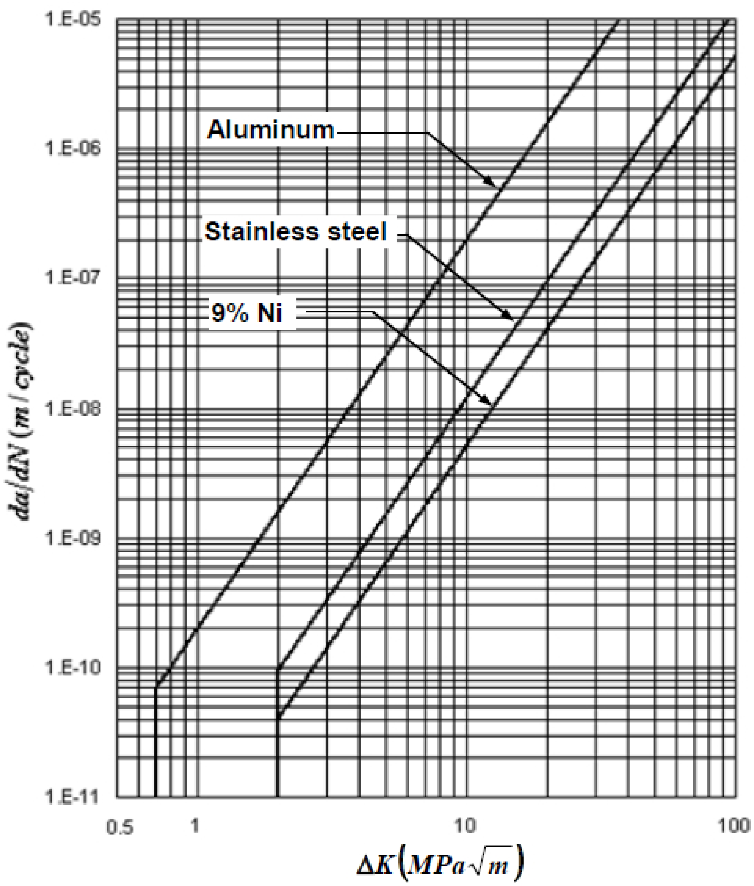
The fatigue crack propagation path is to be assumed as perpendicular to the principal stress direction.

5.9 Material Properties *(1 June 2017)*

The fracture toughness of a material, K_c, can be directly measured from fracture testing. When the fracture toughness of the tank material is not available, the Master curve approach or equivalent process is to be used to determine the fracture toughness of ferritic steels from the Charpy V-notch impact test data. A detailed procedure and assumptions used to determine the fracture toughness are to be submitted for review.

Adequate Paris constants are to be used for the crack propagation assessment. Crack propagation tests are to be performed for base metal, weld metal and heat affected zone. Fracture mechanics analysis is to in general be based on crack growth data taken as mean plus two standard deviations of the test data. If test data is not available, crack growth curves defined in Appendix 5, Figure 10 are to be used for stainless steel, aluminum, and 9% Ni.

FIGURE 10
Crack Growth Curves *(1 June 2011)*



Details of Crack Growth Curves

Material	*m*	*C*	$\Delta K_{th}, MPa\sqrt{\mathbf{m}}$
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

5.11 Acceptance Criteria *(1 June 2017)*

The two parameters of applied stress and stress intensity factor, together with material properties such as yielding and ultimate strength and fracture toughness, are to be used for the failure assessment. Level 2 (normal assessment) in BS 7910:2005 is recommended for fracture assessment. The schematic of Level 2

Failure Assessment Diagram (FAD) is shown in Appendix 5, Figure 11. The area is bounded by the axes and by the assessment line. In the FAD, there are two assessment parameters: the fracture ratio and the load ratio.

The fracture ratio, K_r, is defined as the ratio of the stress intensity factor to the fracture toughness:

$$K_r = \frac{K_I}{K_{mat}}$$

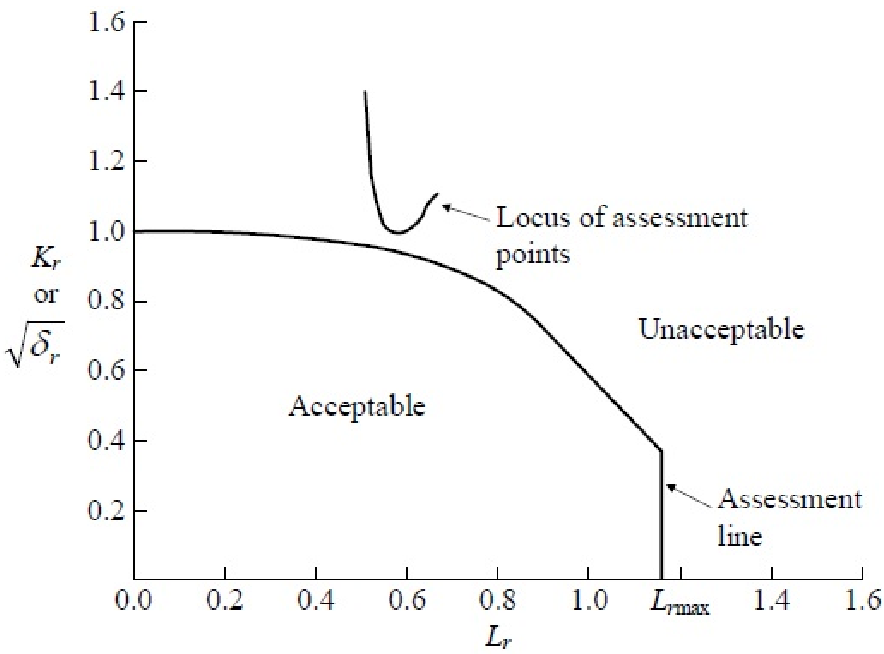
The load ratio, L_r, is defined as the ratio of the reference stress to the flow strength:

$$L_r = \frac{\sigma_{ref}}{\sigma_y}$$

The detailed calculation for two parameters, L_r and K_r, is referring to BS 7910:2005. The flaw is acceptable if (K_r, L_r) falls within the enclosed region.

For a semi-elliptical surface crack, the crack will either snap to become a through thickness crack as it reaches a critical height, or continue increasing through the whole thickness. After the penetration to the outer surface of the tank wall, the crack becomes a through thickness crack and the tank begins to leak. It is at that moment that gas leakage can be detected via the gas detection system. For a through thickness crack, the crack will propagate for the period of 15 days based on the IGC requirements. The final crack length determined from the crack propagation analysis is to be less than the critical crack length of the material determined from the operating life of the ship corresponding to 10^8 wave encounter. The estimated crack propagation life to reach a through thickness crack is to be greater than the design life of the vessel.

FIGURE 11
Level 2 Failure Assessment Diagram (FAD) (1 June 2017)



5.13 FEA with Refined Mesh

A detailed fine mesh FEA is required for the critical areas that do not meet the acceptance criteria. The hot spot stress is to be calculated from the FEA model with a refined mesh for the critical areas as described in A5/1.9.

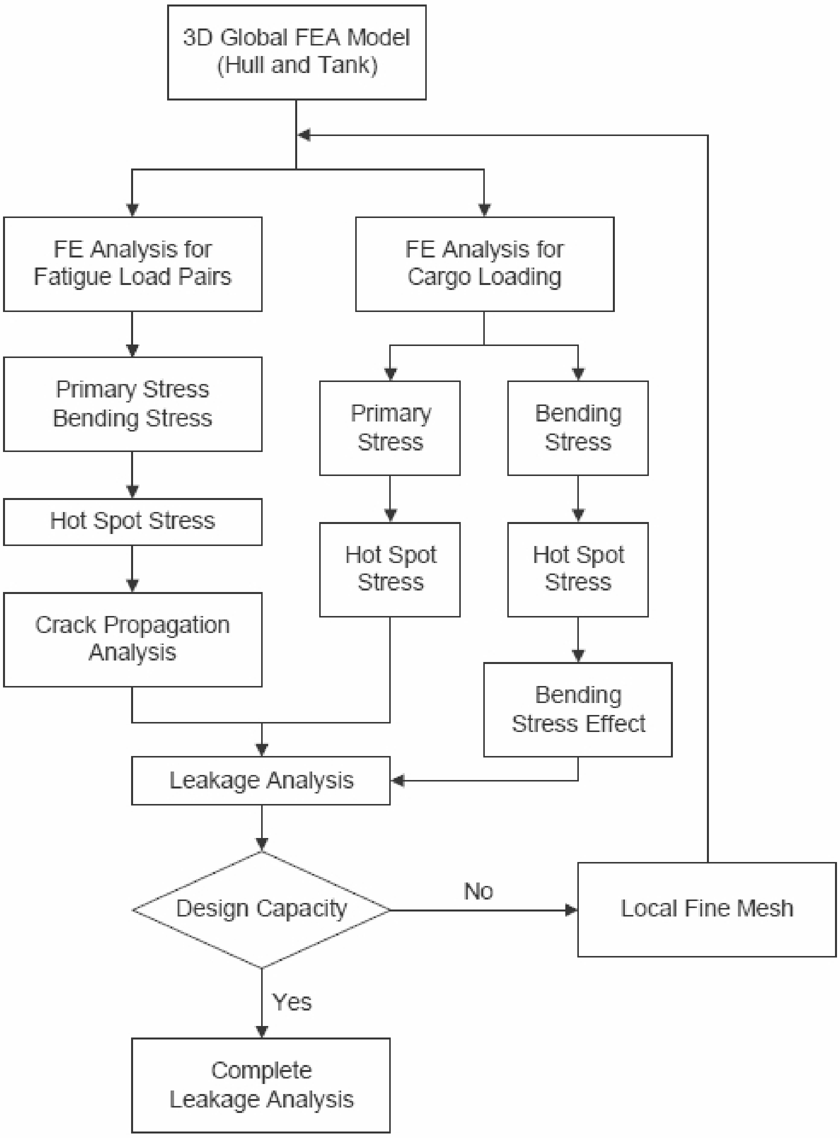
7 Leakage Analysis *(1 June 2017)*

The secondary barrier of an independent tank is to be designed to be capable of containing any envisaged leakage of liquid cargo for a period of 15 days. Leakage of cargo is to be contained by the secondary barrier for a period of 15 days after the detection of initial leakage. The leakage rate of liquid cargo from a crack in an independent tank is to be less than the design capacity of the secondary barrier.

The tank is to be verified against possible failure from a growing crack for 15 days after the detection of gas leakage. The final size of a crack growing from a penetrating crack is to be less than the critical size that can lead to a failure of the structure.

Leakage analysis procedure is shown in Appendix 5, Figure 12.

FIGURE 12
Leakage Assessment Procedure *(1 June 2011)*



7.1 Estimation of Leakage Rate *(1 June 2017)*

The shape of a crack opening can be assumed as an ellipse with crack length, $2a_{pf}$, and width, $2b$. The final size of a crack propagated during 15 days from a penetrating initial crack is to be used to assess the leakage rate of a liquid cargo. The width of a crack may be determined from finite element analysis with very fine mesh. It can be estimated as a function of crack length, membrane stress, and Young's modulus. A parametric study may be needed to determine the relation between dominating parameters affecting the crack width. A detailed analysis procedure and assumptions of parameters to determine the width of a crack are to be submitted for approval.

The leakage rate of the liquid cargo through the crack opening, W, in mm^3/sec, may be determined by the following equation:

$$W = k_f\left(\frac{\pi}{4\mu}\right)\left(\frac{p}{t}\right)\left(\frac{a_{pf}^3 b^3}{a_{pf}^2 + b^2}\right)$$

where

μ = viscosity of the liquid cargo, in kgf-sec/mm^2

p = internal pressure, in kgf/mm^2

= $p_o + g\gamma h$

p_o = vapor pressure, in kgf/mm^2

γ = cargo density, kg/mm^3

h = head, in mm

t = plate thickness, in mm

a_{pf} = a half of the crack length, in mm

b = a half of the crack width, in mm

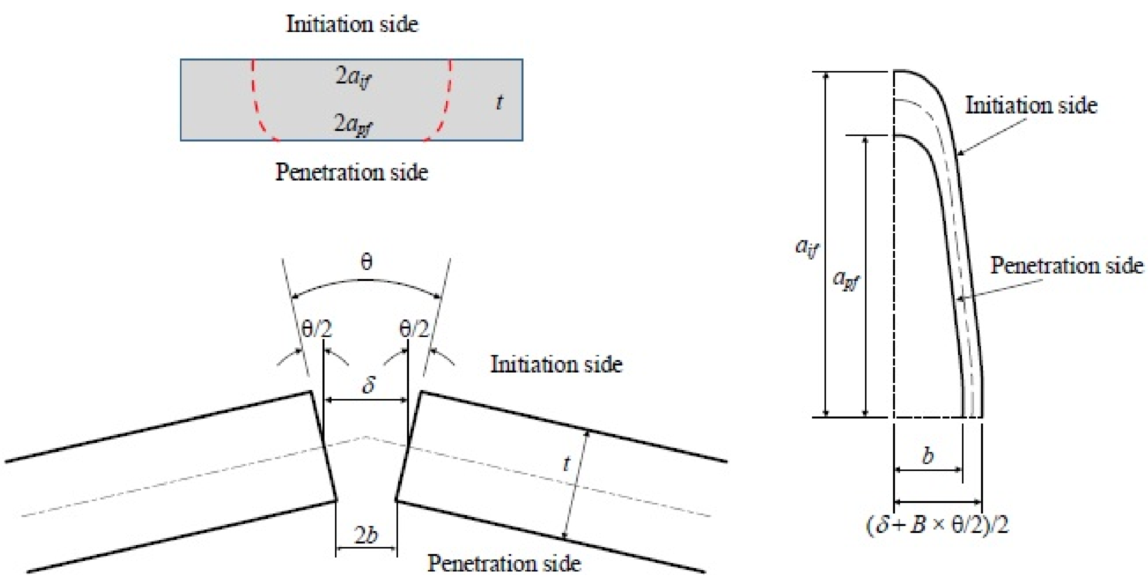
k_f = friction correction factor

7.3 Effect of Bending Stress *(1 June 2017)*

The crack closing effect from local bending stress of a hull panel may be considered for the analysis. Bending stresses of a panel between stiffeners is to be calculated from 5C-1-5/3.5 of the *Marine Vessel Rules*, as described in A5/1.7.

A finite element analysis with localized very fine mesh is to be carried out to determine the rotated angle from the vertical line and the reduction of crack width. A detailed analysis is to be carried out to determine the reduced crack width as a function of crack length, bending stress, Young's modulus, and plate thickness. The reduction effect of a crack opening by the rotation of a panel is shown in Appendix 5, Figure 13. A detailed analysis procedure and assumptions of parameters to determine the reduced crack width are to be submitted for approval.

FIGURE 13
Crack Closing Effect by Panel Bending *(1 June 2017)*



Appendix 5, Figure 13 shows the crack opening in a plate caused by membrane and bending stresses. The shape of the crack opening is assumed as an ellipse and the crack opening area, which gas goes through, is defined by:

$$A = \pi a_{pf} b$$

where b is the short axis defined by:

$$b = \frac{1}{2}\left(\delta - \frac{t \cdot \theta}{2}\right)$$

At the mid-surface of the plate, the displacement due to membrane stress, σ_m, is:

$$\delta = 4a\left(\frac{\sigma_m}{E}\right)$$

and the rotation due to bending stress, σ_b, can be expressed by:

$$\theta = \left(\frac{8a}{B}\right)\left(\frac{1+v}{3+v}\right)\left(\frac{\sigma_b}{E}\right)$$

where a is the crack length at the mid-surface:

$$a = \sqrt{a_{if}^2 - \frac{a_{ip}^2}{4}}$$

v = Poisson's ratio, may be taken as 0.3 for steel.

The bending stresses are determined by:

$\sigma_b = 0.182p\left(\frac{s}{t}\right)^2$ in the longitudinal direction

$\sigma_b = 0.266p\left(\frac{s}{t}\right)^2$ in the transverse direction

where

p	=	internal pressure, in kgf/cm^2
s	=	stiffener spacing, in mm
t	=	plate thickness, in mm

For a real ship, the applied membrane stress is not a constant but varies due to ship motion. Thus, an equivalent membrane stress is to be introduced to calculate the short axis, b. The equivalent membrane stress may be determined as:

$$\sigma_{m,eq} = \sigma_m \qquad if \qquad \sigma_m > \frac{\Delta\sigma_O}{2}$$

$$\sigma_{m,eq} = \frac{\left(\sigma_m + \frac{\Delta\sigma_O}{2}\right)}{2} \qquad if \qquad \sigma_m \le \frac{\Delta\sigma_O}{2}$$

7.5 Acceptance Criteria

The fatigue crack propagated from the initial crack size is not to grow to cause total failure of the structure for 15 days. Final crack size after 15 days propagation is to be smaller than the critical crack size determined from the fracture toughness of the tank material.

The secondary barrier is to be capable of containing any envisaged leakage of liquid cargo through the tank for a period of 15 days. The extent of the secondary barrier is to be determined on the basis of the estimated cargo leakage. The estimated maximum leakage rate of liquid cargo through the crack opening is to be less than the design leakage rate of the secondary barrier.

7.7 FEA with Refined Mesh

A detailed fine mesh FEA is required for the critical areas that do not meet the acceptance criteria. The hot spot stress is to be calculated from the FEA model with a refined mesh for the critical areas as described in A5/1.9.

9 Thermal Stress Analysis

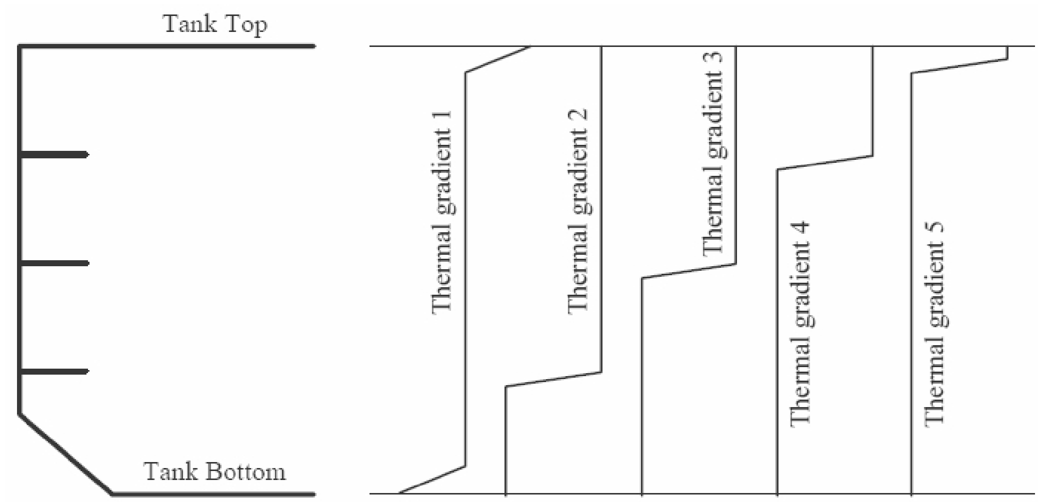
Non-uniform thermal contraction of an independent cargo tank from a temperature gradient produced by the loading of liquid cargo can create high local stresses. Thermal stress analysis is to be carried out to verify the structural integrity of a tank under thermal load during the loading of liquid cargo or initial cooling down period.

9.1 Loading Condition

Thermal loading produced by a temperature gradient from different filling level of a tank is to be considered. Filling levels up to each horizontal girder are to be considered separately as shown in Appendix 5, Figure 14. LNG tanks are cooled down with spray of LNG as part of a cool down cycle. Thermal load from this cool down period is to be included in the loading conditions.

Static internal pressure from the gas and corresponding level of liquid cargo are to be applied in addition to the thermal gradient.

FIGURE 14
Thermal Loading *(1 June 2011)*



9.3 Thermal Stress Estimation

The thermal stress of a tank is to be calculated from the contraction of a structure due to the thermal gradient. A global finite element model of a tank with support structure is to be used for the analysis. The proper thermal expansion coefficient for the tank material is to be used. Each thermal gradient specified in A5/9.1 is to be applied separately to assess the thermal stress at critical locations.

9.5 Fatigue Damage

Thermal stress from the temperature gradient may be considered as a cyclic fatigue loading for low cycle fatigue damage analysis. Critical areas are to be verified for possible fatigue damage from thermal loading. The procedure to assess low cycle fatigue damage from the loading and unloading of liquid cargo is specified in A5/3.5.

9.7 Acceptance Criteria

Yielding of the tank structure is to be checked following the guideline specified in Subsection 6/5. Allowable stresses are specified in 6/5.7 for watertight boundaries, 6/5.9 for main supporting members and structural details, and 6/5.11 for supports and chocks.

Each panel and supporting structures are to be checked against buckling failure also. The failure criteria for buckling and ultimate strength were specified in Subsection 6/7.