ShipRight
Design and Construction

Structural Design Assessment

Procedure for Primary Structure of Passenger Ships

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Lloyd's Register

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Document History	
Document Date:	**Notes:**
November 2001	Preliminary release.
July 2002	Final release.
May 2004	Revisions as identified in Notice – 'Changes incorporated in May 2004 version'.
March 2017	Consolidated version as incorporated in 'SDA Primary Structure of Passenger Ships, March 2017 version'.
April 2017	Corrigenda changes and image quality improvements.

Edited for Rulefinder version with typo correction.

Introduction

Section 1
Application

1.1 General

1.1.1 The *ShipRight Structural Design Assessment (SDA) procedure* defined in this document is for the assessment of the strength of the primary structure of passenger ships using finite element (FE) methods.

1.1.2 The ShipRight SDA is mandatory for passenger ships where:

(a) it is required to utilise the load carrying capability of the superstructure for longitudinal strength; or
(b) it is considered that the superstructure will be subject to a significant load from flexure of the hull girder; or
(c) where a limited number of transverse bulkheads above the bulkhead deck are present to carry the racking response; or
(d) where the pillaring system is not carried down to the tank top and aligned with double bottom girders; or heavy or concentrated loads are arranged on the tank top; or a novel or unusual arrangement of primary supporting members is proposed.

1.1.3 For passenger ships other than those in *Ch 1, 1.1 General 1.1.2* the SDA procedure may be applied on a voluntary basis.

1.1.4 The SDA procedure requires the following:

- a detailed analysis of the ship's structural response to specified load scenarios, and
- other direct calculations as applicable.

1.1.5 Passenger ships are defined as multi-decked ships designed exclusively for the carriage of passengers. These ships are characterised by having a superstructure extending over almost the entire ship length, the sides of which are penetrated by many large openings. This procedure is not to be applied to Ro-Ro ships or conventional passenger ferries, except where directed by the relevant procedure.

1.1.6 The direct calculation of the ship's structural response is to be based on a three-dimensional (3-D) plate FE analysis carried out in accordance with this document.

1.1.7 The SDA procedure comprises of four main parts:

- Chapter 2 - verification of global strength and double bottom strength using a mathematical model of the entire hull.
- Chapter 3 - verification of the structural response of components and details using follow-up fine mesh models.
- Chapter 4 - verification of the double bottom strength.
- Chapter 5 - verification of the strength of transverses and girders supporting decks.

1.1.8 *Ch 2 Global Response Analysis of Complete Ship* of this procedure is to be applied to all passenger ships for which the **ShipRight SDA** notation is required.

1.1.9 *Ch 3 Verification of Structural Details* of this procedure, in addition to *Ch 2 Global Response Analysis of Complete Ship*, is required for passenger ships where there are major hull openings, discontinuities and novel or unusual features and arrangements.

1.1.10 The structural strength of the bottom structure and side transverse is to be verified in accordance with *Ch 2 Global Response Analysis of Complete Ship*. Where the structural arrangement is neither of that as described in *Ch 1, 1.1 General 1.1.2.(a)*, *Ch 1, 1.1 General 1.1.2.(b)* or *Ch 1, 1.1 General 1.1.2.(c)*, *Ch 2 Global Response Analysis of Complete Ship* and *Ch 3 Verification of Structural Details* assessments are not required, and the structural strength of the bottom structure and side transverse is to be verified in accordance with *Ch 4 Verification of Double Bottom Strength*.

1.1.11 *Ch 5 Verification of Primary Structure Supporting Decks* of this procedure, in addition to *Ch 2 Global Response Analysis of Complete Ship*, is required for passenger ships in order to verify the structural adequacy of the transverse and longitudinal primary members in supporting decks.

1.1.12 A detailed report of the calculations is to be submitted and must include the information listed in *Ch 1, 3 Direct calculation procedure report*. The report must show compliance with the specified structural design criteria specified in the relevant chapters of this procedure.

1.1.13 If the computer programs employed are not recognised by Lloyd's Register (LR), full particulars of the program will also be required to be submitted, *see Pt 3, Ch 1, 3.1 Alternative arrangements and scantlings* of LR's *Rules and Regulations for the Classification of Ships* (hereinafter referred to as the Rules for Ships).

1.1.14 LR may, in certain circumstances, require the submission of computer input and output to further verify the adequacy of the calculations carried out.

1.1.15 Where alternative procedures are proposed, these are to be agreed with LR before commencement.

1.1.16 Passenger ships of unusual form or structural arrangements may need special consideration and additional calculations to those contained in this procedure may be required.

1.1.17 It is recommended that the designer discusses with LR the SDA analysis requirements at an early stage of the design phase.

■ *Section 2* **Symbols**

2.1 Definition

2.1.1 The symbols used in this procedure are defined as follows:

L = Rule length, in meters *see Pt 3, Ch 1,6 Definitions* of the Rules for Ships

B = moulded breadth, in meters *see Pt 3, Ch 1,6 Definitions* of the Rules for Ships

D = depth of ship, in meters *see Pt 3, Ch 1,6 Definitions* of the Rules for Ships

k_L, k = higher tensile steel factor, *see Pt 3, Ch 2,1.2 Steel* of the Rules for Ships

SWSF = still water shear force

SWBM = still water bending moment

VWBM = Rule design vertical wave bending moment, *see Pt 4, Ch 2,2.4 Design vertical wave bending moments* of the Rules for Ships

VWSF = Rule design wave shear force, *see Pt 4, Ch 2,2.5 Design wave shear force* of the Rules for Ships

C_1 = wave bending moment factor, *see Pt 3, Ch 4, Table 4.5.1 Wave bending moment factor* of the Rules for Ships

M_{wo} = *see Pt 4, Ch 2,2.4 Design vertical wave bending moments* of the Rules for Ships

f_1 = ship service factor, *see Pt 4, Ch 2,2.4 Design vertical wave bending moments* of the Rules for Ships

f_{fS} = is the sagging (negative) moment correction factor, *Pt 4, Ch 2,2.4 Design vertical wave bending moments* of the Rules for Ships

f_{fH} = is the hogging (positive) moment correction factor, *see Pt 4, Ch 2,2.4 Design vertical wave bending moments* of the Rules for Ships

T = draught, in metres, *see Pt 3, Ch 1,6 Definitions* of the Rules for Ships

C_b = block coefficient, *see Pt 3, Ch 1,6 Definitions* of the Rules for Ships

g = gravity constant

ρ = density of sea-water

h = local head for pressure evaluation

t = thickness of plating

t_c = thickness deduction for corrosion

σ_{cr} = critical buckling stress corrected for plasticity effects

σ_c = elastic critical buckling stress

σ_o = specified minimum yield stress of steel (steel having a yield stress above 355 N/mm^2 will be specially considered), *see Pt 3, Ch 2,1.2 Steel* of the Rules for Ships

= σ_a (0,2 per cent proof stress or 70 per cent of the ultimate strength of aluminium alloy, whichever is lesser, *see Ch 13,8.3 Fabrication and welding* of the LR's *Rules for the Manufacture, Testing and Certification of Materials*)

σ_L = = 235/k_L N/mm^2 for steel

= σ_a for aluminium alloy

λ = factor against elastic buckling

= $\sigma_{cr}/\sigma_{actual}$

τ = shear stress

σ_{actual} = equivalent design stress

σ_e = von Mises equivalent stress

$$= \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2}$$

σ_x = direct stress in element x direction

σ_y = direct stress in element y direction

τ_{xy} = shear stress in element x-y plane

2.1.2 Consistent units to be used throughout the analysis. Results presentation in Newtons (N) and millimetres (mm) is preferred.

2.1.3 All Rule equations are to use units as defined in the Rules for Ships.

■ *Section 3* Direct calculation procedure report

3.1 General

3.1.1 A report is to be submitted to LR for approval of the primary structure and global strength of the ship, which is to contain the following information:

- list of plans used including dates and versions;
- detailed description of structural modelling including all modelling assumptions;
- plots to demonstrate correct structural modelling and assigned properties;
- full details of material properties used for all components;
- details of boundary conditions;
- details of all load cases applied with calculated shear force and bending moment distributions;
- details of applied loadings and confirmation that individual and total applied loads are correct;
- details of boundary support forces and moments;
- plots and results that demonstrate the correct behaviour of the ship structural models to the applied loads;
- summaries and plots of global and local deflections;

- summaries and sufficient plots of von Mises, directional and shear stresses to demonstrate that the design criteria contained in this SDA procedure has not been exceeded in any member;
- plate buckling analysis and results;
- pillar buckling analysis and results;
- tabulated results showing compliance, or otherwise, with the design criteria; and
- proposed amendments to structure where necessary, including revised assessment of stresses and buckling capabilities.

Contents

■ *Section 1* Application

1.1 Introduction

1.1.1 For the application of *Ch 2 Global Response Analysis of Complete Ship*, *see Ch 1, 1.1 General 1.1.8*.

■ *Section 2* Objectives

2.1 General

2.1.1 The objectives of *Ch 2 Global Response Analysis of Complete Ship* are:

(a) To establish the structural contribution of the superstructure in resisting hull girder loads.
(b) To derive the stress distribution over the complete cross-section and length of the ship taking due account of the behaviour and effectiveness of the superstructure.
(c) To provide boundary conditions for the fine mesh models required by *Ch 3 Verification of Structural Details* for the investigation of the detailed stress response of the following critical structural components:
   (i) side screens and supports in way of lifeboat recesses;
   (ii) the structure in way of windows and other significant shell or superstructure side and bulkhead openings;
   (iii) the structure in way of door openings in internal longitudinal bulkheads contributing to global hull girder strength or where influenced by hull girder response; and
   (iv) areas of unusual structural arrangements.
(d) To obtain force distribution in pillars.
(e) To obtain the stress in the transverse structure due to racking.
(f) To verify the structural adequacy of the ship's double bottom structure.

■ *Section 3* Structural modelling

3.1 General

3.1.1 The effectiveness of the superstructure is dependent on its length, flexibility of its support, integration at its ends, size and number of openings in side walls and internal decks.

3.1.2 A 3-D plate element model of the ship is to be used. This model should extend over the full length and depth of the ship. It is recommended that the model is representing the full breadth of the ship. However, a half-breadth model may be used depending upon the degree of structural symmetry. The model should represent, with reasonable accuracy, the actual geometric shape of the hull. All effective longitudinal material is to be included. Similarly all transverse primary structures, i.e. watertight and fire divisional bulkheads are to be represented in the model.

3.1.3 The FE model is to be represented using a right-handed, Cartesian co-ordinate system with:

- *x* measured in the longitudinal direction, positive forward
- *y* measured in the transverse direction, positive to port from the centreline
- *z* measured in the vertical direction, positive upwards from the baseline

3.1.4 The size and type of plate elements selected are to provide a satisfactory representation of the deflection behaviour of the decks and stress distribution within the transverse bulkhead structures. In general, the plate element mesh is to follow the primary stiffening arrangement. Thus, it is anticipated that:

- Longitudinally, there will be at least one element between transverses; *see Ch 2, 3.1 General 3.1.5* regarding acceptable aspect element ratios.
- Vertically, one element between longitudinal stiffeners. A minimum of three elements is preferred over the web of double bottom girders and floors. In general, one element is acceptable over the web of deck transverses and girders. However, three elements are preferred in way of web with opening with deletion of elements where appropriate, *see Ch 2, 3.1 General 3.1.6*.
- Transversely, one element between longitudinal stiffeners.

3.1.5 Depending on the spacing of transverse members, it may be necessary to refine this mesh arrangement in the longitudinal direction to achieve satisfactory element aspect ratios. An aspect ratio of less than three is recommended, but acceptable aspect ratios are dependent on the analysis code being used.

3.1.6 All window openings, door openings, deck openings and shell openings of a significant size are to be represented. Additional mesh refinement may be necessary to model these openings, but it may be sufficient to represent the effects of the opening by deleting the appropriate elements. Similarly, the model is to accurately reflect shell and superstructure side recesses, sweep brackets and superstructure breaks.

3.1.7 Window, door and large shell openings are to be modelled such that the deformation pattern under hull shear and bending loads is adequately represented. Any idealisation adopted is to be verified by means of check models and comparison with the performance of suitable fine mesh models. An example plot is shown in *Figure 2.3.4 Window representation in fine mesh check model*. The overall deflection of the two models is to be of the same order.

3.1.8 The fine mesh model may reflect the meshing level required by *Ch 3 Verification of Structural Details* analysis. This avoids having to create a third model (follow-up model *Ch 3 Verification of Structural Details*) with again different mesh arrangement and different performance.

3.1.9 The proposed scantlings, excluding Owner's extras and any additional thicknesses fitted to comply with the optional *ShipRight Enhanced Scantlings Descriptive Note*, **ES**, are to be incorporated in the model. All primary structures, such as deck plating, bottom and side shell plating, longitudinal and transverse bulkhead plating, transverse floors, superstructure side and internal structural walls, are to be represented by plate elements having both membrane and bending stiffness.

3.1.10 The secondary stiffeners are to be represented by line elements positioned in the plane of the plating having axial and bending properties (bars) representing the stiffener with the eccentricity of the neutral axis modelled. Where appropriate, a single line element may represent more than one secondary stiffener.

3.1.11 Pillars where fitted may be represented by line elements having axial and bending stiffness and appropriate stress recovery points. If modelled using plate element, and accurate nodal stress output is not available, a line element of nominal area will need to be arranged at the extremities of the section in order to obtain the extreme fibre stresses.

3.1.12 *Figure 2.3.1 Port side view of complete model*, *Figure 2.3.2 Centreline section view showing internal mesh* and *Figure 2.3.3 Local section of hull showing geometrical representation* indicate acceptable mesh arrangements of various structural components of a typical large passenger ship.

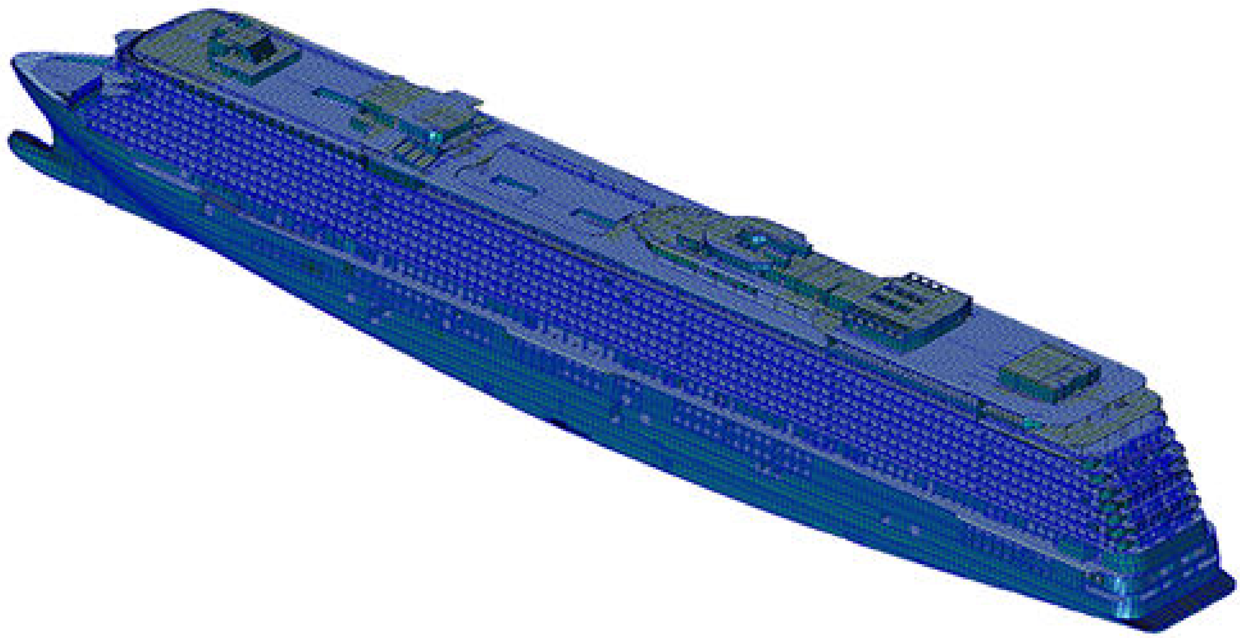


Figure 2.3.1 Port side view of complete model

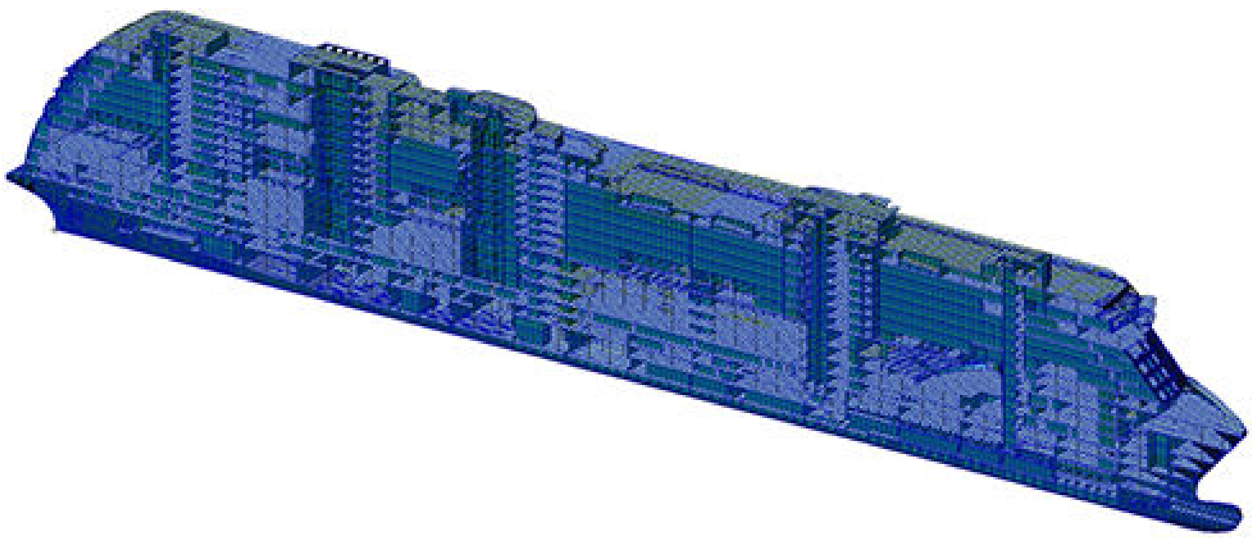


Figure 2.3.2 Centreline section view showing internal mesh

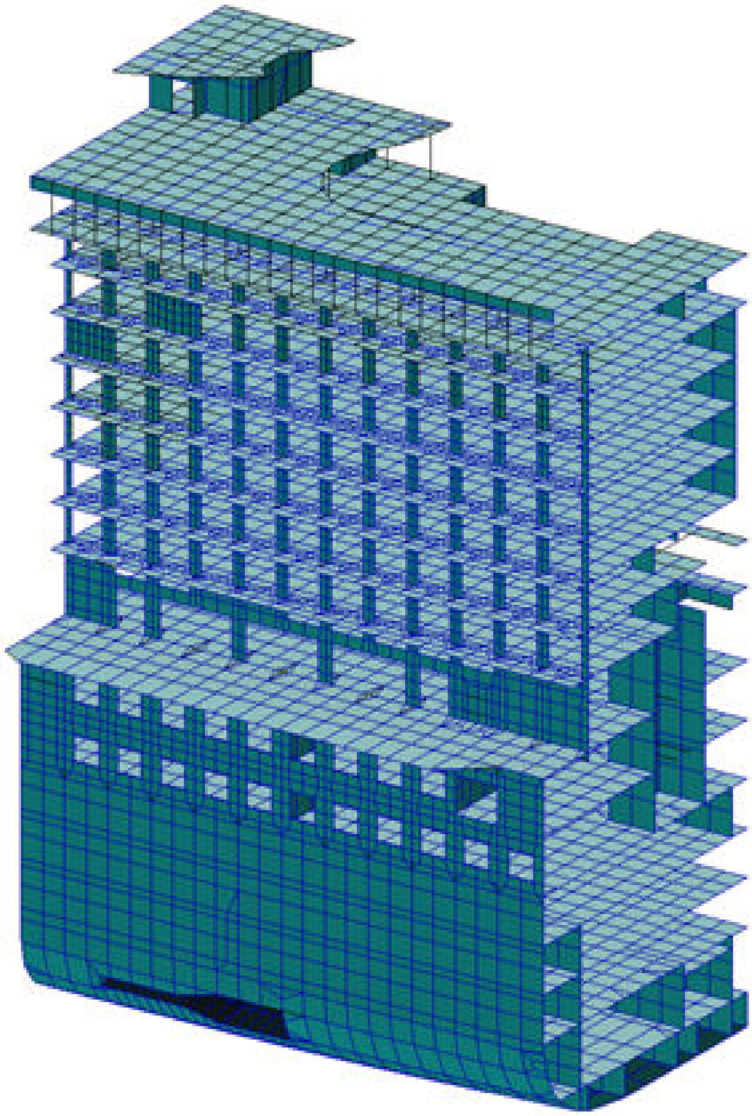
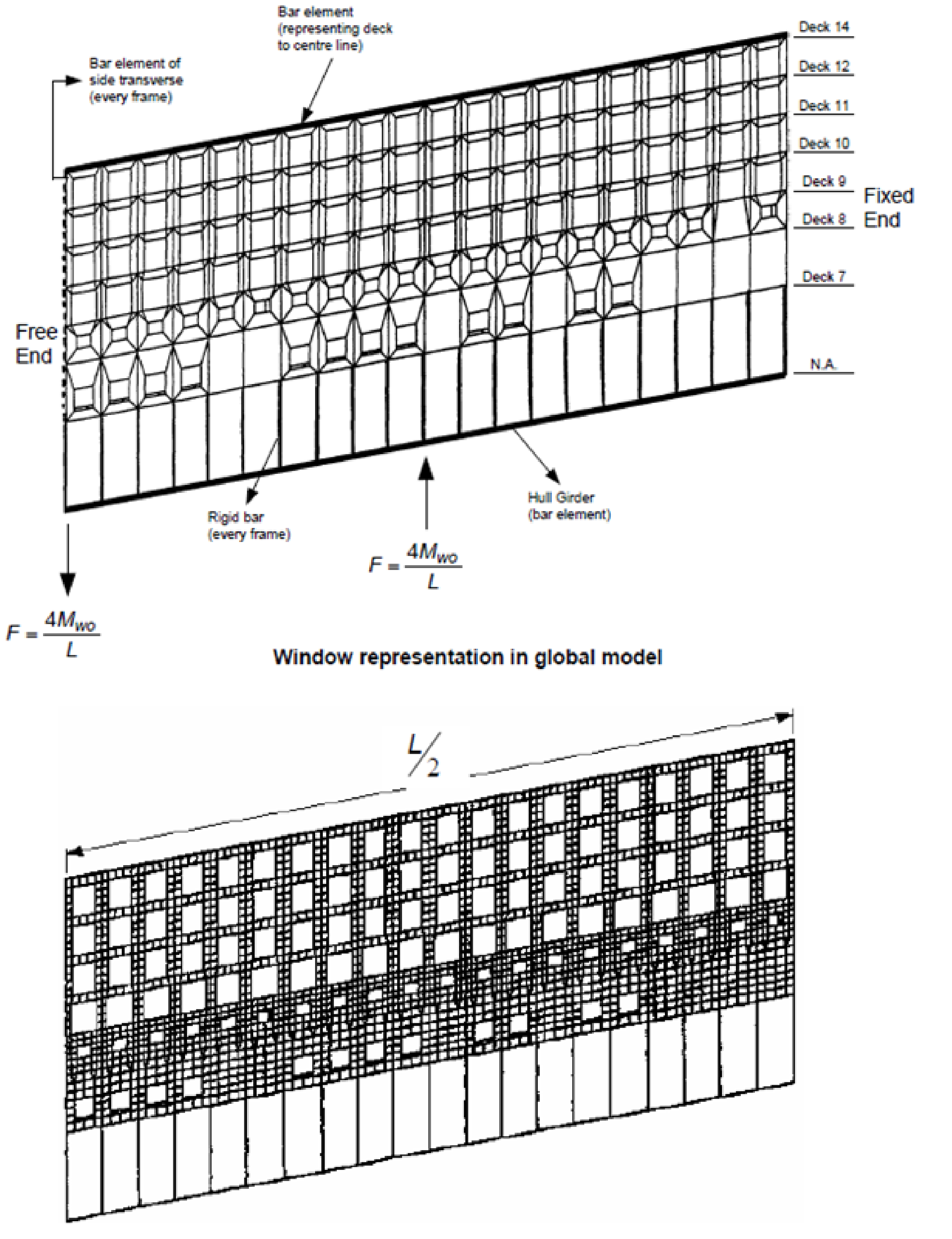


Figure 2.3.3 Local section of hull showing geometrical representation



Window representation in fine mesh check model

Hull girder (bar element) represents the hull properties below deck 7 (in this example) of half breadth.
Neutral axis indicated on this figure is of hull below deck 7 (in this example).
Deck (bar element) represents deck to centre line.

Figure 2.3.4 Window representation in fine mesh check model

Section 4
Loading conditions

4.1 General

4.1.1 The standard load combination cases specified in *Table 2.4.1 Load combination cases for assessment* are to be considered. The stresses and buckling factor of safety results from these load combinations are to be compared against the acceptance criteria specified in *Ch 2, 6 Acceptance criteria*. The purpose of the assessment is to ensure that the acceptance criteria in *Ch 2, 6 Acceptance criteria* are satisfied and additionally that the longitudinal strength of the hull structure is in compliance with the Rule loading scenario as specified in *Pt 4, Ch 2,2 Longitudinal strength* of the Rules for Ships.

Table 2.4.1 Load combination cases for assessment

Load combination	Description	Still water loads	Hull girder loads	Additional local loads	FE load cases (*see Ch 2, 4.3 FE load cases*)
LC1	Hogging wave condition	Still water (hogging): • Deadweight and lightship • External pressure in still water *see Ch 2, 4.2 Load components 4.2.1*	• Permissible still water bending moment and shear force (hogging) • Hogging design wave bending moment and shear force, *see Ch 2, 4.2 Load components 4.2.3*	Local wave crest, *see Ch 2, 4.2 Load components 4.2.8*	SC1, SC3a, SC3b (*see* Note 2)
LC2	Sagging wave condition	Still water (sagging or minimum hogging): • Deadweight and lightship • External pressure in still water *see Ch 2, 4.2 Load components 4.2.2*	• Permissible still water bending moment and shear force (sagging) • Sagging design wave bending moment and shear force, *see Ch 2, 4.2 Load components 4.2.4*	Local wave trough, *see Ch 2, 4.2 Load components 4.2.8*	SC2, SC4a, SC4b (*see* Note 2)
LC3	Maximum shear force amidships (*see* Note 3)	Still water (hogging): • Deadweight and lightship • External pressure in still water *see Ch 2, 4.2 Load components 4.2.1*	• Permissible still water bending moment (hogging) and maximum permissible still water shear force • Design wave bending moment and shear force, *see Ch 2, 4.2 Load components 4.2.5*	–	SC1, SC5 (*see* Note 2)
LC4	Minimum shear force amidships (*see* Note 3)	Still water (sagging or minimum hogging): • Deadweight and lightship • External pressure in still water *see Ch 2, 4.2 Load components 4.2.2*	• Permissible still water bending moment (sagging) and minimum permissible still water shear force • Design wave bending moment and shear force, *see Ch 2, 4.2 Load components 4.2.6*	–	SC2, SC6 (*see* Note 2)

LC5a	Racking – port	• Deadweight and lightship • External pressure in still water *see Ch 2, 4.2 Load components 4.2.7*	–	–	SC7a
LC5b	Racking – starboard (*see* Note 1)				SC7b
Note 1. If the structure is completely symmetrical about the centreline then LC5b case may be omitted (note that in this case any scantling increases due to LC5a is to be applied to both sides of the ship). Note 2. The combined load case is to achieve the hull girder bending moment and shear force distribution specified. At locations where there is a variation between the hull girder loads resulting from the applied FE load cases and required values, the stresses are to be adjusted, *see Ch 2, 6.1 Stress for assessment*. Note 3. LC3 and LC4 are for the assessment of structure within the region 0,4*L* to 0,6*L*.					

4.2 Load components

4.2.1 **Still water (hogging)**. A load case is to be prepared which fulfils the following criteria:

- Ship to be upright at or near to the design draught.
- The still water bending moment (SWBM) and still water shear force (SWSF) curves are to approximate, as far as is possible given the limitation of a single condition to the assigned or specified, maximum permissible still water hogging condition distributions.

4.2.2 **Still water (sagging or minimum hogging).** A load case is to be prepared which fulfils the following criteria:

- Ship to be upright at or near to the design draught.
- The still water bending moment (SWBM) and still water shear force (SWSF) curves are to approximate, as far as is possible given the limitation of a single condition to the assigned or specified, permissible still water sagging condition or minimum hogging condition distributions as appropriate.

4.2.3 **Hogging design wave.** Load combination LC1 is to achieve the following vertical wave bending moment and shear force distribution:

- The Rule hogging design vertical wave bending moment distribution as defined in *Pt 4, Ch 2,2 Longitudinal strength* of the Rules for Ships.
- The design vertical wave shear force, Q_{WH}, associated with the hogging wave bending moment is to be obtained as follows:

Distance from aft end of *L*	Q_{WH}
0	0,0
0,2*L* to 0,3*L*	$0,836 \cdot f_{fH} \cdot Q_{Wo}$
0,4*L*	$0,7 \cdot f_{fH} \cdot Q_{Wo}$
0,6*L*	$-0,7 \cdot f_{fH} \cdot Q_{Wo}$
0,7*L* to 0,85*L*	$-0,91 \cdot f_{fH} \cdot Q_{Wo}$
L	0,0
where $Q_{Wo} = 3 \cdot f_1 \cdot \frac{M_{Wo}}{L}$	

Intermediate values of Q_{WH} are to be determined by linear interpolation. The shear force and bending moment distributions are illustrated in *Figure 2.4.2 Load cases SC3a and SC4a*.

4.2.4 **Sagging design wave.** Load combination LC2 is to achieve the following vertical wave bending moment and shear force distribution:

- The Rule sagging design vertical wave bending moment distribution as defined in *Pt 4, Ch 2,2 Longitudinal strength* of the Rules for Ships.
- The design vertical wave shear force, Q_{WS}, associated with the sagging wave bending moment is to be obtained as follows:

Distance from aft end of *L*	Q_{WS}
0	0,0
0,15*L* to 0,3*L*	$0,836 \cdot f_{fS} \cdot Q_{Wo}$
0,4*L*	$0,65 \cdot f_{fS} \cdot Q_{Wo}$
0,6*L*	$-0,65 \cdot f_{fS} \cdot Q_{Wo}$
0,7*L* to 0,85*L*	$-0.91 \cdot f_{fS} \cdot Q_{Wo}$
L	0,0
where Q_{Wo} is defined in *Ch 2, 4.2 Load components 4.2.3*	

Intermediate values of Q_{WS} are to be determined by linear interpolation. The shear force and bending moment distributions are illustrated in *Figure 2.4.2 Load cases SC3a and SC4a*.

4.2.5 **Design wave for maximum shear force amidships.** Load combination LC3 is for the assessment of structure in the region between 0,4*L* and 0,6*L*. The load combination is to achieve the following vertical wave bending moment and shear force distribution:

- The vertical wave bending moment distribution, $BM_2(x)$, specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.4*.
- The associated design vertical wave shear force, Q_W , is to be obtained as follows:

Distance from aft end of *L*	Q_W
0,4*L* to 0,5*L*	$0,7 \cdot f_{fH} \cdot Q_{Wo}$
0,5*L* to 0,6*L*	$-0,65 \cdot f_{fS} \cdot Q_{Wo}$
where Q_{Wo} is defined in *Ch 2, 4.2 Load components 4.2.3*	

Intermediate values of Q_W are to be determined by linear interpolation.

The wave shear force outside the range of 0,4*L* and 0,6*L* need not be greater than Q_{WH} or less than Q_{WS} specified in *Ch 2, 4.2 Load components 4.2.3* and *Ch 2, 4.2 Load components 4.2.4*. The shear force and bending moment distributions are illustrated in *Figure 2.4.3 Load cases SC5 and SC6*.

4.2.6 **Design wave for minimum shear force amidships.** Load combination LC4 is for the assessment of structure in the region between 0,4*L* and 0,6*L*. The load combination is to achieve the following vertical wave bending moment and shear force distribution:

- The vertical wave bending moment distribution, $-BM_2(x)$, specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.4*.
- The associated design vertical wave shear force, Q_{WS}, is to be obtained as follows:

Distance from aft end of *L*	Q_W
0,4*L* to 0,5*L*	$0,65 \cdot f_{fS} \cdot Q_{Wo}$
0,5*L* to 0,6*L*	$-0,7 \cdot f_{fH} \cdot Q_{Wo}$
where Q_{Wo} is defined in *Ch 2, 4.2 Load components 4.2.3*	

Intermediate values of Q_W are to be determined by linear interpolation.

The wave shear force outside the range of 0,4*L* and 0,6*L* need not be greater than Q_{WH} or less than Q_{WS} specified in *Ch 2, 4.2 Load components 4.2.3* and *Ch 2, 4.2 Load components 4.2.4*. The shear force and bending moment distributions are illustrated in *Figure 2.4.3 Load cases SC5 and SC6*.

4.2.7 **Racking.** Static pressure applied to simulate a loading condition near to the design draught with a maximum vertical centre of gravity and a static heel angle equal to the lesser of the following:

- $\tan^{-1} (2 (D - T_c) / B)$, where T_c is the draught of the loading condition under consideration.
- The maximum roll angle, $\mathbf{\Phi}$, as defined in *Pt 4, Ch 2, Table 2.10.1 Ship motions* of the Rules for Ships, but not to be taken as less than 22°.

4.2.8 **Local wave crest and wave trough.** Application of wave pressure due to local wave crest or wave trough is defined in *Figure 2.4.1 Pressure head distribution P_W for local wave crest and trough*. The wave crest or wave trough is to be acting over the full length of the FE model.

4.2.9 For ships of an unusual hull form, a suitable loads and motions study may be required to be performed in order to verify the applicability of the Rule design vertical wave loadings, *see Pt 4, Ch 2,2.1 General* of the Rules for Ships.

(a) Wave crest

$$P_{WL} = H_W + h$$

$$P_H = H_W\left(1 - (1 - k_z)\frac{h}{T}\right)$$

(b) Wave trough

$$P_{WL} = H_W - h$$

$$P_H = H_W\left(1 - (1 - k_z)\frac{h}{T}\right)$$

where

H_W = $0{,}046L\,e^{-0{,}0044L}$ m for $L < 227$ m
= 3,846 m for $L \geq 227$ m
e = 2,7183
h = distance below the still waterline, m
k_z = e^{-d}
d = $2\pi\frac{T}{L}$
T = is to be taken as T_{min} or T_{max} as appropriate

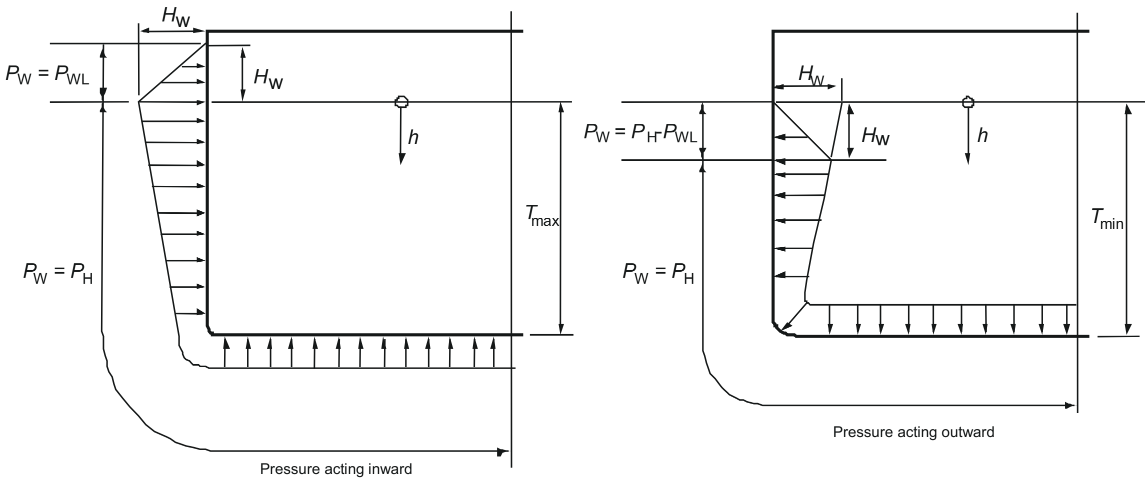


Figure 2.4.1 Pressure head distribution P_W for local wave crest and trough

4.3 FE load cases

4.3.1 The FE load cases as specified in *Table 2.4.2 FE load cases for deriving stress responses* are to be prepared in order to generate the required stress response for the assessment load combinations in *Table 2.4.1 Load combination cases for assessment*.

Table 2.4.2 FE load cases for deriving stress responses

FE load cases		External loads	Other load components	Boundary condition (*see Ch 2, 5 Boundary conditions*)
SC1	Still water (hogging)	Pressure due to still water draught (hogging), *see Ch 2, 4.2 Load components 4.2.1*	Steel weight (*see* Note 2) Machinery and outfit (*see* Note 3) Deadweight items and passenger loads (*see* Note 4) Tank loads (*see* Note 5)	BC1
SC2	Still water (sagging or minimum hogging)	Pressure due to still water draught (sagging), *see Ch 2, 4.2 Load components 4.2.2*		
SC3a	Hogging design wave, *see Ch 2, 4.2 Load components 4.2.3*	Approximate load distribution $P_1(x)$ specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.3* to generate required hogging bending moment and shear force, *see* Note 1	–	BC1
SC3b	Local wave crest	Wave pressure due to wave crest acting over the full length of the FE model, *see Ch 2, 4.2 Load components 4.2.8* and *Figure 2.4.2 Load cases SC3a and SC4a*		BC2
SC4a	Sagging design wave, *see Ch 2, 4.2 Load components 4.2.4*	Approximate load distribution $P_1(x)$ specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.3* to generate required sagging bending moment and shear force, *see* Note 1	–	BC1
SC4b	Local wave trough	Wave pressure due to wave trough acting over the full length of the FE model, *see Ch 2, 4.2 Load components 4.2.8* and *Figure 2.4.2 Load cases SC3a and SC4a*		BC2
SC5	Design wave for maximum shear force amidships, *see Ch 2, 4.2 Load components 4.2.3*	Approximate load distribution $P_2(x)$ specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.4* to generate required bending moment and shear force, *see* Note 1	–	BC1
SC6	Design wave for minimum shear force amidships, *see Ch 2, 4.2 Load components 4.2.4*	Approximate load distribution $-P_2(x)$ specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.4* to generate required bending moment and shear force, *see* Note 1	–	BC1

SC7a	Racking – port	Static pressure applied to simulate a static heel angle on port side, *see Ch 2, 4.2 Load components 4.2.7*	Lightweight and deadweight items (*see* Note 6)	BC1
SC7b	Racking – starboard (*see* Note 7)	Static pressure applied to simulate a static heel angle on starboard side, *see Ch 2, 4.2 Load components 4.2.7*		

Note 1. A distribution of vertical forces as specified in *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force* to be applied on the side shell, at every web frame position.

Note 2. As generated from the modelled steel area, suitably factored to achieve the specified steel weight including the position of the longitudinal centre of gravity. In this regard it may be useful to divide the model longitudinally into a number of material zones each having a separate factored value of steel density.

Note 3. All deadweight items are to be included. Major items such as rudder, main generators, etc. are to be applied as masses where inertia release method is used or otherwise as point loads or pressure loads at their correct locations. Minor or unknown items may be included in the steel weight.

Note 4. Applied as distributed pressure to relevant deck areas.

Note 5. To be applied as pressure loads or nodal forces at the tank base or boundary, based on the actual liquid head. Any over-pressurisation of the tank is to be omitted.

Note 6. Due to loading condition near to design draft and maximum vertical centre of gravity. Including tanks and swimming pool above the bulkhead deck only.

Note 7. If the structure is completely symmetrical about the centreline then SC7b case may be omitted.

4.4 Procedure to apply the Rule design vertical wave bending moment and shear force

4.4.1 The required design vertical wave bending moment and shear force are to be distributed along the length of the FE model in accordance with *Table 2.4.1 Load combination cases for assessment*.

4.4.2 The required bending moment and shear force distributions may be applied, as illustrated in *Figure 2.4.2 Load cases SC3a and SC4a* and *Figure 2.4.3 Load cases SC5 and SC6*, by applying the approximate load distributions $P_1(x)$ *and* $P_2(x)$ described below.

4.4.3 The approximated load distribution, $P_1(x)$, is applied to FE load cases SC3a and SC4a (*see Table 2.4.2 FE load cases for deriving stress responses*). The load distribution and the resulting shear force distribution, $SF_1(x)$, and bending moment distribution, $BM_1(x)$, are as follows:

$$P_1(x) = \frac{M_w}{L^2}\left(20a_1x^3 + 12a_2x^2 + 6a_3x + 2a_4\right) \quad \text{kN/m}$$

$$SF_1(x) = \frac{M_w}{L}\left(5a_1x^3 + 4a_2x^2 + 3a_3x + 2a_4\right)x \quad \text{kN}$$

$$BM_1(x) = M_w\left(a_1x^3 + a_2x^2 + a_3x + a_4\right)x^2 \quad \text{kNm}$$

where

M_w = $f_{fH}\,M_{Wo}$ for load case SC3a.

M_w = $f_{fS}\,M_{Wo}$ for load case SC4a.

a_1 = 7,841

a_2 = -1,457

a_3 = -20,609

a_4 = 14,225

x = $\frac{d}{L}$; $\quad 0 \le x \le 1$

d = distance measured from the aft end of the Rule length, in meters

4.4.4 The approximated load distribution, $P_2(x)$, is applied to FE load cases SC5 and SC6 (*see Table 2.4.2 FE load cases for deriving stress responses*). The load distribution and the resulting shear force distribution, $SF_2(x)$, and bending moment distribution, $BM_2(x)$, are as follows:

$$P_2(x) = \frac{M_w}{L^2}\left(42a_1x^5 + 30a_2x^4 + 20a_3x^3 + 12a_4x^2 + 6a_5x + 2a_6\right) \quad \text{kN/m}$$

$$SF_2(x) = \frac{M_w}{L}\left(7a_1x^5 + 6a_2x^4 + 5a_3x^3 + 4a_4x^2 + 3a_5x + 2a_6\right)x \quad \text{kN}$$

$$BM_2(x) = M_w\left(a_1x^5 + a_2x^4 + a_3x^3 + a_4x^2 + a_5x + a_6\right)x^2 \quad \text{kNm}$$

where

M_w = greater of $|f_{fH}\, M_{Wo}|$ and $|f_{fS}\, M_{Wo}|$ for load case SC5

M_w = lesser of $-|f_{fH}\, M_{Wo}|$ and $-|f_{fS}\, M_{Wo}|$ for load case SC6

a_1 = -130,68

a_2 = 457,39

a_3 = -589,55

a_4 = 330,4

a_5 = -68,3

a_6 = 0,74

$x = \frac{d}{L}; \quad 0 \le x \le 1$

d = distance measured from the aft end of the Rule length, in meters

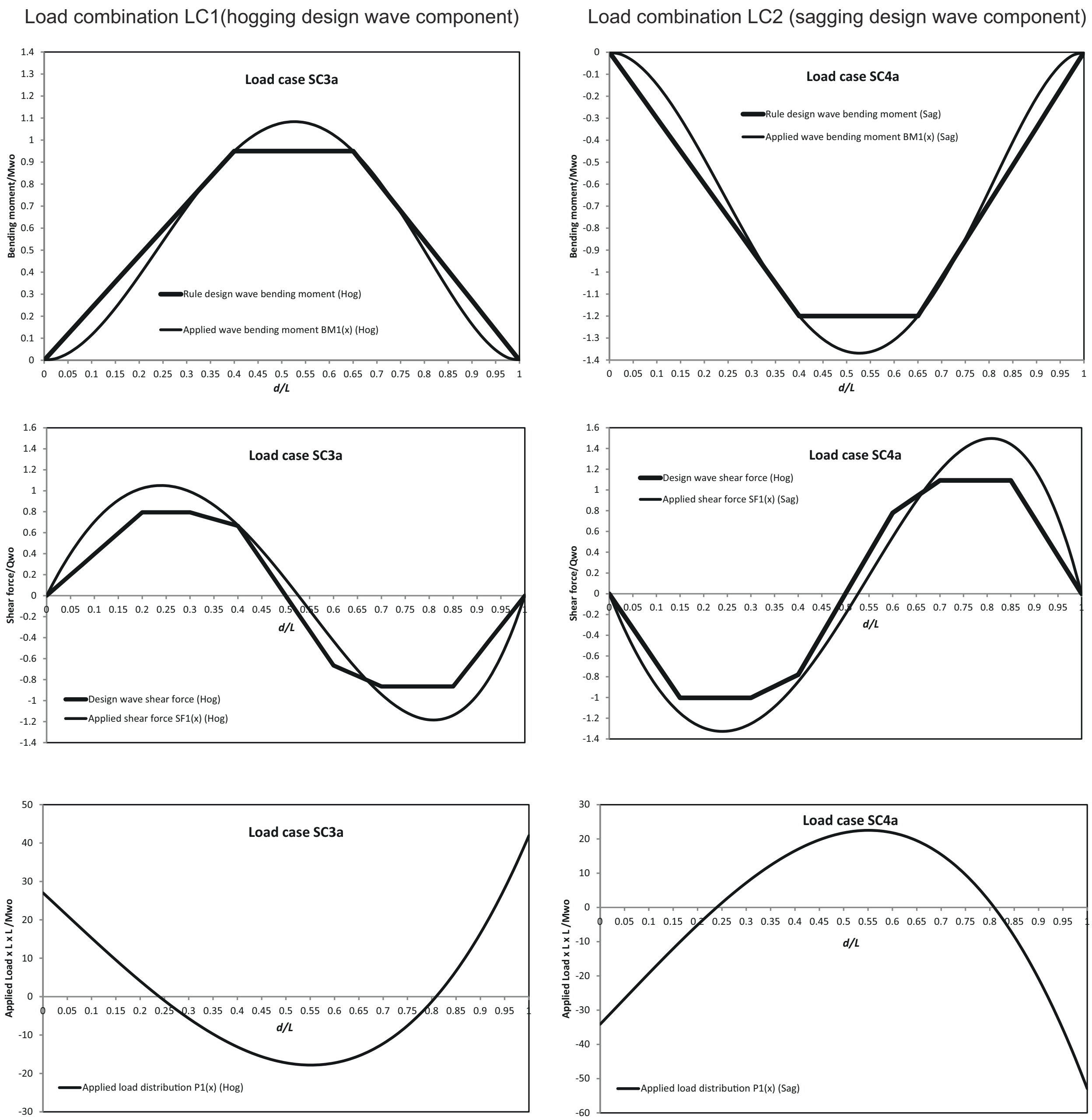
4.4.5 The load distribution described in paragraphs *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.3* and *Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.4* is to be applied to the FE model as a series of vertical nodal forces on the side shell, at every web frame position below the waterline.

4.4.6 Minor adjustment of the applied loads may be required to ensure global equilibrium.

4.4.7 A check should be carried out by tabular integration methods to ensure that the derived load distribution will result in the required vertical bending moment and shear force.

4.4.8 At locations where there is a variation between the applied FE loads and required loads as specified in *Table 2.4.1 Load combination cases for assessment*, the derived stresses are to be adjusted, *see Ch 2, 6.1 Stress for assessment*.

4.4.9 Other proposed methods of modelling the required vertical wave bending moment and shear force distributions will be specially considered.



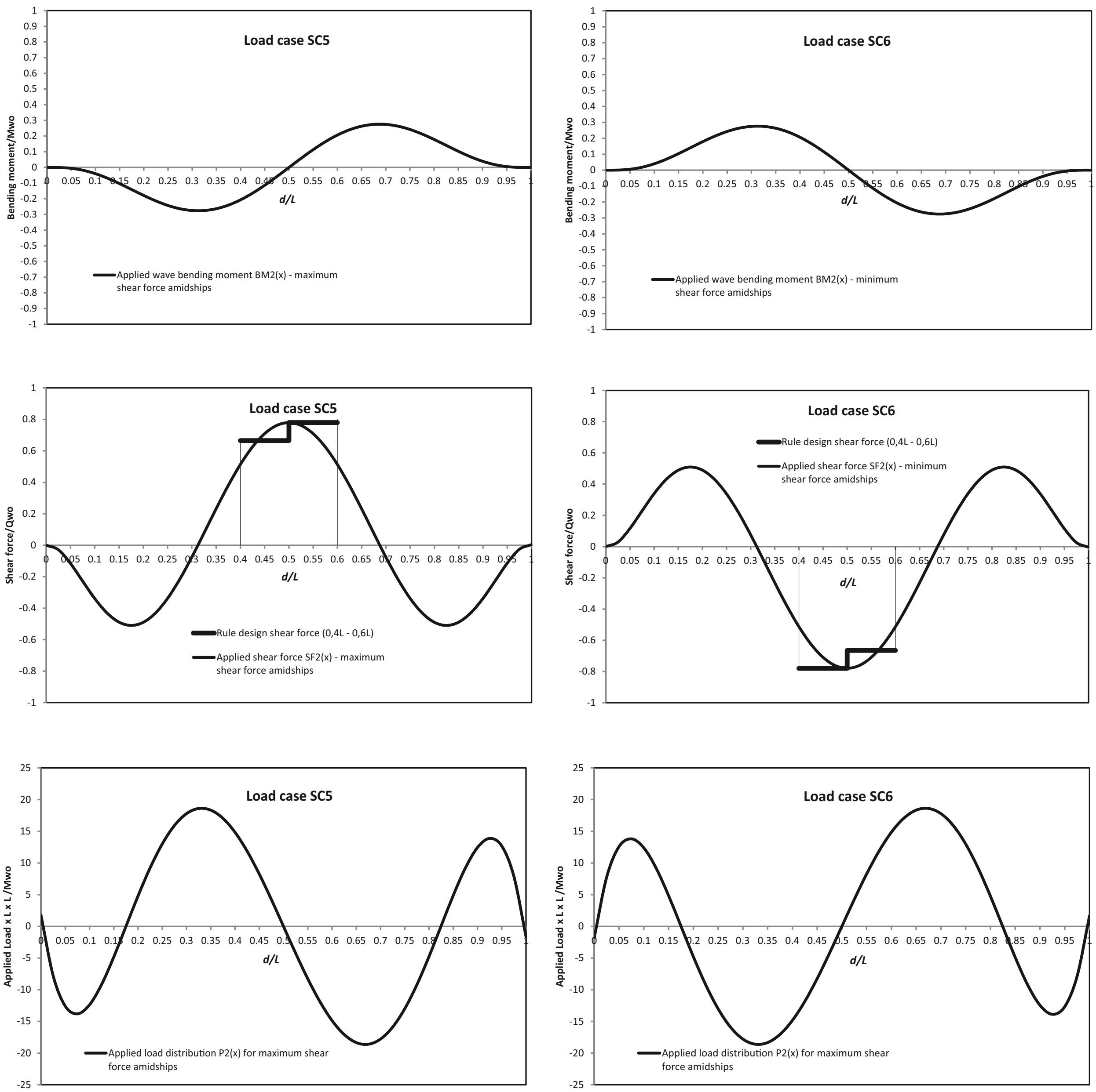
Examples based on f_{fH} of 0,95 and f_{fS} of -1,2

(Typical applied load, wave bending moment and shear force distributions compared with required design values)

Figure 2.4.2 Load cases SC3a and SC4a

Load combination LC3 (wave component)

Load combination LC4 (wave component)



Examples based on f_{fH} of 0,95 and f_{fS} of -1,2

(Typical applied load, wave bending moment and shear force distributions compared with required design values)

Figure 2.4.3 Load cases SC5 and SC6

Section 5
Boundary conditions

5.1 General

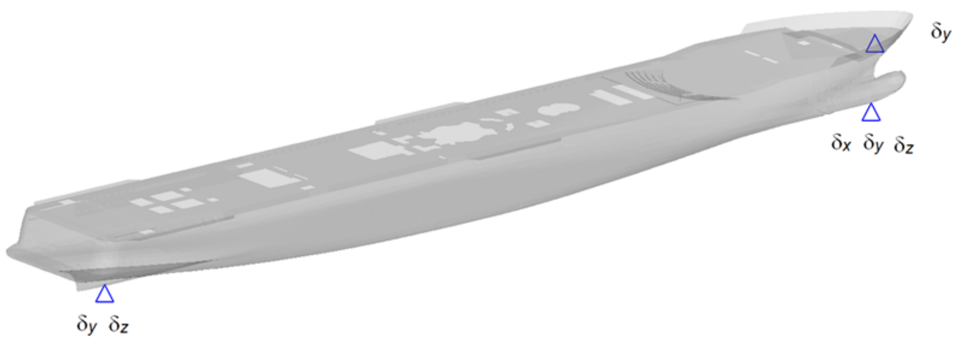
5.1.1 The FE loading cases specified in *Ch 2, 4.3 FE load cases* require boundary conditions as given in *Table 2.5.1 Boundary conditions for a full-breadth model*.

5.1.2 The boundary conditions specified in *Table 2.5.2 Additional boundary conditions for a half-breadth model* combined with those in *Table 2.5.1 Boundary conditions for a full-breadth model* are appropriate for a half-breadth model.

5.1.3 The model is to be free of imposed constraints except for those necessary to prevent rigid body motion. Care is to be taken to ensure that, within practicable limits, there is no net imbalance of forces and moments in any of the six degrees of freedom, *see Ch 2, 5.2 Load balance procedure*. Care is to be taken to ensure that the FE model is not over-constrained.

5.1.4 The boundary conditions described in this Section are preferred. However, alternative equivalent boundary conditions may be used.

Table 2.5.1 Boundary conditions for a full-breadth model

Set	Description
BC1	(a) The model is to be free of imposed constraints, except for those necessary to prevent rigid body motion. Rigid body motions may be prevented by the use of free-body constraints (e.g. the Inertia Relief facility in Nastran terminology. Where a reference point is used then the position of the reference points is not critical provided that the point selected has stiffness in the required degrees of freedom and the complete set describes the rigid body motion. The centre of gravity of the ship may be selected as a reference point.) (b) Alternatively, model may be constrained as follows: • At the AP on the centreline: Translation $\delta_y = \delta_z = 0$ • At the FP on the centreline: Translation $\delta_x = \delta_y = \delta_z = 0$ • At the uppermost deck on the centreline at the FP: Translation $\delta_y = 0$ 

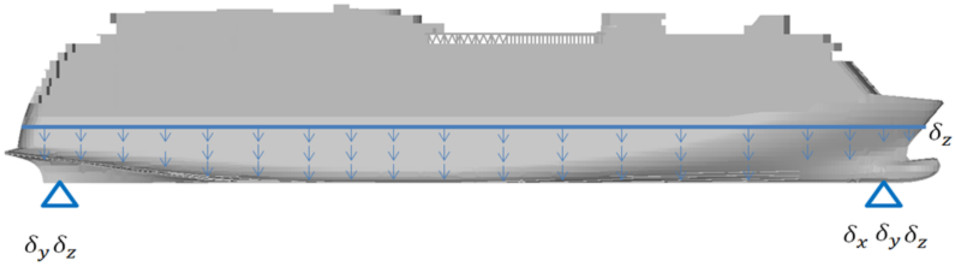
BC2	(a) If for set BC1, free-body constraints (i.e. Inertia Relief method) are used, the model is to be additionally constrained as follows: • Uppermost continuous deck at the side shell intersection: Translation $\delta_x = \delta_y = \delta_z = 0$ (b) Otherwise the model may be constrained as follows: • At the AP on the centreline: Translation $\delta_y = \delta_z = 0$ • At the FP on the centreline: Translation $\delta_x = \delta_y = \delta_z = 0$ • Uppermost continuous deck at the side shell intersection: Translation $\delta_z = 0$ (c) Any induced global bending of the ship is to be removed by application of vertical constraints at each web frame. In order to remove the reaction force at these vertical constraints, thus avoiding vicious stress response, it is recommended that counteracting vertical forces are distributed to the side shell nodes at every web frame to eliminate the reaction forces. The magnitude of these forces is to be such as to remove the vertical imbalance of the model caused by the applied load. 
Note 1. Where a half breadth ship model is employed the racking analysis, loadings will require sub-dividing into symmetric and anti-symmetric components with appropriate boundary conditions.	

Table 2.5.2 Additional boundary conditions for a half-breadth model

Set	Boundary conditions, centre line plane
BC1	Symmetry constrains: • Translation $\delta_y = 0$ • Rotation $\theta_x = \theta_z = 0$
BC2	Symmetry constrains: • Translation $\delta_y = 0$ • Rotation $\theta_x = \theta_z = 0$ Anti-symmetry constrains: • Translation $\delta_x = \delta_z = 0$ • Rotation $\theta_y = 0$
Note 1. These boundary conditions are additional to those given in *Table 2.5.1 Boundary conditions for a full-breadth model* and take precedence over the requirements of *Table 2.5.1 Boundary conditions for a full-breadth model*. Note 2. The transverse constraints in *Table 2.5.1 Boundary conditions for a full-breadth model* do not need to be included in the half-breadth model. Note 3. Care is to be taken to ensure that the FE model is not over-constrained and that there are no conflicting constraints.	

5.2 Load balance procedure

5.2.1 Balance of external pressure against inertia loads is necessary to minimise reaction forces at the constraints of the full ship FE model in order to obtain the correct structural response.

5.2.2 With the ship in either a vertical or heeled position, as specified by the load case considered, the waterline is to be adjusted vertically, and trim, using an iteration process, to achieve a vertically balanced position where the buoyancy force and trim moment are equal to that induced by the ship's weight. Other proposed methods for load balancing (e.g. introducing counteracting vertical and horizontal forces) will be specially considered.

5.2.3 When calculating the forces and moments due to the lightship, deadweight items and external pressure, attention should be paid to resolving the force components about the reference axes, taking into account effects of the trim angle and heel angle where appropriate.

5.2.4 For heeled load cases, SC7a and SC7b, care is to be taken with the balance of the racking (restoring) moment, M_{xx}, as shown in *Figure 2.5.1 Balancing loads for load cases*.

5.2.5 The inertia relief method is preferred to be used to balance the ship FE model in a heeled condition to simulate the inertia loads acting on the structure due to accelerations caused by the unbalanced racking moment.

5.2.6 Alternately, the racking moment, M_{xx}, may be balanced by introducing equal and opposite vertical force pairs at the intersection of the side shell and freeboard deck at each frame along the ship length, *see Figure 2.5.1 Balancing loads for load cases*. The magnitude of the force, F, to be applied at each frame may be obtained as follow:

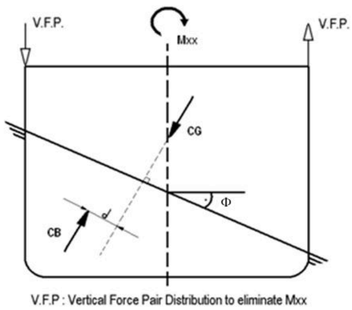
$$F = \frac{M_{\mathrm{xx}}}{\sum_1^n B_{\mathrm{i}}}$$

n = total number of frames where the vertical force pairs are applied

B_{i} = the local beam at the level of the freeboard deck

Other proposed methods to balance the racking moment will be specially considered.

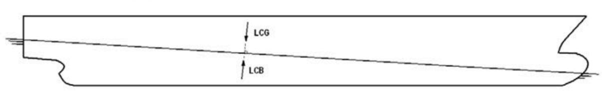
5.2.7 For load cases SC3b and SC4b (wave crest and trough), the bending of the hull girder is to be removed by application of vertical constraints at each web frame, as specified in boundary conditions BC2 in *Table 2.5.1 Boundary conditions for a full-breadth model*. In order to remove the reaction force at these vertical constraints, thus avoiding vicious stress response, it is recommended that counteracting vertical forces or grounded springs are distributed to the side shell nodes at every web frame to eliminate the reaction forces. The magnitude of these forces is to be such as to remove the vertical imbalance of the model caused by the applied wave crest/trough pressure.



Transverse load balance for static heel load cases

$M_{xx} = d \cdot \Delta$, where Δ is the ship displacement

Longitudinal load balance for all load cases



(Trim angle is exaggerated on this figure)

Figure 2.5.1 Balancing loads for load cases

■ *Section 6*
Acceptance criteria

6.1 Stress for assessment

6.1.1 The stresses for the assessment load combination cases specified in *Table 2.4.1 Load combination cases for assessment* are to be calculated by combining the FE load cases specified in *Ch 2, 4.3 FE load cases* and adjusted, where required, in accordance with *Ch 2, 6.1 Stress for assessment 6.1.2*.

6.1.2 At locations where there is a variation between the hull girder bending moment/shear force resulting from the FE load cases and the required combined still water and wave bending moment/shear force specified in *Table 2.4.1 Load combination cases for assessment*, the derived stresses are to be adjusted using the factorisation method described in *Ch 6 Adjustment of Global BM and SF* prior to comparing with the acceptance criteria. The buckling factors of safety are to be calculated using the adjusted stresses. Any variation between the hull girder bending moment/shear force resulting from the FE load cases and the required combined still water and wave bending moment/shear force in *Table 2.4.1 Load combination cases for assessment* may be ignored for locations outside the Rule length, *L*.

6.2 Stress criteria

6.2.1 The stresses resulting from the application of the assessment load combinations specified in *Table 2.4.1 Load combination cases for assessment* are not to exceed the membrane stress criteria given in *Table 2.6.1 Maximum permissible membrane stresses for structure except pillars* and *Table 2.6.2 Maximum permissible stresses for pillars*. Where plate elements with bending properties are used, the membrane stress can be obtained as the stress evaluated at the mid-plane of the plate.

6.2.2 Structures in way of high stress gradients, such as major openings or discontinuities, are to be subjected to further investigation as indicated in *Ch 3 Verification of Structural Details* of this procedure.

6.2.3 The structural analysis recommended in this Chapter of the procedure uses a relatively coarse mesh model. The permissible stress criteria in *Table 2.6.1 Maximum permissible membrane stresses for structure except pillars* and *Table 2.6.2 Maximum permissible stresses for pillars* are based on the recommended mesh size. Fine mesh models or fine mesh regions of the model will usually indicate higher stresses and should be assessed, in accordance with the criteria given in *Ch 3 Verification of Structural Details* and *Ch 5 Verification of Primary Structure Supporting Decks* as appropriate.

6.2.4 Where openings are not represented in the primary supporting member in the FE model, the mean shear stress in way is to be increased in direct proportion to the modelled shear area divided by net shear area. The equivalent stress of the element is to be recalculated using the increased shear stress for comparison with relevant permissible value in *Table 2.6.1 Maximum permissible membrane stresses for structure except pillars*. The net shear area in way of an opening is to be calculated in accordance with *Table 2.6.5 Net shear area*.

6.2.5 Plots showing the comparison between the target bending moment and shear force with the required distributions are to be produced. An example of the plots is shown in *Figure 2.6.1 Load combination LC1: Bending moment and shear force components* and *Figure 2.6.2 Load combination LC3: Bending moment and shear force components*.

6.3 Buckling criteria

6.3.1 The buckling capability of plate panels is to be assessed based on the gross plate thickness (excluding Owner's extras and any additional thicknesses fitted to comply with the optional *ShipRight Enhanced Scantlings Descriptive Note*, **ES**) with a standard thickness deduction, t_c given in *Table 2.6.4 Standard thickness deduction to be used to derive critical buckling stresses*. The local stresses (*see Ch 6, 4.1 General*) are to be increased by the ratio of $t / (t - t_c)$, where t is the thickness used in the FE model.

6.3.2 The critical buckling stress of plate panels are to be derived taking into account all relevant compressive and shear stress components and using a procedure such as that incorporated in the ShipRight software.

6.3.3 The edge restraint factor, *c*, defined in *Pt 3, Ch 4,7 Hull buckling strength* of the Rules for Ships, may be taken into account in calculating the critical buckling stress of wide panels subjected to compressive loading on the long edges of the panel. The edge restraint factor, *c*, is not to be used in the calculation of critical buckling stress for compression applied on the short edges.

6.3.4 When the calculated elastic critical buckling stress, σ_C, exceeds 50 per cent of the specified minimum yield stress, then the buckling stress is to be adjusted for the effects of plasticity using the Johnson–Ostenfeld correction:

$$\sigma_{cr} = \sigma_c \qquad \text{when} \qquad \sigma_c \leq 0,5\sigma_o$$

$$\sigma_{cr} = \sigma_o\left(1 - \frac{\sigma_o}{4\sigma_c}\right) \quad \text{when} \quad \sigma_c > 0,5\sigma_o$$

where

σ_{cr} = critical buckling stress.

6.3.5 A minimum factor against elastic buckling, λ, is specified in *Table 2.6.3 Minimum factor against buckling* . The column stability of pillars and vertical webs acting as pillars is to comply with the requirements of *Table 2.6.2 Maximum permissible stresses for pillars*. Provided that the wall or plate thickness of the pillar complies with the requirements specified in the Rules for Ships, local wall buckling of the pillar is considered satisfactory.

6.3.6 Alternative buckling assessment method may be specifically considered subject to agreement by LR.

Table 2.6.1 Maximum permissible membrane stresses for structure except pillars

Structural items	Load case	Allowable stresses *see* Notes 1 and 2			
		σ_e	σ_x	σ_y	τ_{xy}
Bottom shell plating	LC1, LC2, LC3, LC4	σ_L	0,92 σ_L	0,63 σ_0	–
Double bottom girders		σ_L	–	–	0,46 σ_L
Inner bottom plating		σ_L	0,92 σ_L	0,63 σ_0	–
Double bottom floors		0,75 σ_0	–	0,63 σ_0	0,35 σ_0
Side transverse		0,75 σ_0	–	0,63 σ_0	0,35 σ_0
Other longitudinal effective structures		0,92 σ_L	0,75 σ_L	–	0,46 σ_L
Other transverse structures		0,75 σ_0	–	0,63 σ_0	0,35 σ_0
All structures	LC5a, LC5b	0,75 σ_0	0,63 σ_0	0,63 σ_0	0,35 σ_0

Note 1. For plate elements, the specified direct and equivalent allowable stresses should be compared to the centroidal element membrane stress in the relevant structural item. For girders, stringers, vertical webs and floors, the specified values of allowable shear stress relate to the mean shear stress over the depth of the member; for bulkhead, shell and deck plating, they relate to shear stress of single element.

Note 2. Where openings are not represented in the primary supporting member in the FE model, the mean shear stress in way is to be increased in direct proportion to the modelled shear area divided by net shear area. The equivalent stress of the element is to be recalculated using the increased shear stress for comparison with relevant permissible value. The net shear area in way of an opening is to be calculated in accordance with *Table 2.6.5 Net shear area*. If the resulting stress level exceeds 90% of the specified allowable value, further investigation by means of fine mesh follow-up models may be required.

Table 2.6.2 Maximum permissible stresses for pillars

Pillars	Load cases	Acceptance criteria	*See* Note
In tension	LC1, LC2, LC3, LC4, LC5a, LC5b	$\sigma_{Axial} \leq 0,60\sigma_o$	1, 2
		$\sigma_{Extreme\_fibre} \leq 0,84\sigma_o$	
In compression		$\sigma_{Axial} \leq 0,80\sigma_{crit}$	2
		$\sigma_{Extreme\_fibre} \leq 0,84\sigma_o + \sigma_{Axial} \times (1 - \sigma_o/\sigma_{crit})$	
All		$\tau_{Shear} \leq 0,47\sigma_o$	–
where			

$$\sigma_{crit} = \frac{\sigma_o}{\left(1 + \frac{\sigma_o}{E}\left(\frac{L_e}{\pi r}\right)^2\right)}$$ L_e = effective length of pillar, in mm, and is taken as 0,8 overall length of pillar r = least radius of gyration of pillar cross-section, in mm
Note 1. Special attention to be paid to the weld attachments of the heads and heels of tensile pillars.   Note 2.For pillars, stresses to be calculated at the extreme fibre of the pillar section; if line elements are used to represent pillars then bending properties including relevant stress recovery points are to be specified. If two-dimensional (2-D) elements are used to represent non-circular pillars then stress is to be obtained for the node points at the extreme fibres of the pillar cross-section. If accurate nodal stresses are not available, the stresses are to be obtained from a line element of nominal area located at the extreme fibre of the pillar cross-section.

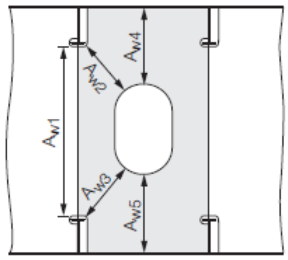
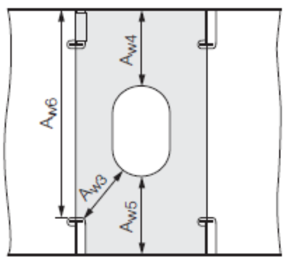
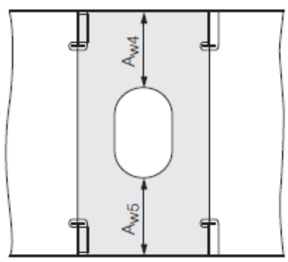
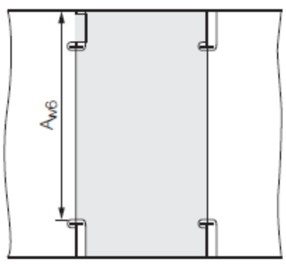
Table 2.6.3 Minimum factor against buckling

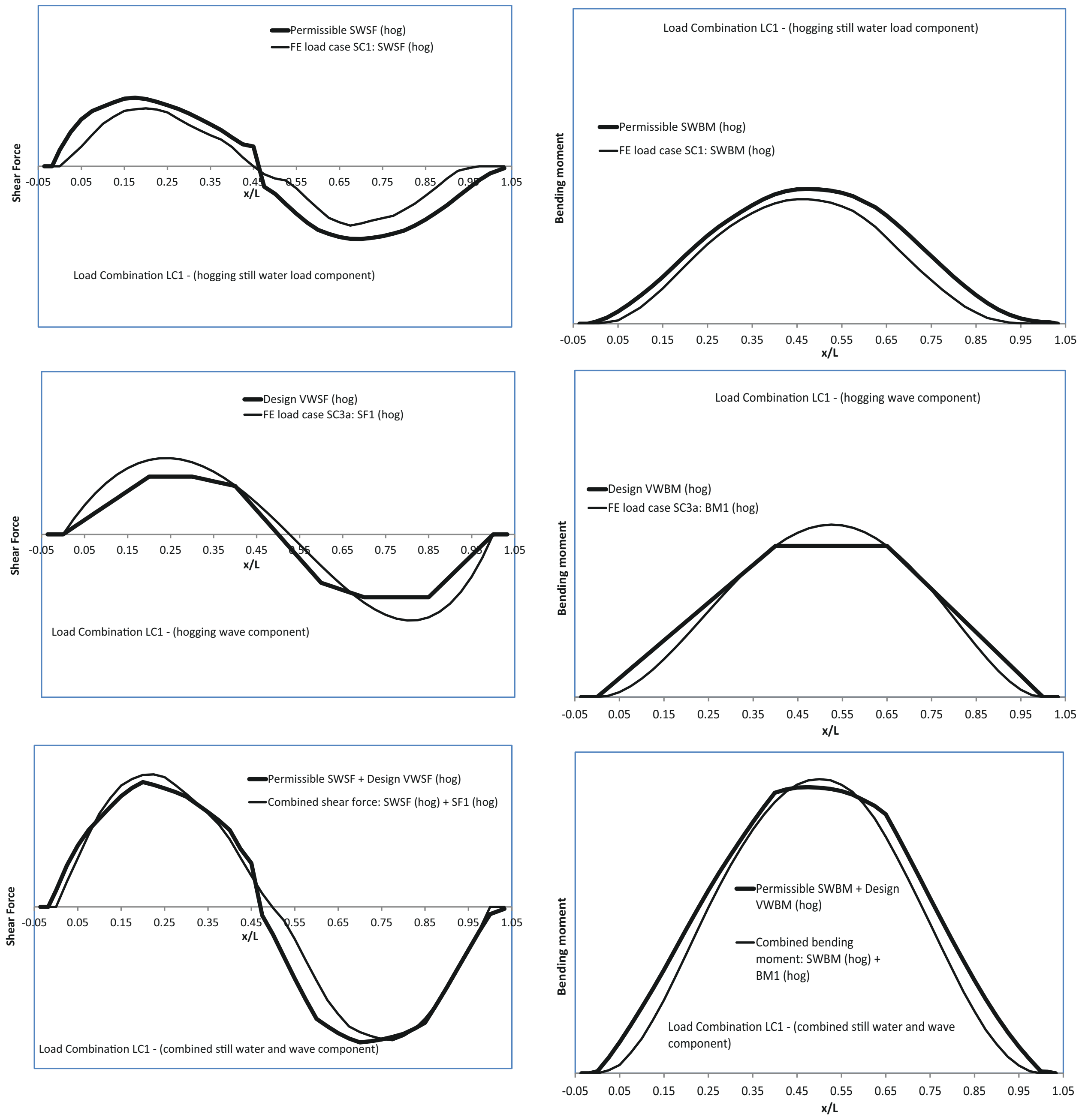
Structural items	Applicable to		Buckling factor
	LC1, LC2, LC3, LC4	LC5a, LC5b	
All structures		✓	1,0
Bottom shell plating	✓		1,0
Double bottom girders	✓		1,0
Inner bottom plating	✓		1,0
Double bottom floors	✓		1,1
Side transverse	✓		1,1
Other longitudinal effective structures	✓		1,0
Other transverse structures	✓		1,1

Table 2.6.4 Standard thickness deduction to be used to derive critical buckling stresses

Structural items	Thickness deduction, t_c, mm
Boundaries and internal structure of tanks	1,0
Exposed weather passenger decks	1,0
Bottom shell and side shell not in way of tank Other internal structures (except the boundaries of tanks) Exposed decks protected by sheathing or protective coatings	0,0

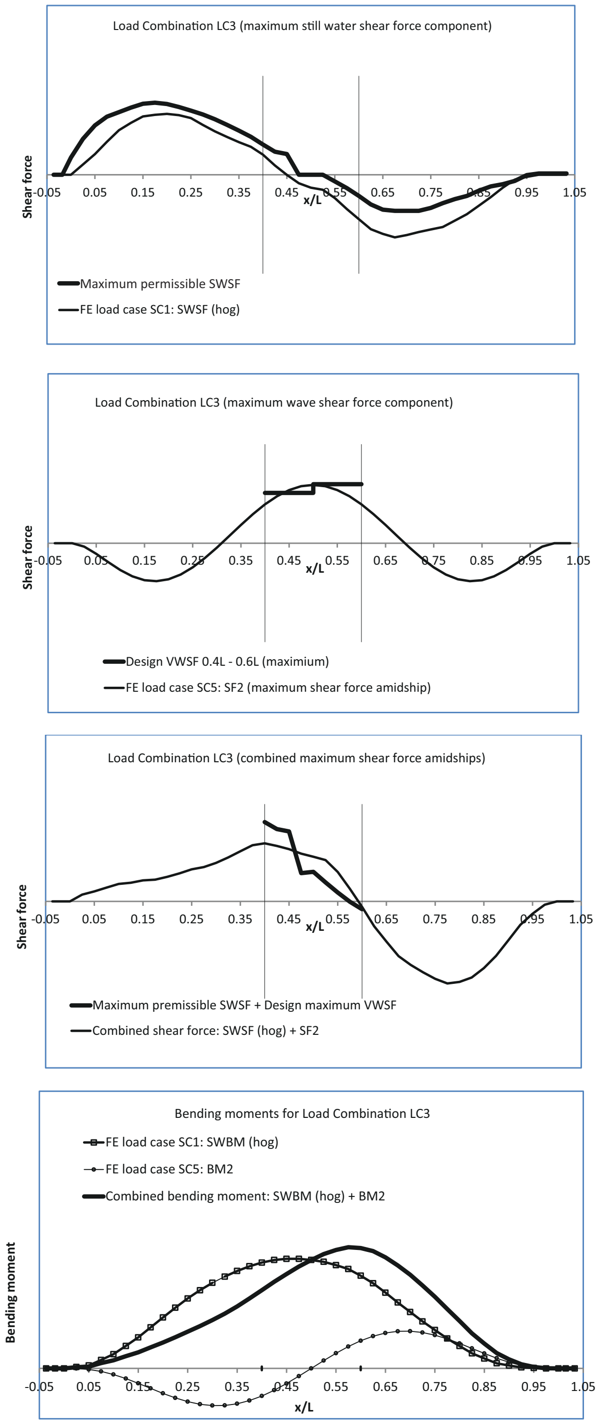
Table 2.6.5 Net shear area

Type	Net shear area	Note
(a) 	Minimum of the following: A_{w1}, $(A_{w2} + A_{w3})$, $(A_{w4} + A_{w5})$, $(A_{w2} + A_{w5})$ and $(A_{w3} + A_{w4})$	A_{w2} or A_{w3} is the minimum shear area between access opening and cut-out for stiffener
(b) 	Minimum of the following: A_{w6}, $(A_{w4} + A_{w5})$ and $(A_{w4} + A_{w3})$	A_{w3} is the minimum shear area between access opening and cut-out for stiffener
(c) 	$(A_{w4} + A_{w5})$	
(d) 	A_{w6}	



(for illustration purposes only and not to be scaled)

Figure 2.6.1 Load combination LC1: Bending moment and shear force components



(for illustration purposes only and not to be scaled)

Figure 2.6.2 Load combination LC3: Bending moment and shear force components

Contents

■ *Section 1* Application

1.1 Introduction

1.1.1 For the application of *Ch 3 Verification of Structural Details*, *see Ch 1, 1.1 General 1.1.9*.

■ *Section 2* Objectives

2.1 General

2.1.1 The objective of *Ch 3 Verification of Structural Details* is to determine the stress responses in way of highly stressed critical structural components and those with unusual features and to verify the stress levels are within acceptable limits.

■ *Section 3* Structural modelling

3.1 General

3.1.1 Separate detailed fine mesh FE models covering the structural components specified *Ch 3, 3.1 General 3.1.2* are to be prepared and loaded with enforced displacements obtained from the full ship global analysis, *see Ch 2 Global Response Analysis of Complete Ship*. Alternatively, these areas may be modelled in fine mesh and incorporated into the global FE model.

3.1.2 Fine mesh FE models are required for the areas detailed below. Typical models are indicated in *Figure 3.3.1 Typical fine mesh models*.

- Side screens/sweeps in way of the shell at the ends of the superstructure.
- Side screens/closely spaced windows in way of high hull girder shear forces.
- In way of the ends of the side deck strips of the uppermost continuous deck.
- Large shell doors (e.g. embarkation platforms with adjacent access doors).
- Steps/knuckles in upper decks where arranged transversely.
- In way of any novel or unusual feature which is expected to present a discontinuity or concentration of stress in the longitudinal material.
- Structure in way of high stress concentration or areas exceeding the stress criteria specified in *Ch 2 Global Response Analysis of Complete Ship*.

3.1.3 The FE model is to be represented using a right-handed Cartesian co-ordinate system with:

- *x* measured in the longitudinal direction, positive forward;
- *y* measured in the transverse direction, positive to port from the centreline; and

- z measured in the vertical direction, positive upwards from the baseline.

3.1.4 The plating and supporting primary structure are to be represented by plate elements having both membrane and bending stiffness.

3.1.5 The extent of fine mesh models is to be such that the application of boundary displacements (taken from *Ch 2 Global Response Analysis of Complete Ship*) will not invalidate the response at the relevant points of the local fine mesh model. The extent of fine mesh models is to be chosen carefully such that their boundaries coincide with primary members, such as girders and floors.

3.1.6 The structural geometry, particularly in areas of concern, is to be accurately represented. The level of refinement is to be such as to enable stress concentrations to be identified.

3.1.7 The element mesh size should comply with the following:

- The mesh size adopted should be such that the structural geometry can be adequately represented and the stress concentrations can be adequately determined. In general, the minimum required mesh size in fine mesh areas is not to be greater than 1/10 of the depth of the member (smallest dimension), $15t \times 15t$ or 150mm × 150mm, whichever is the lesser, where t being the thickness of the main plate in way of area of interest. In some locations a finer mesh may be necessary to represent the structural geometry but need not be less than $t \times t$. *See also Ch 3, 3.1 General 3.1.6*.
- In general, in way of radius corners, bracket radius edges and openings, it is required that a minimum of 15 elements in a 90 degree arc of the free edge of the plate is achieved. However, the element size is not to be greater than 150mm × 150mm and need not be less than $t \times t$. *See also Ch 3, 3.1 General 3.1.6*.
- Where FE analysis programs do not supply accurate nodal stresses, a line element (e.g. rod element) of small nominal area is to be incorporated at the plating free edge to obtain the peak edge stresses.
- Between closely spaced openings, in general a minimum of 5 elements should be arranged between such openings. However, the element size need not be less than $t \times t$.

3.1.8 All cut-outs, (e.g. for ventilation systems, services, access openings, etc.) are to be represented in the model.

3.1.9 The proposed scantlings, excluding Owner's extras and also excluding any additional thicknesses fitted to comply with the optional *ShipRight Enhanced Scantlings Descriptive Note*, **ES**, are to be incorporated in the model. Sacrificial abrasion strips or increased thickness to allow for abrasion on vehicle decks, especially those for tracked vehicles, are not to be included in the analysis.

3.1.10 Secondary stiffeners inside the fine mesh zone within one stiffener spacing or 500mm, whichever is greater, in all directions from the area of interest, are to be modelled using plate elements having both membrane and bending capability. Secondary stiffeners outside the fine mesh zones may be represented by line elements positioned in the plane of the plating having axial and bending properties (bars) representing the stiffener with the eccentricity of the neutral axis modelled.

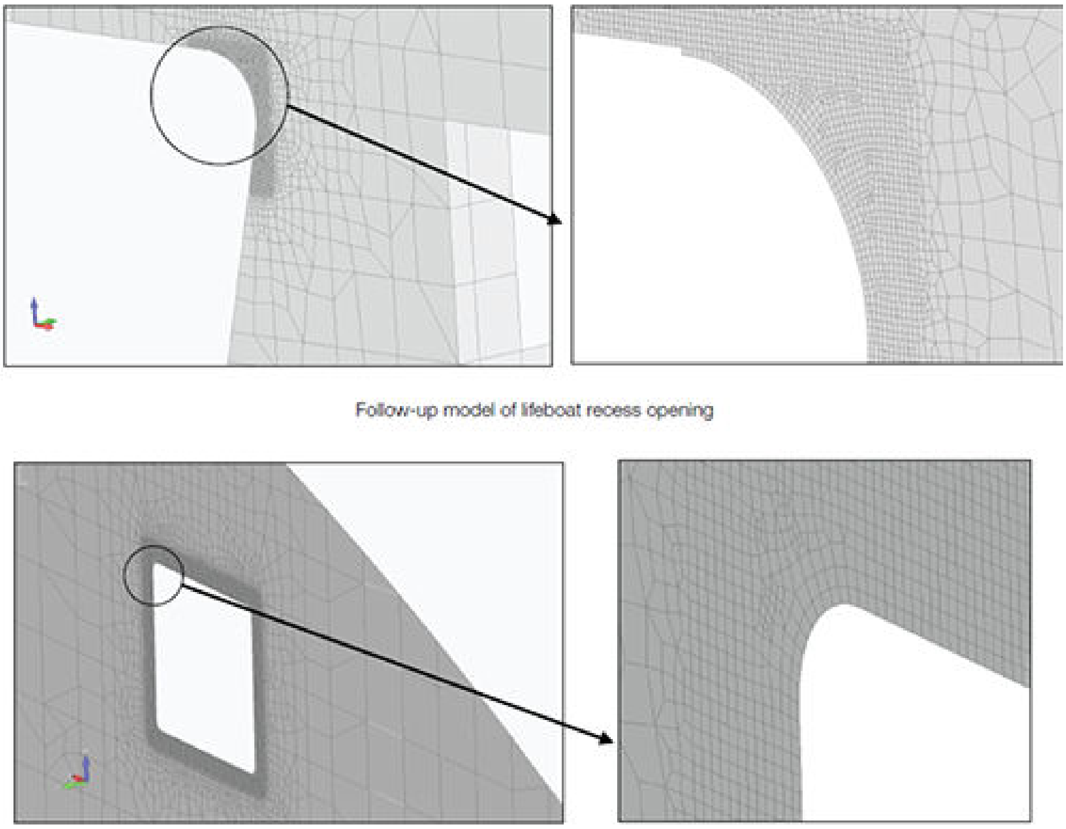


Figure 3.3.1 Typical fine mesh models

■ *Section 4*
Loading and boundary conditions

4.1 General

4.1.1 The assessment load cases detailed in *Ch 2, 4.1 General* are to be investigated. The fine mesh models are to be loaded with:

- the structural self-weight;
- the outfit and equipment loading and any other local loading within the model boundaries;
- enforced displacements at the model boundary obtained from the results of the FE load cases detailed in *Ch 2, 4.3 FE load cases*.

4.1.2 When a 2-D follow-up fine mesh model is developed to investigate in-plane responses, then the out-of-plane degrees of freedom may be constrained.

Section 5
Acceptance criteria

5.1 Stress for assessment

5.1.1 The stress values derived from the FE load cases are to be factored by the ratio of the locally required bending moment/ shear force, as per *Table 2.4.1 Load combination cases for assessment*, to the locally achieved bending moment/shear force following stress factorisation techniques specified in *Ch 6 Adjustment of Global BM and SF* prior to comparing with the acceptance criteria. Any variation between the hull girder bending moment/shear force resulting from the FE load cases and the required combined still water and wave bending moment/shear force in *Table 2.4.1 Load combination cases for assessment* may be ignored for locations outside the Rule length, *L*.

5.2 Stress criteria

5.2.1 The von Mises and direct stresses in the plating between major openings, free edge of sweep brackets and edge of side screens and the direct (tangential) stresses at the free edge of the associated corner radii are to comply with the acceptance criteria in *Table 3.5.1 Stress criteria for major openings, sweep brackets and side screens*.

5.2.2 The von Mises, shear and direct stresses in the plating between window, door and other minor openings and the direct (tangential) stresses at the free edge of the associated corner radii are to comply with the acceptance criteria in *Table 3.5.2 Stress criteria for minor openings, such as windows and doors, etc.*

5.2.3 In additional to *Ch 3, 5.2 Stress criteria 5.2.1* and *Ch 3, 5.2 Stress criteria 5.2.2*, small openings, other than those required by *Ch 5 Verification of Primary Structure Supporting Decks*, such as duct, cable, pipes and other outfitting penetrations with an equivalent area greater than or equal to 250mm × 250mm and lesser than or equal to 450mm × 450mm are to be selected for further assessment where:

$$2,13\left|\sigma_x + \sigma_y\right| + 3,14\left|\tau_{xy}\right| \geq \sigma_0$$

where

σ_x, σ_y, τ_{xy} are the elemental stresses in the coarse mesh where the opening has not be modelled.

5.2.4 The small openings selected for further assessment may be assessed using an appropriate Stress Concentration Factor (SCF) technique agreed by LR and assessed against the peak edge stress acceptance criteria in *Table 3.5.2 Stress criteria for minor openings, such as windows and doors, etc.*

5.2.5 Elsewhere, stress levels are to comply with the acceptance criteria given in *Table 2.6.1 Maximum permissible membrane stresses for structure except pillars*.

Table 3.5.1 Stress criteria for major openings, sweep brackets and side screens

Load case	Structural item	Stress component	Combined stress	Direct stress	Location Reference
LC1, LC2, LC3 and LC4	In way of free edge (e.g. openings and brackets, etc.)	Peak edge stress (*see* Note 1)	-	1,5 G_1 σ_0	1(a)
		Peak element centroid stress	1,2 G_3 σ_0	-	1(b)
	Other fine meshed areas	Peak element centroid stress	σ_0	-	-
Hogging wave minus Sagging wave LC1 - LC2 + (SC2 - SC1) LC3 - LC4 + (SC2 - SC1)	In way of free edge (e.g. openings and brackets, etc.)	Dynamic stress range: $f_{prob} f_{Ln} S_r$	$345 f\ f_{sa}\ h\ k_g\ k_{dl}\ G_2\ W_{s-n}\ t_{\_corr}$		1(a)
	Other fine meshed areas in way of welds				1(c)

Symbols:

G_1 = 0,67

G_2 = 0,85

G_3 = 0,77

S_r = $|\sigma_{hog} - \sigma_{sag}|$

σ_{hog} = stress due to hogging wave

σ_{sag} = stress due to sagging wave

f_{prob} = probability level correction factor

= 0,625

f_{Ln} = hogging/sagging non-linear correction factor

= $0,625 + \dfrac{3}{4\left(f_{fH} - f_{fS}\right)}$

f = *see Table 3.5.3 Definition of f-factor* and *Figure 3.5.1 Definition of f-factors: (schematic only)*

f_{sa} = 1,0 for dedicated North Atlantic service

= 1,2 for world-wide service

h = $0,79$ for $L = 100\text{m}$

= $\dfrac{186}{10^8}L^2 + \dfrac{34}{10^5}L + 0,7$ for $180\text{m} \le L \le 320\text{m}$

= $1,0$ for $L > 320\text{m}$

Intermediate values are to be obtained by linear interpolation

k_{dl} = $(20/DFL)^{0,25}$; where DFL is the specified fatigue life in years but not to be taken as less than 20

k_g = 1,0 in general

= 1,12 for free edges where the edge corners have been removed and free edge has been ground smooth, *see* Note 2

= 1,12 for welds which have been suitably toe ground and profiled, *see* Note 3

$W_{s\text{-}n}$ = aluminium alloy and high tensile steel correction factor for free edges and plating

= 1,0 for all steel grades having a nominal yield stress of 235 N/mm^2

= 1,0 for all steel grades having a nominal yield stress of 270 N/mm^2

= 1,0 for steel grades A and D having a nominal yield strength

= 1,056 for steel grades EH32 and FH32

= 1,12 for steel grades EH36 and FH36

= 1,15 for steel grades EH40 and FH40

= 1,0 for all steel grades for all nominal yield strengths in way of welds or within 15mm from a weld toe

= 0,32 for all aluminium alloys

$t_{\_corr}$ = thickness correction

= for $t \ge 22$ $t_{\_corr} = (22/t)^n$

= for $t < 22$ $t_{\_corr} = 1,0$

n = *see Table 3.5.4 Thickness correction factor, n*

Note 1. This is a theoretical peak stress obtained from a linear elastic finite element using a line element (e.g. rod element) of a small nominal area incorporated at the plating free edge, or von Mises nodal stress values from the nodes on the free edge of the model.

Note 2. Applicable to cut edges of plate with thickness up to 100mm. All visible defects, such as drag lines, should be removed from the flame cut edges by grinding or machining. Any flame cut edges are to be subsequently machined or ground smooth. Where the corners of the plate are removed in accordance with LR, *ShipRight FDA – Level 1 Procedure, Ch 2, 2.4.3 Machining methods*, the additional fatigue life improvement factor as specified in the *ShipRight FDA – Level 1 Procedure*, *Ch 2, Table 2.4.5 Fatigue strength improvement factors* can be applied.

Note 3. Guidance on suitable toe ground and profiled of welds can be found in LR, *ShipRight FDA – Level 1 Procedure, Ch 2, 2.4.3 Machining methods*.

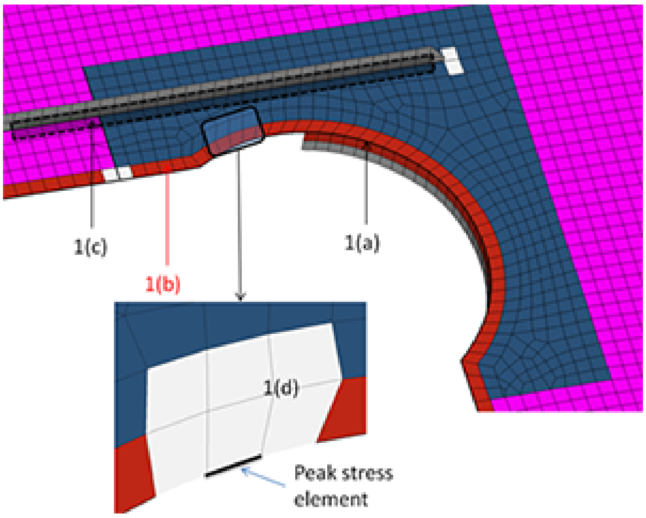


Table 3.5.2 Stress criteria for minor openings, such as windows and doors, etc.

Load case	Structural item	Stress component	Combined stress	Direct stress	Shear stress	Location Reference
LC1, LC2, LC3 and LC4	All Fine meshed areas	Peak element centroid stress	1,2 *G*1 σ_0	-	-	-
	In way of opening	Peak edge stress, *see* Note 1	-	1,5 *G*1 σ_0	-	1(a)
		Average stress, *see* Note 2	*G*1 σ_0	-	-	1(b)
	Between openings	Average stress	0,94 σ_0	-	0,47 σ_0	2(a)
	Other fine meshed areas	Average stress, *see* Note 2	σ_0	-	-	-
		σ_{coarse}, *see* Note 3	*See, Table 2.6.1 Maximum permissible membrane stresses for structure except pillars*			-
Hogging wave minus Sagging wave LC1 - LC2 + (SC2 - SC1) LC3 - LC4 + (SC2 - SC1)	In way of opening	Dynamic stress range: $f_{prob} f_{Ln} S_r$	$345 f\ f_{sa}\ h\ k_g\ k_{dl}\ G_2\ W_{s-n}\ t_{corr}$			1(a)
	Other fine meshed areas in way of welds					1(c)

Symbols: G_1 = 1,0 G_2 = 1,0 For other symbols, *see Table 3.5.1 Stress criteria for major openings, sweep brackets and side screens*
Note 1. This is a theoretical peak stress obtained from a linear elastic finite element using a line element (e.g. rod element) of a small nominal area incorporated at the plating free edge, or von Mises nodal stress values from the nodes on the free edge of the model. Note 2. The average stress from the element being assessed and the elements directly connected to its boundary nodes is to be calculated independently of the sign of the individual stress levels. Averaging is not to be carried across structural discontinuities or abutting structures. Note 3. σ_{coarse} are the values of combined stress, direct stress and shear stress, as required, averaged over an area equal to the size of the coarse mesh element in way of the structure being considered. The averaging is to be based only on elements with their boundary located within the desired area. Stress averaging is not to be carried out across structural discontinuities or abutting structures.

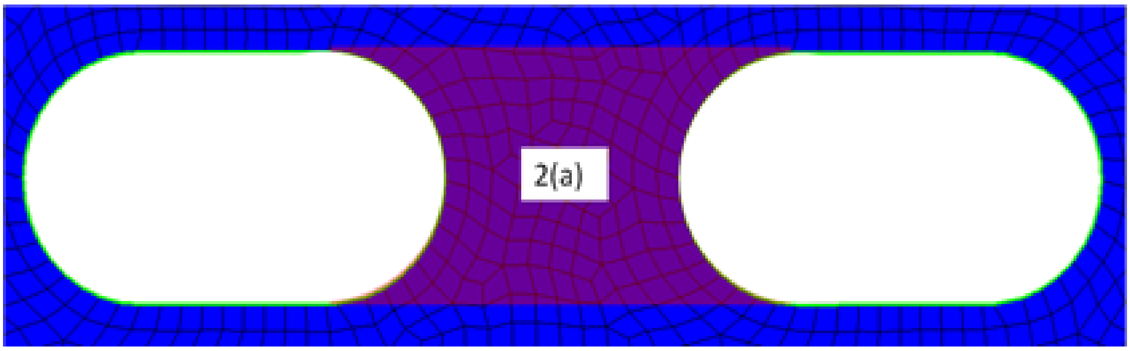


Table 3.5.3 Definition of *f*-factor

The value of the *f*-factor relates primarily to whether the detail is non-welded or welded and if welded, the proximity of the weld to the stress concentration.

The *f*-factor, except as defined in (d), is independent of the geometrical arrangement of the detail being considered. The geometrical stress concentration associated with a particular detail is derived from the fine mesh model analysis.

Position (*see* Note 1)	*f*-factor value	
	Steel	Aluminium alloy
(a) In way of welded details except (c) (b) Weld ends or return welds at free edge of plate or attached member	0,65 (*see* Note 2)	0,80 (*see* Note 2)
(c) Opening with welded face plate	0,65 (*see* Note 2)	0,80 (*see* Note 2)
(d) For welded structure which is not adequately modelled in the analysis because the mesh size is too coarse (e.g. anti-buckling stiffeners close to edges of openings which are modelled as line elements or brackets modelled by plate elements larger than $t \times t$)	0,48 (*see* Note 3)	0,55 (*see* Note 3)
(e) Free edges of structure:	(*see* Note 4)	(*see* Note 4)
• At a distance of $d \leq 15$mm from a weld toe	0,65	0,80

• Otherwise	1,0	1,0

Note 1. *t* is the lowest thickness of the welded plates at the position being considered.

Note 2. The stress to be used is the element centroid principle stress in the plate element at the weld connection.

Note 3. The stress in the model at the position where the structure will be located is to be used for the assessment.

Note 4. The stress to be used for the assessment is either the axial stress from a line element arranged at the free edge, or von Mises nodal stress values from the nodes on the free edge of the model.

Table 3.5.4 Thickness correction factor, *n*

Joint category	Thickness correction factor, *n*	
	As-built (*see* Note 1)	Improved (*see* Note 2)
Free edge (cut edge free of welds)	0,1	0,0
Butt welds normal to stress, *see* Note 4	0,2	0,1
Butt welds parallel to stress, *see* Note 3	0,1	0,1
Face plates attached to plate edges including return welds	0,1	0,1
Attachments normal to stress, *see* Note 4	0,25	0,2
Welds at end of unsupported attachments parallel to stress	0,2	0,1
Welds at end of attachments parallel to stress: with support member in same direction as attachment, *see* Note 3	0,0	0,0

Note 1.	For free edge:	Any cutting of edges by machine or flame cutting with a controlled procedure.
	For weld:	As-welded.
Note 2.	For free edge:	Any cut edges subsequently machined or ground smooth.
	For fillet weld:	Weld toe treated by post-weld improvement method, or weld profile improved.
	For butt weld or seam:	Ground flush or weld toe treated by post-weld improvement method.
Note 3.	Parallel to stress:	45^o < stress direction $\leq 90^o$ to the normal to the weld.
Note 4.	Normal to stress:	$0^o \leq$ stress direction $\leq 45^o$ to the normal to the weld.

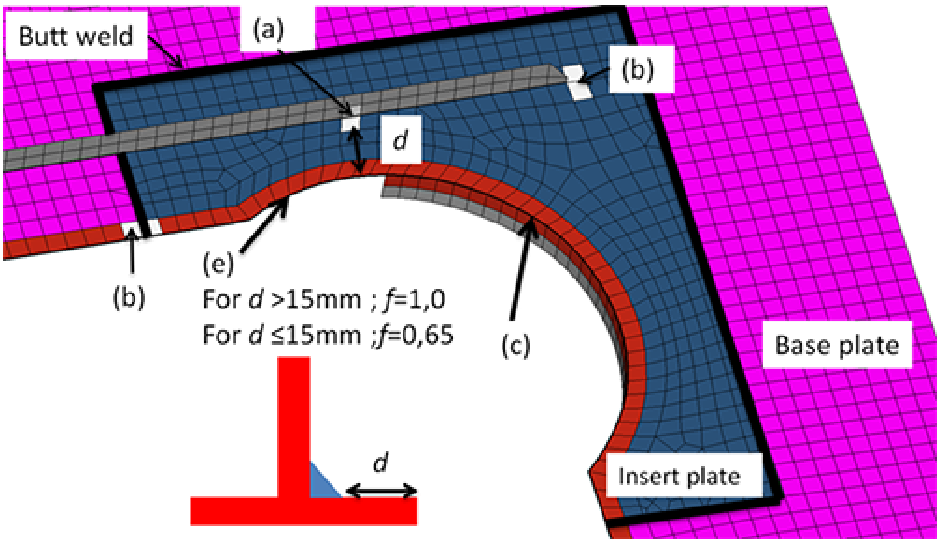


Figure 3.5.1 Definition of f-factors: (schematic only)

Contents

Chapter 4

Section

■ *Section 1* Application

1.1 Introduction

1.1.1 For the application of *Ch 4 Verification of Double Bottom Strength*, *see Ch 1, 1.1 General 1.1.10*.

■ *Section 2* Objectives

2.1 General

2.1.1 The objective of *Ch 4 Verification of Double Bottom Strength* is to verify the structural adequacy of the ships double bottom structure.

■ *Section 3* Structural modelling

3.1 General

3.1.1 A FE model of the engine room double bottom structure and supporting side structures is to be prepared. A typical model arrangement is indicated in *Figure 4.3.1 Typical engine room double bottom model*.

3.1.2 The longitudinal extent of the model is to comprise half + one + half compartments, where a compartment is the space between main subdivision bulkheads. Generally the longest compartment, exhibiting the features listed in *Ch 4, 1.1 Introduction 1.1.1*, is to be chosen for the analysis. The model is to extend transversely from centreline to ship's side. Vertically, the model needs only include the bottom and side structure up to the first main continuous deck. Where structural or load symmetry does not exist, a full breadth model should be developed.

3.1.3 The FE model is to be represented using a right-handed Cartesian co-ordinate system with:

- x measured in the longitudinal direction, positive forward.
- y measured in the transverse direction, positive to port from the centreline.
- z measured in the vertical direction, positive upwards from the baseline.

3.1.4 The mesh size adopted should be as follows:

- transversely, one element between longitudinals;
- vertically, one element between longitudinals;
- longitudinally, at least one element between transverse frames;

- web plating of primary members such as plated floors and girders, at least three elements.

3.1.5 It may be necessary to use a finer mesh to ensure adequate element aspect ratios.

3.1.6 In principle, all openings are to be represented.

3.1.7 The proposed scantlings are to be incorporated in the model. However, Owner's extras and any additional thicknesses fitted to comply with the optional *ShipRight Enhanced Scantlings Descriptive Note*, **ES**, are to be excluded.

3.1.8 All plated areas, e.g. outer shell, inner bottom, girders, horizontal stringers, floors and transverses are to be represented with plate elements having both membrane and bending stiffness.

3.1.9 The secondary stiffeners are to be represented by line elements positioned in the plane of the plating having axial and bending properties (bars) representing the stiffener with the eccentricity of the neutral axis modelled. Where appropriate, a single line element may represent more than one secondary stiffener.

3.1.10 Face plates to primary stiffening may be represented by line elements having axial stiffness only.

3.1.11 Pillars where fitted may be represented by line elements having axial and bending stiffness and appropriate stress recovery points. If modelled using plate elements, and accurate nodal stress output is not available, a line element of nominal area will need to be arranged at the extremities of the section in order to obtain the extreme fibre stresses.

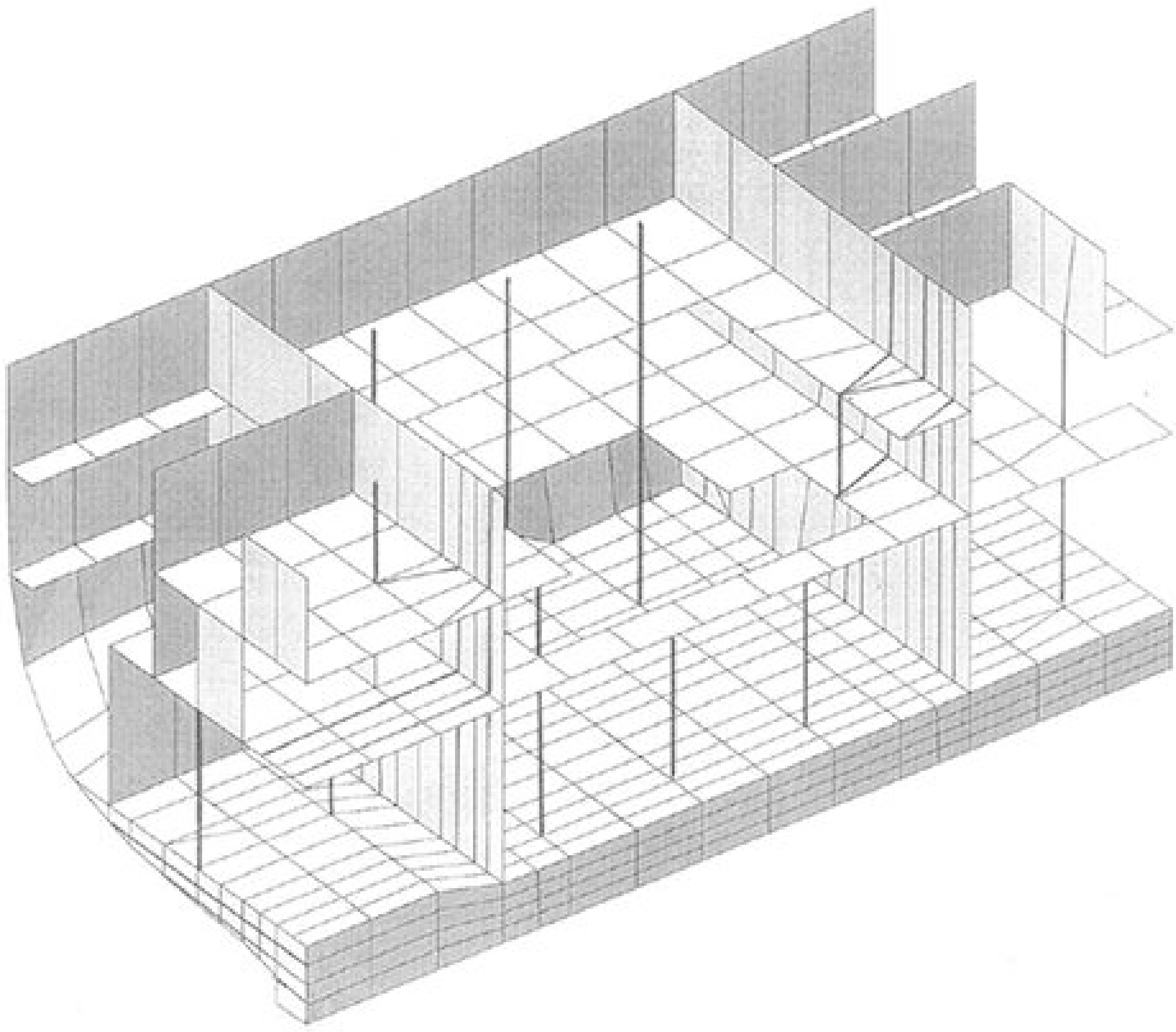


Figure 4.3.1 Typical engine room double bottom model

■ *Section 4*
Loading conditions

4.1 General

4.1.1 The load cases given in *Table 4.4.1 Loading conditions* are to be considered.

4.1.2 The following loads are to be applied to the model:

- Structural self-weight.
- Outfit and equipment loads.
- Hydrostatic loads due to immersion to the draught specified in *Table 4.4.1 Loading conditions*.
- Pressure loads due to a local wave crest or trough, *see Ch 4, 4.1 General 4.1.3*.
- Bending moment value as specified by *Table 4.4.1 Loading conditions*, *see Ch 4, 4.1 General 4.1.4*.

4.1.3 The additional pressure head to be applied as a consequence of a local wave crest or trough is given in *Figure 2.4.1 Pressure head distribution P_W for local wave crest and trough*. This additional wave head is to be applied over the full length of the FE model.

4.1.4 The response to the bending moment value required by *Table 4.4.1 Loading conditions* is to be obtained by applying a suitable moment at the master node on the boundary at one end of the model, *see Ch 4, 4.1 General 4.1.5*. The master node should be located at the height of the effective neutral axis of the hull girder, *see Figure 4.5.1 Boundary conditions for the application of symmetric loads*.

4.1.5 As only a partial depth FE model is required by this chapter, the method to introduce hull girder bending stresses into the FE model, as required for load cases C1 and C2 in *Table 4.4.1 Loading conditions*, needs to be specially considered. The following procedure is suggested:

- The response to the bending moment required by *Table 4.4.1 Loading conditions* is to be reproduced by application of a suitable moment at the master node on the boundary of one end of the model.
- The master node is to be located at the height of the effective neutral axis of the hull girder, *see Figure 4.5.1 Boundary conditions for the application of symmetric loads*.

An additional constraint in the *x*-direction will be required at the master node of End B in *Figure 4.5.1 Boundary conditions for the application of symmetric loads* in order to provide the correct distribution of longitudinal stress.

Table 4.4.1 Loading conditions

Load case	Load case description	Required Still water bending moment	Required Rule vertical wave bending moment	Additional load to apply	Local loads
C1	Hogging wave condition	Permissible hogging	Rule design hogging	Max operating draught T_{max} and wave crest	*see Ch 4, 4.1 General 4.1.2*
C2	Sagging wave condition	Permissible sagging or minimum hogging	Rule design sagging	Min operating draught T_{min} and wave trough	*see Ch 4, 4.1 General 4.1.2*

■ *Section 5*
Boundary conditions

5.1 General

5.1.1 The required boundary conditions for a half-breadth FE model are shown in *Figure 4.5.1 Boundary conditions for the application of symmetric loads*.

5.1.2 For a full breadth FE model the following boundary conditions are to be applied:

- No symmetry constraints are to be applied to the model centreline plane.
- A node on the centreline at the keel at the forward and aft end of the model is to be constrained in the *y*-direction.
- A node at the side shell position on top of the main subdivision bulkheads is to be constrained in the *z*-direction on both port and starboard sides (as shown in *Figure 4.5.1 Boundary conditions for the application of symmetric loads* for a half-breadth model).

5.1.3 The boundary conditions described in this Section are preferred. However alternative equivalent boundary conditions may be used.

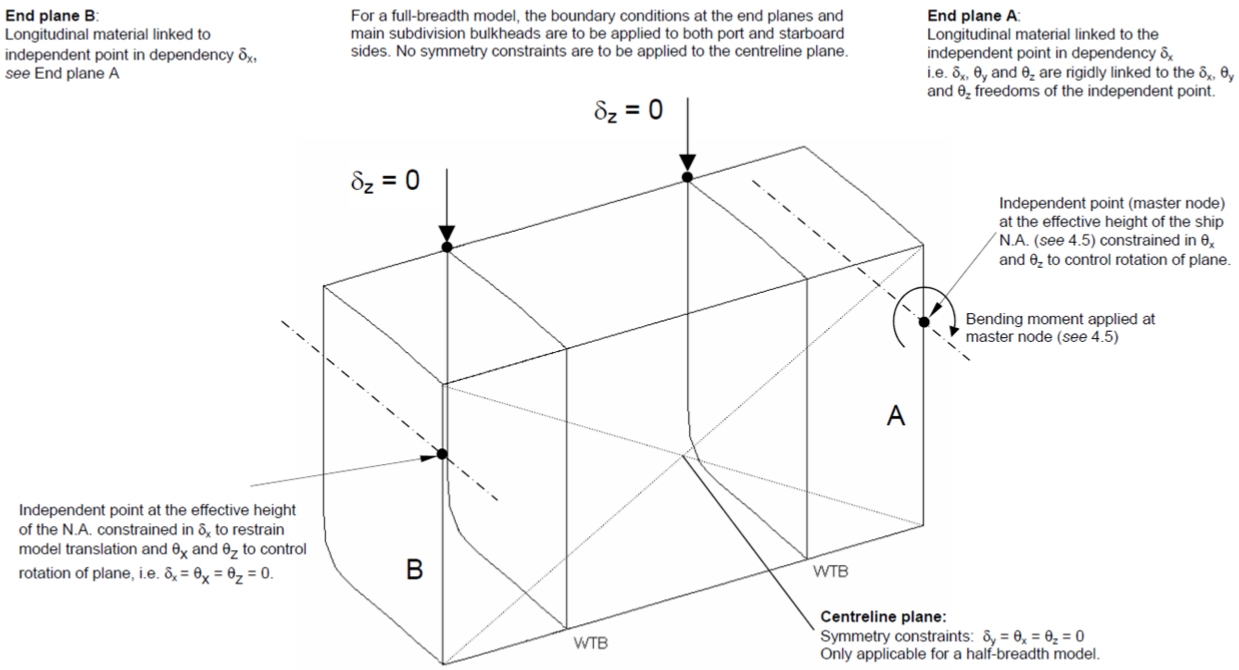


Figure 4.5.1 Boundary conditions for the application of symmetric loads

■ *Section 6* Acceptance criteria

6.1 Allowable stress and buckling criteria

6.1.1 The double bottom structure is to comply with the acceptance criteria given in *Table 4.6.1 Acceptance criteria*.

6.1.2 The buckling capability of plate panels is to be assessed based on the gross plate thickness (excluding Owner's extras and any additional thicknesses fitted to comply with the optional *ShipRight Enhanced Scantlings Descriptive Note*, **ES**) with a standard thickness deduction, t_c given in *Table 2.6.4 Standard thickness deduction to be used to derive critical buckling stresses*. The local stresses (*see Ch 6, 4 Local stresses*) are to be increased by the ratio of t / (t – t_c), where t is the thickness used in the FE model.

6.1.3 The critical buckling stress of plate panels are to be derived taking into account all relevant compressive and shear stress components and using a procedure such as that incorporated in the ShipRight software.

6.1.4 The edge restraint factor, c, defined in *Pt 3, Ch 4,7 Hull buckling strength* of the Rules for Ships, may be taken into account in calculating the critical buckling stress of wide panels subjected to compressive loading on the long edges of the panel.

The edge restraint factor, *c*, is not to be used in the calculation of critical buckling stress for compression applied on the short edges.

6.1.5 When the calculated elastic critical buckling stress, σ_c , exceeds 50 per cent of the specified minimum yield stress, then the buckling stress is to be adjusted for the effects of plasticity using the Johnson–Ostenfeld correction:

$$\sigma_{cr} = \sigma_c \qquad \text{when} \qquad \sigma_c \le 0,5\sigma_o$$

$$\sigma_{cr} = \sigma_o\left(1 - \frac{\sigma_o}{4\sigma_c}\right) \qquad \text{when} \qquad \sigma_c > 0,5\sigma_o$$

where

σ_{cr} = critical buckling stress.

6.1.6 The column stability of pillars and vertical webs acting as pillars is to comply with the requirements of *Table 4.6.2 Maximum permissible stresses for pillars*. Provided that the wall or plate thickness of the pillar complies with the requirements specified in the Rules for Ships, local wall buckling of the pillar is considered satisfactory.

Table 4.6.1 Acceptance criteria

Structural item	Load case	Allowable stresses (*see* Notes 1 and 2)				Minimum buckling factor
		σ_e	σ_x	σ_y	τ_{xy}	λ
Bottom shell plating	C1 C2	σ_L	$0,92\sigma_L$	$0,63\sigma_o$	-	1,0
Double bottom girder	C1 C2	σ_L	-	-	$0,46\sigma_L$	1,0
Inner bottom plating	C1 C2	σ_L	$0,92\sigma_L$	$0,63\sigma_o$	-	1,0
Double bottom floors	C1 C2	$0,75\sigma_o$	-	$0,63\sigma_o$	$0,35\sigma_o$	1,1
Side transverse	C1 C2	$0,75\sigma_o$	-	$0,63\sigma_o$	$0,35\sigma_o$	1,1

Note 1. For plate elements, the specified direct and equivalent allowable stresses should be compared to the centroidal element membrane stress in the relevant structural item. For girders, stringers, vertical webs and floors, the specified values of allowable shear stress relate to the mean shear stress over the depth of the member; for bulkhead, shell and deck plating, they relate to shear stress of single element.

Note 2. Where openings are not represented in the FE model, the mean shear stress in way is to be increased in direct proportion to the modelled shear area divided by net shear area. The equivalent stress of the element is to be recalculated using the increased shear stress for comparison with relevant permissible value. The net shear area in way of an opening is to be calculated in accordance with *Table 2.6.5 Net shear area*. If the resulting stress level exceeds 90% of the specified allowable value, further investigation by means of fine mesh follow-up models may be required.

Table 4.6.2 Maximum permissible stresses for pillars

Pillars	Load cases	Acceptance criteria	*See* Note
In tension	C1 and C2	$\sigma_{Axial} \leq 0{,}60\sigma_o$	1, 2
		$\sigma_{Extreme\_fibre} \leq 0{,}84\sigma_o$	
In compression		$\sigma_{Axial} \leq 0{,}80\sigma_{crit}$	2
		$\sigma_{Extreme\_fibre} \leq 0{,}84\sigma_o + \sigma_{Axial} \times (1 - \sigma_o/\sigma_{crit})$	
All		$\tau_{Shear} \leq 0{,}47\sigma_o$	–

where

$$\sigma_{crit} = \frac{\sigma_o}{\left(1 + \frac{\sigma_o}{E}\left(\frac{L_e}{\pi r}\right)^2\right)}$$

L_e = effective length of pillar, in mm, and is taken as 0,8 overall length of pillar

r = least radius of gyration of pillar cross-section, in mm

Note 1. Special attention to be paid to the weld attachments of the heads and heels of tensile pillars.

Note 2. For pillars, stresses to be calculated at the extreme fibre of the pillar section; if line elements are used to represent pillars then bending properties including relevant stress recovery points are to be specified. If 2-D elements are used to represent non-circular pillars, then stress is to be obtained for the node points at the extreme fibres of the pillar cross-section. If accurate nodal stresses are not available, the stresses are to be obtained from a line element of nominal area located at the extreme fibre of the pillar cross-section.

Contents

Chapter 5

Verification of Primary Structure Supporting Decks — Chapter 5

■ *Section 1*
Objectives

1.1 General

1.1.1 The objective of this Chapter is to consider the structural adequacy of the transverse and longitudinal primary structural members supporting decks.

1.1.2 Independent strength analyses are to be carried out on primary structural members supporting decks where one or more of the following conditions are satisfied:

- Openings in the primary member web plates exceed 25 per cent of the web depth.
- The slots for the passage of longitudinals exceed 50 per cent of the web depth and lugs are not fitted.
- Where a web opening is fitted in way of a slot for the passage of longitudinal and lugs are not fitted, and where the combined depth of these openings exceeds 50 per cent of the web depth.
- Supporting pillars are misaligned or omitted, or continuity is not maintained.
- The primary members employ novel or unusual structural arrangements.

■ *Section 2*
Structural modelling

2.1 General

2.1.1 A 3-D FE model of the primary members including the attached deck plating and secondary members between adjacent primary members is to be developed.

2.1.2 The modelled extent of the primary members is to be chosen such that a fully fixed boundary condition at the pillar heads or a symmetry boundary condition at the mid-span position can be assumed.

2.1.3 All openings in the web plating, including those for the passage of longitudinals, are to be accurately represented.

2.1.4 The mesh density is to be sufficient to enable the detailed structural response to be obtained. For “Tee” section members, a minimum of 10 elements in the web depth is generally considered sufficient. However, this will need to be refined in the areas around web openings. Mesh size is not to be less than $t \times t$. Quadrilateral shell elements are to be used for plated areas such as deck and web plating and member face plates. However, if the primary member is of a symmetric type, then the member face plate may be represented by a line member. Line elements may be used for secondary stiffening members.

2.1.5 In general, the use of triangular plate elements is to be kept to an absolute minimum. Where possible, they are to be avoided in areas where there are likely to be high stresses or a high stress gradient. These include areas:

- in way of lightening/access holes; and
- adjacent to brackets, knuckles or structural discontinuities.

2.1.6 A typical FE model of a deck girder and transverse is shown in *Figure 5.2.1 Model of primary deck transverse and deck girder (viewed from below)*.

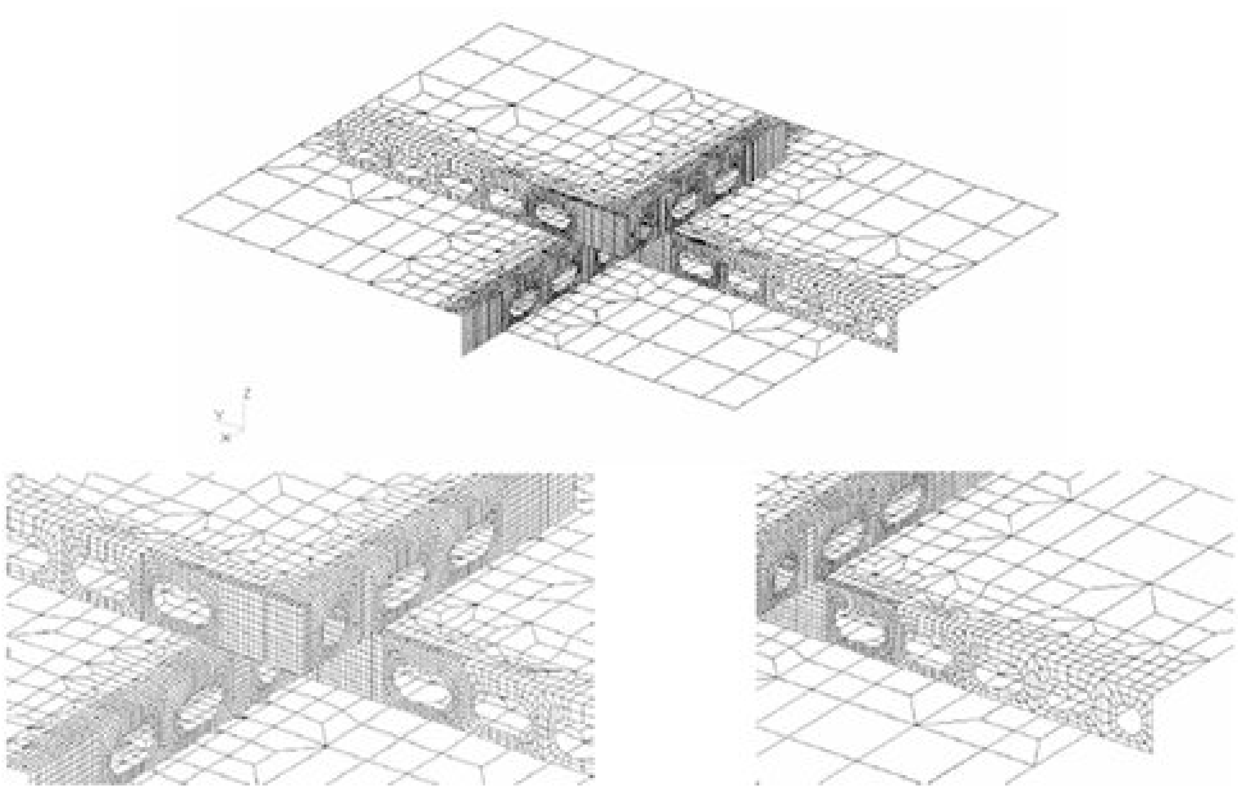


Figure 5.2.1 Model of primary deck transverse and deck girder (viewed from below)

■ *Section 3*
Load cases and boundary conditions

3.1 General

3.1.1 The deck loads, as specified in *Pt 4, Ch 2,3 Deck structure* of the Rules for Ships, appropriate to the location under consideration, are to be applied as a lateral pressure uniformly over the deck area. Concentrated loads, such as those arising from misaligned pillars or from specific non-structural masses, are to be accounted for in the analysis.

3.1.2 For the analysis of deck girders, the direct stresses due to maximum hull girder hogging and sagging bending moment (as specified in LC1 and LC2 in *Table 2.4.1 Load combination cases for assessment*) are also to be included.

■ *Section 4*
Acceptance criteria

4.1 Allowable stress and buckling criteria

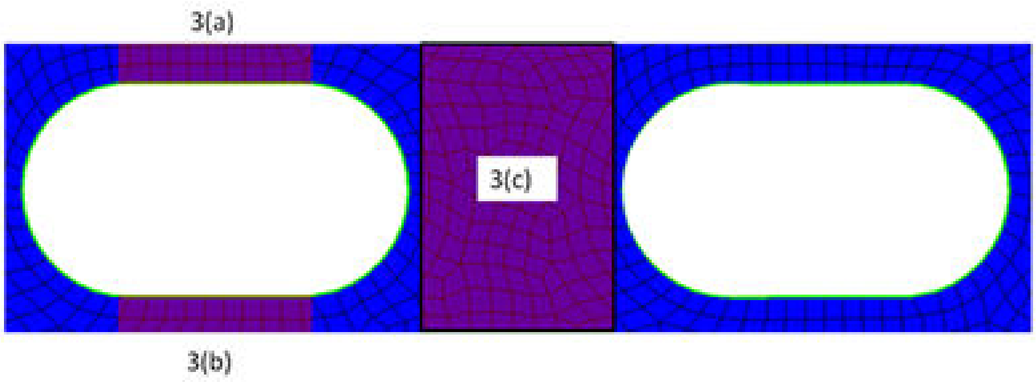
4.1.1 The stress criteria for primary structural members supporting decks are contained in *Table 5.4.1 Stress criteria*.

4.1.2 A minimum buckling factor of 1,0 against elastic buckling is to be obtained in the plated areas of decks and member webs. If the structure forms the boundary of tanks for the carriage of liquid, a corrosion deduction of 1,0 mm is to be applied for the purpose of buckling assessment.

Table 5.4.1 Stress criteria

Structural item	Loading type	Acceptance criteria			
		Average direct stress σ (*see* Note 1)	Average shear stress τ (*see* Note 1)	Average von Mises stress σ_e (*see* Note 1)	Peak element centroid stress
Deck transverse web plating	Local only	–	$0,35\sigma_o$	$0,75\sigma_o$	σ_o
Deck girder web plating	Local only	–	$0,35\sigma_o$	$0,75\sigma_o$	–
Deck transverse face plate	Local only	$0,52\sigma_o$	–	–	–
Deck girder face plate	Local only	$0,52\sigma_o$	–	–	–
Deck girder	Local + Global (*see Ch 5, 3.1 General 3.1.2*)	$0,85\sigma_L$	–	$0,95\sigma_L$	$1,2\sigma_o$

Note 1. To be averaged over the areas 3(a), (b) and (c) as illustrated in figure below for web plating. Averaging is not to be carried across structural discontinuity or abutting structure.



Contents

Section

■ *Section 1* Introduction

1.1 General

1.1.1 The method described in this Chapter may be used for the following purposes:

- to adjust the stress level when the resultant hull girder shear force and/or bending moment in the FE model deviates from required shear force and/or bending moment, *see Ch 2, 6 Acceptance criteria* and *Ch 3, 5 Acceptance criteria*.
- to separate the local stress component from a stress due to combined global hull girder and local loads, *see Ch 2, 6.3 Buckling criteria*.

■ *Section 2* Derivation of BM and SF influence factors

2.1 General

2.1.1 Under pure hull girder shear force and bending moment, the stress in an element is considered to be directly proportional to the load applied at the section under consideration.

2.1.2 The bending moment and shear force influence factors are to be derived for each element. The influence factors for a given element are obtained as follows:

$$\sigma_{x1} = C_{Mx} \cdot BM_1 + C_{Qx} \cdot SF_1$$

$$\sigma_{x2} = C_{Mx} \cdot BM_2 + C_{Qx} \cdot SF_2$$

$$\sigma_{y1} = C_{My} \cdot BM_1 + C_{Qy} \cdot SF_1$$

$$\sigma_{y2} = C_{My} \cdot BM_2 + C_{Qy} \cdot SF_2$$

$$\tau_{xy1} = C_{Mxy} \cdot BM_1 + C_{Qxy} \cdot SF_1$$

$$\tau_{xy2} = C_{Mxy} \cdot BM_2 + C_{Qxy} \cdot SF_2$$

where

C_{Mx}, C_{My}, C_{Mxy} = are the hull bending moment influence factors applying to σ_x, σ_y and τ_{xy} for the element

C_{Qx}, C_{Qy}, C_{Qxy} = are the hull shear force influence factors applying to σ_x, σ_y and τ_{xy} for the element

BM_1, SF_1 = is the bending moment and shear force resulting from the application of distributed load P_1 for load case SC3a (*see Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.3*) at the *x*-position of the centre of the element

BM_2, SF_2 = is the bending moment and shear force resulting from the application of distributed load P_2 for load case SC5 (*see Ch 2, 4.4 Procedure to apply the Rule design vertical wave bending moment and shear force 4.4.4*) at the *x*-position of the centre of the element

σ_{x1}, σ_{y1}, τ_{xy1} = are the element direct stresses and shear stress resulting from the application of distributed load P_1

σ_{x2}, σ_{y2}, τ_{xy2} = are the element direct stresses and shear stress resulting from the application of distributed load P_2

It follows that:

$$C_{\mathrm{Mx}} = \frac{(SF_1\ \sigma_{x2} - SF_2\ \sigma_{x1})}{(BM_2\ SF_1 - BM_1\ SF_2)}$$

$$C_{\mathrm{My}} = \frac{(SF_1\ \sigma_{y2} - SF_2\ \sigma_{y1})}{(BM_2\ SF_1 - BM_1\ SF_2)}$$

$$C_{\mathrm{Mxy}} = \frac{(SF_1\ \tau_{xy2} - SF_2\ \tau_{xy1})}{(BM_2\ SF_1 - BM_1\ SF_2)}$$

$$C_{\mathrm{Qx}} = \frac{(-BM_1\ \sigma_{x2} + BM_2\ \sigma_{x1})}{(BM_2\ SF_1 - BM_1\ SF_2)}$$

$$C_{\mathrm{Qy}} = \frac{(-BM_1\ \sigma_{y2} + BM_2\ \sigma_{y1})}{(BM_2\ SF_1 - BM_1\ SF_2)}$$

$$C_{\mathrm{Qxy}} = \frac{(-BM_1\ \tau_{xy2} + BM_2\ \tau_{xy1})}{(BM_2\ SF_1 - BM_1\ SF_2)}$$

■ *Section 3* Global stress adjustment

3.1 General

3.1.1 Where the resultant hull girder shear force and/or bending moment in the FE model deviates from the required shear force and/or bending moment, as required by *Ch 2, 6 Acceptance criteria* and *Ch 3, 5 Acceptance criteria*, the stresses of each finite element are to be adjusted. The adjusted stresses of an element are to be calculated as follows:

$$\sigma_x = \sigma_{x-\mathrm{FE}} + C_{\mathrm{Mx}} \cdot \Delta BM + C_{\mathrm{Qx}} \cdot \Delta Q$$

$$\sigma_y = \sigma_{y-\mathrm{FE}} + C_{\mathrm{My}} \cdot \Delta BM + C_{\mathrm{Qy}} \cdot \Delta Q$$

$$\tau_{xy} = \tau_{xy-\mathrm{FE}} + C_{\mathrm{Mxy}} \cdot \Delta BM + C_{\mathrm{Qxy}} \cdot \Delta Q$$

where

C_{Mx}, C_{My}, C_{Mxy} = are the hull bending moment influence factors for the element, *see Ch 6, 2.1 General*

C_{Qx}, C_{Qy}, C_{Qxy} = are the hull shear force influence factors for the element, *see Ch 6, 2.1 General*

$\sigma_{x\text{-FE}}$, $\sigma_{y\text{-FE}}$, $\tau_{xy\text{-FE}}$ = are the finite element direct stresses and shear stress at the centre of the element

σ_x, σ_y, τ_{xy} = are the adjusted direct stresses and shear stress at the centre of the element

ΔBM = is the difference between the required bending moment and resultant bending moment in the FE model at the longitudinal position of the element

ΔQ = is the difference between the required shear force and resultant shear force in the FE model at the longitudinal position of the element

Section 4
Local stresses

4.1 General

4.1.1 Where the local stress components are to be derived for an element, these stresses can be obtained as follows:

$$\sigma_{Local-x} = \sigma_{x-FE} - \left(C_{Mx} \cdot BM + C_{Qx} \cdot Q\right)$$

$$\sigma_{Local-y} = \sigma_{y-FE} - \left(C_{My} \cdot BM + C_{Qy} \cdot Q\right)$$

$$\tau_{Local-xy} = \tau_{xy-FE} - \left(C_{Mxy} \cdot BM + C_{Qxy} \cdot Q\right)$$

C_{Mx}, C_{My}, C_{Mxy} = are the hull bending moment influence factors for the element, *see Ch 6, 2.1 General*

C_{Qx}, C_{Qy}, C_{Qxy} = are the hull shear force influence factors for the element, *see Ch 6, 2.1 General*

$\sigma_{Local\text{-}x}$, $\sigma_{Local\text{-}y}$, $\tau_{Local\text{-}xy}$ = are the local direct stresses and shear stress at the centre of the element

$\sigma_{x\text{-}FE}$, $\sigma_{y\text{-}FE}$, $\tau_{xy\text{-}FE}$ = are the finite element direct stresses and shear stress at the centre of the element

BM = is the resultant hull girder bending moment from the FE model at the longitudinal position of the element

Q = is the resultant hull girder shear force from the FE model at the longitudinal position of the element

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