ShipRight
Design and Construction

Structural Design Assessment

Procedure for Membrane Tank LNG Ships

September 2016
<table>
<thead>
<tr>
<th>Date</th>
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</tr>
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<tr>
<td>May 2000</td>
<td>Preliminary release.</td>
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<tr>
<td>November 2001</td>
<td>Preliminary editorial revisions.</td>
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<td>July 2002</td>
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<td>July 2008</td>
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Section 1

Introduction

1.1 Introduction

1.1.1 The ShipRight Structural Design Assessment (SDA) procedure is mandatory for all Membrane Tank LNG ships.

1.1.2 The Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquefied Gases in Bulk incorporating the IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) is referred to in this document as Lloyd’s Register’s Rules for Ships for Liquefied Gases. References to the IGC Code in this procedure are equivalent to references to the Rules for Ships for Liquefied Gases.

1.1.3 For compliance with the ShipRight SDA procedure, direct calculations are to be adopted for the determination and verification of ship primary member scantlings, including the structure supporting the cargo tanks as specified in Lloyd’s Register’s Rules for Ships for Liquefied Gases.

1.1.4 The minimum requirements specified in this procedure, in addition to the requirements in Lloyd’s Register’s Rules and Regulations for the Classification of Ships (hereinafter referred to as the Rules for Ships) and Lloyd’s Register’s Rules for Ships for Liquefied Gases are to be complied with. Additional design requirements imposed by the containment system manufacturer are to be complied with.

1.1.5 The SDA procedure requires the following:

- A detailed analysis of the ship’s structural response to applied static and dynamic loadings using finite element analysis.
- An analysis to assess the strength of tank boundary structures against collapse due to the dynamic loads imposed by the sloshing of LNG in partially filled cargo tanks, see Pt 3, Ch 3.5.4 of the Rules for Ships.
- Other direct calculations as applicable.

1.1.6 This document details the SDA procedure for the finite element analysis of the ship’s hull structure. The primary structure of the ship in the cargo region, including the structure in way of the foremost bulkhead of No.1 tank, the aftmost bulkhead of the aftmost cargo tank and double bottom structure in way of the engine room, are to be verified using the procedure specified in Ch 2 Analysis of primary structure of membrane tank LNG ships. Stress level in structural components and details are to be verified using the procedure specified in Ch 4 Analysis of structural details.

1.1.7 The following areas are to be investigated either by extension of the model or by separate models:

- Scarfing arrangement at the ends of the trunk deck, see Ch 3 Analysis of trunk deck scarphing arrangements with the aft end.
- Scarfing arrangement at the ends of the longitudinal bulkheads and hopper tanks depending on the hull structural configuration, see Ch 3 Analysis of trunk deck scarphing arrangements with the aft end.

1.1.8 In general, the direct calculation is to be based on a three-dimensional finite element analysis (3-D FEA) carried out in accordance with the procedures contained in these guidance notes. Where alternative procedures are proposed, these are to be agreed with Lloyd’s Register before commencement.

1.1.9 A detailed report of the calculations is to be submitted and must include the information detailed in Ch 1, 3.1 Direct calculation procedures report 3.1.1. The report must show compliance with the specified structural design criteria given in Sections 5 and 6 of Ch 2 Analysis of primary structure of membrane tank LNG ships and Ch 3 Analysis of trunk deck scarphing arrangements with the aft end.

1.1.10 If the computer programs employed are not recognised by Lloyd’s Register, full particulars of the programs will also be required to be submitted, see Pt 3, Ch 1.5.1 of the Rules for Ships.
1.1.11 Lloyd’s Register may require the submission of computer input and output to verify further the adequacy of the calculations carried out.

1.1.12 Ships which have novel features or unusual hull structural or tank configurations may need special consideration.

1.1.13 It is recommended that the designer consult with Lloyd’s Register on the SDA analysis requirements early on in the design cycle.

IMPORTANT NOTE

The objective of this procedure is to assess the strength of the ship primary structure to withstand the design loads. The ability of the containment system to accommodate the global or local deformations of the ship structure is not considered in this procedure. Therefore, it is necessary for the designers to consider and demonstrate separately that the containment system design in terms of strength and fatigue capability can withstand the global and local deformations of the ship structure. Additional design requirements with respect to the ship structure specified by the containment system supplier are to be complied with. It is recommended that the designer consult the containment system supplier early on in the design cycle.

Section 2
Symbols

2.1 Symbols

2.1.1 The symbols used in these guidance notes are defined as follows:

- \( L \) = Rule length, as defined in Pt 3, Ch 1,6 of the Rules for Ships
- \( B \) = moulded breadth, as defined in Pt 3, Ch 1,6 of the Rules for Ships
- \( D \) = depth of ship, as defined in Pt 3, Ch 1,6 of the Rules for Ships
- \( k_L, k \) = higher tensile steel factor, see Pt 3, Ch 2,1.2 of the Rules for Ships
- \( SWBM \) = still water bending moment
- \( VWBM \) = design vertical bending moment
- \( M_W \) = design vertical bending moment, including hog and sag factor, \( f_2 \), and ship service factor, \( f_1 \), see Pt 3, Ch 4,5 of the Rules for Ships
- \( M_{WO} \) = vertical wave bending moment, excluding hog and sag factor and ship service factor, see Pt 3, Ch 4,5 of the Rules for Ships
- \( f_1 \) = the ship service factor, see Pt 3, Ch 4,5 of the Rules for Ships
- \( f_2 \) = the hogging/sagging factor, see Pt 3, Ch 4,5 of the Rules for Ships
- \( M_S \) = Rule permissible still water bending moment, see Pt 3, Ch 4,5 of the Rules for Ships
- \( M_{SW} \) = design still water bending moment, see Pt 3, Ch 4,5 of the Rules for Ships
- \( M_{SW} \) = still water bending moment distribution envelope to be applied to the FE models for stress and buckling assessments. The values of \( M_{SW} \) are to be greater than \( M_S \) but not to be less than \( 0.25 M_S \). These values are to be incorporated into the ship’s Loading Manual and loading instrument as the assigned permissible still water bending moment values. \( M_{SW} \) hereinafter referred to as the permissible still water bending moment. See also Ch 2, 4.1 Introduction 4.1.5
- \( T_{SC} \) = scantling draught
- \( T \) = condition draught
- \( \theta \) = heel angle
- \( V \) = service speed (knots)
- \( g \) = acceleration due to gravity
\( \rho = \) density of sea-water (specific gravity to be taken as 1.025)

\( h = \) local head for pressure evaluation

\( \rho_c = \) maximum cargo density at the design temperature, S.G. is not to be taken as less than 0.5

\( P_o = \) design vapour pressure, see Ch 4, Cargo Containment 4.1.2 of the Rules for Ships for Liquefied Gases

\( A_x, A_y, A_z = \) maximum dimensionless acceleration factors (i.e., relative to the acceleration of gravity) in the longitudinal, transverse and vertical directions respectively

\( h_x, h_y, h_z = \) local head for pressure evaluation measured from the tank reference point in the longitudinal, transverse and vertical directions respectively

\( t = \) thickness of plating

\( t_c = \) thickness deduction for corrosion

\( \sigma_c = \) elastic critical buckling stress

\( \sigma_o = \) specified minimum yield stress of material (special consideration will be given to steel where \( \sigma_o \geq 355 \) N/mm\(^2\), see Pt 3, Ch 2.1 of the Rules for Ships)

\( \sigma_L = \frac{235}{K_L} \) N/mm\(^2\)

\( K_L = \) as defined in Pt 3, Ch 3.2.4 of the Rules for Ships

\( \lambda = \) factor against buckling

\( \tau = \) shear stress

\( \sigma_e = \) von Mises equivalent stress given by

\[
\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2}
\]

where

\( \sigma_x = \) direct stress in element x direction

\( \sigma_y = \) direct stress in element y direction

\( \tau_{xy} = \) shear stress in element x-y plane.

2.1.2 Consistent units are to be used throughout all parts of the analysis. Results presentation in Newtons and mm preferred.

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

### Section 3

#### Direct calculation procedures report

3.1 **Direct calculation procedures report**

3.1.1 A report is to be submitted to Lloyd’s Register for approval of the primary structure of the ship and is to contain:

- list of plans used, including dates and versions;
- detailed description of structural model, including all modelling assumptions;
- plots to demonstrate correct structural modelling and assigned properties;
- details of material properties used;
- details of displacement boundary conditions;
- details of all still water and dynamic loading conditions reviewed with calculated shear force (SF) and bending moment (BM) distributions;
- details of the calculations for the waterlines used for the dynamic loading conditions;
- details of the acceleration factors for each loading condition;
• 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 structural model 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 are not exceeded in any member;
• plate 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 properties.
CHAPTER 1 INTRODUCTION

CHAPTER 2 ANALYSIS OF PRIMARY STRUCTURE OF MEMBRANE TANK LNG SHIPS

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Section 1

1.1 Objectives

1.1.1 The objective of the structural analysis is to verify that the stress level and buckling capability of primary structures under the applied static and dynamic loads are within acceptable limits.

1.1.2 The analysis and applied loading is to be sufficient to evaluate the responses of the following primary structural item within the cargo tank region, including structural members in way of the foremost bulkhead of No. 1 cargo tank, the aftmost bulkhead of the aftmost cargo tank and the double bottom structure in way of the engine room:

- Outer hull plating.
- Inner hull plating.
- Double hull transverse webs and stringers.
- Double bottom floors and girders.
- Hopper tanks transverses.
- Topside tank transverses.
- Upper and trunk deck transverses and girders.
- Transverse bulkhead plating.
- Transverse bulkhead diaphragms and stringers.

1.1.3 In addition to the stress and buckling criteria given in this procedure, design requirements imposed by the containment system manufacturer are to be complied with, see Ch 1, 1.1 Introduction 1.1.4.

IMPORTANT NOTE

The objective of this procedure is to assess the strength of the ship primary structure to withstand the design loads. The ability of the containment system to accommodate the global or local deformations of the ship structure is not considered in this procedure. Therefore it is necessary for the designers to consider and demonstrate separately that, in terms of strength and fatigue capability, the containment system design can withstand the global and local deformations of the ship structure. Additional design requirements with respect to the ship structure specified by the containment system supplier are to be complied with. It is recommended that the designer consult the containment system supplier early on in the design cycle.

Section 2

2.1 Structural Modelling

2.1.1 A 3-D finite element model of the complete ship length is to be used to assess the primary structure of the ship.
2.1.2 Unless there is asymmetry of the ship or cargo tank primary structure about the ship’s centreline, only one side of the ship needs to be modelled with appropriate boundary conditions imposed at the centreline. However, it is recommended that both sides of the ship be modelled as this will simplify the loading and analysis of the asymmetric transverse loading condition.

2.1.3 The FE model is to be represented using a righthanded 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.

2.1.4 Typical arrangements representing Membrane Tank LNG ships are shown in Figure 2.2.1 3-D FE model of a membrane tank LNG ship to Figure 2.2.3 Typical FE model of a transverse watertight bulkhead. The proposed scantlings, excluding Owner’s extras and any additional thicknesses to comply with the optional ShipRight ES Procedure, are to be used throughout the model. The selected size and type of elements are to provide a satisfactory representation of the deflection and stress distributions within the structure.

2.1.5 In general, the plate element mesh is to follow the primary stiffening arrangement for both the structure of the ship and cargo tanks. The minimum mesh size requirements are:

- transversely, one element between every longitudinal stiffener;
- longitudinally, three or more elements between web frames;
- vertically, one element between every stiffener; and
- three or more elements over the depth of double bottom girders, floors, side transverses, the vertical webs and horizontal stringers of transverse cofferdam bulkheads and trunk deck.

2.1.6 In areas in way of transverse bulkhead to inner bottom, inner trunk deck and inner side structure connections as described in Ch 4, 2.1 Structural modelling 2.1.2, the element size should not exceed longitudinal spacing transversely and vertically and 600 mm longitudinally.

2.1.7 The bow and the stern of the ship are to be modelled, but it is not necessary to include all the structure within the bow region forward of the collision bulkhead and stern region aft of the aft peak bulkhead. It is sufficient to model most longitudinal plating, stringers and continuous stiffeners, together with sufficient transverse structure to support the modelled longitudinal material.

2.1.8 Secondary stiffening members are to be modelled using line elements positioned in the plane of the plating having axial and bending properties (bars). The bar elements are to have:

- a cross-sectional area representing the stiffener area, excluding the area of attached plating; and
- bending properties representing the combined plating and stiffener inertia.

2.1.9 Face plates and plate panel stiffeners of primary members are to be represented by line elements (rods or bars) with the cross-sectional area modified where appropriate, in accordance with Table 2.2.1 Line element effective cross-section area and Figure 2.2.4 Effective area of face bars.

2.1.10 In general, the use of triangular plate elements is to be kept to a 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.

2.1.11 Dome openings, access openings, lightening holes, etc., in primary structure are to be represented in areas of interest, e.g., in floor plates adjacent to the hopper knuckle, trunk decks, girders at their ends, etc. 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.

2.1.12 Lightening holes, access openings, etc., away from the locations referred to in Ch 2, 2.1 Structural Modelling 2.1.11 may be modelled by deleting the appropriate elements or by applying a correction factor to the resulting shear stresses, see Ch 2, 5 Permissible stresses.

2.1.13 The cargo tank membrane and insulation need not be included in the model as their contribution to hull strength is negligible.

2.1.14 The light mass of the ship is to be represented in the model. The weight and inertia forces of the ship’s engine and other heavy items should be correctly transferred to the supporting structure.
Analysis of primary structure of membrane tank LNG ships

Figure 2.2.1 3-D FE model of a membrane tank LNG ship
Figure 2.2.2 Typical FE model of a transverse web frame
Figure 2.2.3 Typical FE model of a transverse watertight bulkhead
Analysis of primary structure of membrane tank LNG ships

Figure 2.2.4 Effective area of face bars
<table>
<thead>
<tr>
<th>Structure represented by element</th>
<th>Symmetrical</th>
<th>Asymmetrical</th>
<th>Effective area, $A_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary member face bars</td>
<td></td>
<td></td>
<td>$A_e = 100% A_n$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_e = 100% A_n$</td>
</tr>
<tr>
<td>Curved bracket face bars (continuous)</td>
<td>Symmetrical</td>
<td></td>
<td>From Figure 2.2.4 Effective area of face bars</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_e = 100% A_n$</td>
</tr>
<tr>
<td>Straight bracket face bars (discontinuous)</td>
<td>Symmetrical</td>
<td></td>
<td>$A_e = 60% A_n$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A_e = 60% A_n$</td>
</tr>
<tr>
<td>Straight bracket face bars (continuous around toe curvature)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Straight portion</td>
<td>Symmetrical</td>
<td></td>
<td>$A_e = 100% A_n$</td>
</tr>
<tr>
<td></td>
<td>Asymmetrical</td>
<td></td>
<td>$A_e = 60% A_n$</td>
</tr>
<tr>
<td>Curved portion</td>
<td>Symmetrical</td>
<td></td>
<td>From Figure 2.2.4 Effective area of face bars</td>
</tr>
<tr>
<td></td>
<td>Asymmetrical</td>
<td></td>
<td>$A_e = 60% A_n$</td>
</tr>
<tr>
<td>Web stiffeners – Sniped both ends, connected other end</td>
<td>Flat bars</td>
<td></td>
<td>$A_e = 25%$ stiffener area</td>
</tr>
<tr>
<td></td>
<td>Other sections</td>
<td></td>
<td>$A_e = \frac{A}{1 + \left(\frac{Y_o}{r}\right)^2} - A_p$</td>
</tr>
<tr>
<td>Web stiffeners – Sniped one end,</td>
<td>Flat bars</td>
<td></td>
<td>$A_e = 75%$ stiffener area</td>
</tr>
<tr>
<td></td>
<td>Other sections</td>
<td></td>
<td>$A_e = \frac{A}{1 + \left(\frac{Y_o}{r}\right)^2} - A_p$</td>
</tr>
</tbody>
</table>

Symbols:

(Consistent units to be used throughout)

- $A$ = cross-section area of stiffener and associated plating
- $A_n$ = average face bar area over length of line element
- $A_p$ = cross-section area of associated plating
- $I$ = moment of inertia of stiffener and associated plating
- $Y_o$ = moment of inertia of stiffener and associated plating
- $r$ = radius of gyration
- $r = \sqrt[\frac{I}{A}]$
Section 3

Boundary conditions

3.1 Introduction

3.1.1 The boundary conditions to be applied to the FE model are dependent on the load case to be analysed. Different boundary conditions need to be applied for symmetric, asymmetric and anti-symmetric load cases.

3.1.2 The boundary conditions described in this Section include the different requirements for full-breadth and half-breadth FE ship models for the upright load cases and the requirements for a full-breadth model for the transverse load cases. It is recommended that a full-breadth model is used for the transverse static and dynamic load cases as this simplifies the loading, boundary conditions and results post processing. However, if a half-breadth model is used for these transverse load cases, guidance on suitable boundary conditions is given in Ch 5 Appendix A: Alternative procedure for transverse load cases (half-breadth FE model).

3.1.3 The boundary conditions suitable for each load case are shown in Table 2.3.1 Boundary conditions for full ship model.

### Table 2.3.1 Boundary conditions for full ship model

<table>
<thead>
<tr>
<th>Load case</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave load cases, see Ch 2, 4.2 Wave load cases:</td>
<td>See Ch 2, 3.2 Symmetrical boundary conditions for global loads</td>
</tr>
<tr>
<td>• Bending moment sub-load cases</td>
<td>and Figure 2.3.1 Boundary conditions for the application of symmetric global loads</td>
</tr>
<tr>
<td>• Wave crest/trough sub-load cases</td>
<td>See Ch 2, 3.3 Symmetrical boundary conditions for local loads and</td>
</tr>
<tr>
<td></td>
<td>Figure 2.3.2 Boundary conditions for the application of symmetric local loads</td>
</tr>
<tr>
<td>Vertical dynamic load cases, see Ch 2, 4.3 Vertical dynamic</td>
<td>See Ch 2, 3.2 Symmetrical boundary conditions for global loads</td>
</tr>
<tr>
<td>load cases</td>
<td>and Figure 2.3.1 Boundary conditions for the application of symmetric global loads</td>
</tr>
<tr>
<td>Static heel load cases, see Ch 2, 4.4 Static heel load cases</td>
<td>See Ch 2, 3.4 Asymmetric boundary conditions for transverse loads, inertial relief</td>
</tr>
<tr>
<td></td>
<td>solution is recommended or alternative boundary conditions given in Figure 2.3.3</td>
</tr>
<tr>
<td></td>
<td>Alternative boundary conditions for transverse cases for a full-breadth model if</td>
</tr>
<tr>
<td></td>
<td>an inertial relief solution cannot be applied</td>
</tr>
<tr>
<td>Transverse dynamic load cases, see Ch 2, 4.5 Transverse</td>
<td>See Ch 2, 3.4 Asymmetric boundary conditions for transverse loads, inertial relief</td>
</tr>
<tr>
<td>load cases</td>
<td>solution is recommended or alternative boundary conditions given in Figure 2.3.3</td>
</tr>
<tr>
<td></td>
<td>Alternative boundary conditions for transverse cases for a full-breadth model if</td>
</tr>
<tr>
<td></td>
<td>an inertial relief solution cannot be applied</td>
</tr>
<tr>
<td>Collision load cases, see Ch 2, 4.6 Collision load cases</td>
<td>See Figure 2.3.1 Boundary conditions for the application of symmetric global loads</td>
</tr>
</tbody>
</table>

3.2 Symmetrical boundary conditions for global loads

3.2.1 Symmetric boundary conditions suitable for the analysis of global loads are shown in Figure 2.3.1 Boundary conditions for the application of symmetric global loads. These boundary conditions allow the FE model to deflect globally under the action of hull girder vertical shear forces and bending moments.

3.3 Symmetrical boundary conditions for local loads

3.3.1 Symmetric boundary conditions suitable for the analysis of local loads are shown in Figure 2.3.2 Boundary conditions for the application of symmetric local loads. Vertical grounded springs are to be distributed to nodes of the elements in the side shell in way of the transverse bulkheads. Where a double cofferdam bulkhead is fitted, the ground springs may be distributed only to
the watertight bulkhead. The distribution may be in proportion to the projected vertical cross-sectional area of the elements. The spring stiffness, $k_s$, may be obtained as:

$$k_s = G \cdot \frac{A}{l}$$

where

$G$ = modulus of rigidity

$l$ = distance between transverse bulkheads

$A$ = projected vertical cross-sectional area of the element in the side shell

3.3.2 These boundary conditions remove the effects of hull girder bending from the FE model and are therefore only suitable for calculating stresses resulting from local loads.

3.4 Asymmetric boundary conditions for transverse loads

3.4.1 For a full-breadth model, it is recommended that an inertial relief solution be used for removing rigid body motion for these cases. 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. The feature of this solution sequence is that any out-of-balance loads are reacted by inertial forces acting on the mass elements of the model; the reference points are only reference values and hence no inappropriate stress and deflections are generated at these positions. However, if the FE package being used does not provide this facility then alternative boundary conditions given in Figure 2.3.3 Alternative boundary conditions for transverse cases for a full-breadth model if an inertial relief solution cannot be applied may be used.

3.4.2 For a half-breadth model, two load cases need to be considered where the symmetric and anti-symmetric load components are applied separately. These separated load components are then applied to the FE model with symmetric and anti-symmetric boundary conditions respectively. See Ch 5 Appendix A: Alternative procedure for transverse load cases (half-breadth FE model).

![Figure 2.3.1 Boundary conditions for the application of symmetric global loads](image-url)
Figure 2.3.2 Boundary conditions for the application of symmetric local loads

NOTE:
Vertical grounded springs are to be distributed to nodes of the elements in the side shell in way of the transverse bulkheads. Where a double cofferdam bulkhead is fitted, the ground springs may be distributed only to the watertight bulkhead. See 3.3.1.
Section 4
Loading condition

4.1 Introduction
4.1.1 This Section specifies the standard load cases which are to be considered in the stress and buckling assessments. These include load components arising from static and dynamic effects.

4.1.2 Some of the standard load cases in this Section may not need to be examined if the ship is not to operate in such loading conditions. In this case, a note is to be included in the Loading Manual stating that these loading conditions are not permitted. The load cases to be analysed should be discussed and agreed with Lloyd’s Register at the earliest opportunity.

4.1.3 Additional load cases may need to be examined if the ship is in an unusual configuration or is to be operated in conditions which would give rise to higher stresses. If the ship’s Loading Manual contains conditions in which ballast tanks in way of empty cargo tanks are empty or have reduced filling level, then these conditions are to be analysed. If only conditions in which full ballast tanks in way of empty cargo tanks are analysed, the ship’s Loading Manual is to state clearly that, if the fill level of a cargo tank is less than or equal to its lower filling limit in a sea-going condition, the double bottom ballast tanks in way are to be at least 95 per cent filled.

4.1.4 The fully loaded conditions are defined on the basis that the ship’s scantling draught is not significantly different from the operating draught. If this is not so, then special consideration will be given.

4.1.5 The assigned permissible still water bending moment, $M_{SW}$, to be used in the analysis may be less than the Rule permissible still water bending moments, $M_S$, determined in accordance with Pt 3, Ch 4.5.5 of the Rules for Ships. However, $M_{SW}$ is not to be taken as less than 0.25 times $M_S$. The values of $M_{SW}$ used in the analysis are to be incorporated into the ship’s Loading Manual and loading instrument as the assigned permissible still water bending moment values.
4.1.6 A ship’s loading conditions with a full load of consumables are to be considered for the analysis.

4.1.7 Unless required for contractual reasons, this SDA procedure does not require the ship’s Loading Manual to contain loading conditions using the minimum cargo s.g. of 0.5. The relevant parameters for the determination of acceleration components, i.e., condition draught, $C_b$ and $GM$ may be obtained from the review of the loading conditions presented in the Loading Manual. However, the FE analysis is to be carried out using a minimum value of cargo s.g. of 0.5.

4.2 Wave load cases

4.2.1 The wave load cases to be analysed are specified in Table 2.4.1 Wave load cases. Each wave load case consists of two sub-load cases: bending moment sub-load case and local wave crest/trough sub-load case.

4.2.2 The bending moment sub-load cases are based on the ship’s operating loading conditions specified in Table 2.4.1 Wave load cases and include all static load components. The Rule design vertical wave bending moment and the permissible vertical still water bending moment envelope, $M_{SW}$ (see Ch 2, 4.1 Introduction 4.1.5 and Ch 1, 2 Symbols), are to be applied. Explanatory notes for the application of the vertical bending moments are given in Ch 2, 4.10 Application of assigned permissible still water and design vertical wave bending moment envelope. All deadweight and lightweight items are to be applied. The ship is balanced on a trimmed waterline.

4.2.3 For the local wave crest/trough sub-load cases, external pressure due to a local wave crest or wave trough is applied to the model, see Ch 2, 4.11 Procedure to apply local wave crest or trough. The model is balanced by vertical grounded springs distributed to the grid points on the side shell in way of the transverse bulkheads; the procedure is described in Ch 2, 3.3 Symmetrical boundary conditions for local loads. No other loads are to be applied.

4.2.4 Load case S1.1, full load hogging bending moment, in Table 2.4.1 Wave load cases may be omitted if alternate load cases, S2.1 and S3.1, are analysed.

4.2.5 If the sagging still water bending moment, $M_{SW}$, is greater than 60 per cent of the Rule permissible still water bending moment, $M_S$, in addition to load cases S2.1 and S3.1, Alternate load 1 and Alternate load 2 conditions in Table 2.4.1 Wave load cases are to be investigated with the application of sagging still water bending moment, $M_{SW}$, and sagging vertical wave bending moment, $M_W$, in a wave trough.

4.2.6 The ballast load case, S4, may be omitted, provided that:
- Load cases S2.1 and S3.1 are analysed.
- Ship’s draught in the ballast condition does not exceed the draught(s) used in the analysis of load cases S2.1 and S3.1.
- Ballast is carried in double bottom tanks, tanks in the double skin and in fore and aft peak tanks only.

4.2.7 Where the ship’s Loading Manual consists of loading conditions where the double bottom tanks in way of a loaded cargo tank are filled, additional wave trough load cases for these loading conditions are to be considered in conjunction with the application of the sagging still water bending moment, $M_{SW}$, and sagging vertical wave bending moment, $M_W$.

### Table 2.4.1 Wave load cases

<table>
<thead>
<tr>
<th>Load case</th>
<th>Bending moment sub-load case</th>
<th>Wave crest/trough sub-load case</th>
<th>Tank loading pattern</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWBM</td>
<td>VVBM</td>
<td>External Pressure</td>
<td>Internal Pressure</td>
</tr>
<tr>
<td>Full load</td>
<td>S1.1</td>
<td>See 9,10</td>
<td>$M_{SW}$ Hog</td>
<td>$M_W$ Hog</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
## Analysis of primary structure of membrane tank LNG ships

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Symbol</th>
<th>Condition</th>
<th>Boundary Conditions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
<td>S1.2</td>
<td>$M_{SW}$</td>
<td>Balanced WL</td>
<td>See Table 2.4.6, Tank loading pattern, 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_{W}$</td>
<td>Vertical springs</td>
<td>See Ch 2, 3.2 Symmetrical boundary conditions for local loads and Figure 2.3.1</td>
</tr>
<tr>
<td>Alternate 1</td>
<td>S2.1</td>
<td>$M_{SW}$</td>
<td>Balanced WL</td>
<td>See Table 2.4.6, Tank loading pattern, 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_{W}$</td>
<td>Vertical springs</td>
<td>See Ch 2, 3.3 Symmetrical boundary conditions for local loads and Figure 2.3.2</td>
</tr>
<tr>
<td>Alternate 2</td>
<td>S3.1</td>
<td>$M_{SW}$</td>
<td>Balanced WL</td>
<td>See Table 2.4.6, Tank loading pattern, 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_{W}$</td>
<td>Vertical springs</td>
<td>See Ch 2, 3.3 Symmetrical boundary conditions for local loads and Figure 2.3.2</td>
</tr>
<tr>
<td>Ballast</td>
<td>S4</td>
<td>$M_{SW}$</td>
<td>Balanced WL</td>
<td>See Table 2.4.6, Tank loading pattern, 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_{W}$</td>
<td>Vertical springs</td>
<td>See Ch 2, 3.3 Symmetrical boundary conditions for local loads and Figure 2.3.2</td>
</tr>
</tbody>
</table>

**NOTES**

1. The Rule design vertical wave bending moment and the permissible vertical still water bending moment envelope, $M_{SW}$, are to be applied to bending moment sub-load cases, see Ch 1, 2.1 Symbols 2.1.1 and Ch 2, 4.1 Introduction 4.1.5 for definition of $M_{SW}$. 

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**SDA Procedure for Membrane Tank LNG Ships**

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2. All lightweight and deadweight items are to be applied in bending moment sub-load cases.

3. External pressure is applied to the wave crest and wave trough sub-load cases. No lightweight, deadweight and other load items are to be applied. See Ch 2, 4.2 Wave load cases 4.2.3 and Ch 2, 4.11 Procedure to apply local wave crest or trough for the application of wave crest and wave trough. See Ch 2, 3.3 Symmetrical boundary conditions for local loads for the application of vertical ground springs and vertical balance forces.

4. Bending moment sub-load case and wave crest/trough sub-load case are run separately. The resultant stresses are to be combined by superimposition.

5. Alternately loaded condition with odd number tanks full and even number tanks empty. Figure shown is a ship with four cargo tanks.

6. Alternately loaded condition with even number tanks full and odd number tanks empty. Figure shown is a ship with four cargo tanks.

7. Full ballast tanks are shown in way of empty cargo tanks. If the ship’s Loading Manual contains conditions in which ballast tanks in way of empty cargo tanks are empty or have reduced filling level, then these conditions are to be analysed. If only conditions in which full ballast tanks in way of empty cargo tanks are analysed, the ship’s Loading Manual is to state clearly that, if the fill level of a cargo tank is less than or equal to its lower filling limit in a sea-going condition, the double bottom ballast tanks in way are to be at least 95 per cent filled. See also Ch 2, 4.1 Introduction 4.1.3 and Ch 2, 4.2 Wave load cases 4.2.7.

8. Ballast condition to be analysed without consideration of residual cargo below the lower fill limit.

9. If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, then load case S1.1 is to be analysed. Otherwise, this load case may be omitted. See Ch 2, 4.2 Wave load cases 4.2.4.

10. Loadcase S1.1, full load hogging bending moment, in Table 2.4.1 Wave load cases may be omitted if alternate load loadcases, S2.1 and S3.1, are analysed, see Ch 2, 4.2 Wave load cases 4.2.4.

11. Ballast load case, S4, may be omitted if the conditions specified in Ch 2, 4.2 Wave load cases 4.2.6 are satisfied.

12. If the sagging still water bending moment, \( M_{SW} \), is greater than 60% of the Rule permissible still water bending moment, \( M_{SW}^P \), in addition to load cases S2.1 and S3.1, Alternate load 1 and Alternate load 2 conditions are to be investigated with the application of sagging still water bending moment, \( M_{SW} \), and sagging vertical wave bending moment, \( M_W \), in a wave trough. See Ch 2, 4.2 Wave load cases 4.2.5.

4.3 Vertical dynamic load cases

4.3.1 The following loads are to be applied to the FE model:

- External hydrostatic pressures due to the quasi-static trimmed waterline.
- Cargo pressure loads acting on the cargo tank structure. These loads are to include design cargo vapour pressure, static pressure and dynamic pressure due to vertical and longitudinal accelerations.
- Inertia forces of lightship mass and other major deadweight items, see Ch 2, 4.3 Vertical dynamic load cases 4.3.5, are to include vertical and longitudinal acceleration factors.
- Rule design vertical wave bending moment distribution.
- Permissible vertical still water bending moment envelope, \( M_{SW}^P \), see Ch 2, 4.1 Introduction 4.1.5 and Ch 1, 2 Symbols.

Explanatory notes for the application of these load components are given in Ch 2, 4.7 Application of loads and Ch 2, 4.10 Application of assigned permissible still water and design vertical wave bending moment envelope.

4.3.2 The vertical dynamic load cases to be analysed are specified in Table 2.4.2 Vertical dynamic load cases.

4.3.3 For the vertical dynamic load cases, two quasi-dynamic conditions are to be considered:

(a) Bow pitched down, which loading condition reflects the ship at:

- maximum downward heave;
- maximum bow down pitch and hence deep draught forward; and
- maximum downwards inertial load due to acceleration over the forward end.

(b) Bow pitched up, which loading condition reflects the ship at:

- maximum downward heave;
- maximum bow up pitch and hence deep draught aft; and
- maximum downwards inertial load due to acceleration over the aft end.

4.3.4 The longitudinal and vertical acceleration factors are to be calculated as described in Ch 2, 4.8 Calculation on acceleration factors.

4.3.5 The longitudinal and vertical acceleration factors to be applied to a particular cargo tank for a given loading condition in Table 2.4.2 Vertical dynamic load cases are to be taken as the maximum acceleration factors for that cargo tank from the loading...
conditions in the ship’s Loading Manual with the same loading pattern. Attention is to be paid to ensuring that the correct maximum vertical accelerations are used for bow pitched up and bow pitched down cases. See Ch 2, 4.8 Calculation on acceleration factors 4.8.3.

4.3.6 The acceleration factors to be applied to other large volume tanks, such as ballast tanks and fuel oil tanks, are to be determined in a similar manner as given in Ch 2, 4.3 Vertical dynamic load cases 4.3.4 and Ch 2, 4.3 Vertical dynamic load cases 4.3.5. However, the loading conditions considered may be limited to those used to determine the cargo tank acceleration factors. When calculating the acceleration factors for particular tank, the centre of gravity of that tank is to be used. It is not necessary to apply acceleration factors to small tanks such as fresh-water tanks, daily-use tanks, lubrication oil tanks, etc.

4.3.7 Longitudinal and vertical acceleration factors are also to be applied to the ship light mass. To simplify the application of these acceleration factors, large equipment items should be represented as mass elements. If the FE package being used does not support the application of varying acceleration values, alternative methods should be discussed with the local Lloyd’s Register Office.

4.3.8 These load cases are to be evaluated using quasi-static techniques. The derived values of vertical acceleration are applied to all deadweight and lightweight items and the resulting dynamic condition is balanced on a trimmed waterline. The effect of longitudinal acceleration may be ignored in the determination of the balanced trimmed waterline.

**Table 2.4.2 Vertical dynamic load cases**

<table>
<thead>
<tr>
<th>Load case</th>
<th>SWBM</th>
<th>WBM</th>
<th>Draught</th>
<th>External pressure</th>
<th>Internal pressure</th>
<th>Tank loading pattern</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
<td>V1.1</td>
<td>Mₗ₉W</td>
<td>Mₗ₉</td>
<td>Vertically balanced quasi-static trimmed draught</td>
<td>Hydrostatic pressure due to quasi-static trimmed waterline</td>
<td>(1 + A₁) g, Aₓ g, P₀</td>
<td>See Table 2.4.6 Tank loading pattern, 1</td>
</tr>
<tr>
<td></td>
<td>V1.2</td>
<td>Mₗ₉W</td>
<td>Mₗ₉</td>
<td>Vertically balanced quasi-static trimmed draught</td>
<td>Hydrostatic pressure due to quasi-static trimmed waterline</td>
<td>(1 + A₁) g, Aₓ g, P₀</td>
<td>See Table 2.4.6 Tank loading pattern, 1</td>
</tr>
<tr>
<td>Alternate 1, see 6</td>
<td>V2.1</td>
<td>Mₗ₉W</td>
<td>Mₗ₉</td>
<td>Vertically balanced quasi-static trimmed draught</td>
<td>Hydrostatic pressure due to quasi-static trimmed waterline</td>
<td>(1 + A₁) g, Aₓ g, P₀</td>
<td>See Table 2.4.6 Tank loading pattern, 3</td>
</tr>
<tr>
<td></td>
<td>V2.2</td>
<td>Mₗ₉W</td>
<td>Mₗ₉</td>
<td>Vertically balanced quasi-static trimmed draught</td>
<td>Hydrostatic pressure due to quasi-static trimmed waterline</td>
<td>(1 + A₁) g, Aₓ g, P₀</td>
<td>See Table 2.4.6 Tank loading pattern, 3</td>
</tr>
</tbody>
</table>
### Table 2.4.3 Static heel load cases

<table>
<thead>
<tr>
<th>Load case</th>
<th>SWBM</th>
<th>WWBM</th>
<th>Draught</th>
<th>External pressure</th>
<th>Internal pressure</th>
<th>Tank loading pattern</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternate 1, see 6, 7</td>
<td>SH-1 see 4</td>
<td>Note 2</td>
<td>Note 2</td>
<td>Heeled/trimmed waterline, see 1</td>
<td>Hydrostatic pressure due to heel angle of 30°</td>
<td>( g (I) P_{o} )</td>
<td>See Table 2.4.6 Tank loading pattern, 3</td>
</tr>
<tr>
<td>Alternate 2, see 6, 7</td>
<td>SH-2 see 5</td>
<td>Note 2</td>
<td>Note 2</td>
<td>Heeled/trimmed waterline, see 1</td>
<td>Hydrostatic pressure due to heel angle of 30°</td>
<td>( g (I) P_{o} )</td>
<td>See Table 2.4.6 Tank loading pattern, 4</td>
</tr>
</tbody>
</table>

**NOTES**

1. The Rule design vertical wave bending moment and the permissible vertical still water bending moment envelope, \( M_{SW} \), are to be applied, see Ch 1, 2.1 Symbols 2.1.1 and Ch 2, 4.1 Introduction 4.1.5 for definition of \( M_{SW} \).

2. All LNG cargo is to include vertical and longitudinal accelerations. All lightweight and deadweight items, other than LNG cargo, are to include vertical acceleration factor.

3. Vertical and longitudinal acceleration factors of a tank are to be taken as the maximum acceleration factors for that tank from all loading conditions in the ship’s Loading Manual with all cargo tanks filled.

4. Vertical and longitudinal acceleration factors of a tank are to be taken as the maximum acceleration factors for that tank from all loaded conditions in the ship’s Loading Manual with odd number tank(s) full and even number tanks empty. Figure shown is a ship with four cargo tanks.

5. Vertical and longitudinal acceleration factors of a tank are to be taken as the maximum acceleration factors for that tank from all loaded conditions in the ship’s Loading Manual with even number tank(s) full and odd number tanks empty. Figure shown is a ship with four cargo tanks.

6. Full ballast tanks are shown in way of empty cargo tanks. If the ship’s loading manual contains conditions in which ballast tanks in way of empty cargo tanks are empty or have reduced filling level, then these conditions are to be analysed. If only conditions in which full ballast tanks in way of empty cargo tanks are analysed, the ship’s Loading Manual is to state clearly that, if the fill level of a cargo tank is less than or equal to its lower filling limit in a sea-going condition, the double bottom ballast tanks in way are to be at least 95 per cent filled. See also Ch 2, 4.1 Introduction 4.1.3 and Ch 2, 4.2 Wave load cases 4.2.7.
1. The ship is to be heeled at an angle of 30° and balanced vertically on a trimmed waterline. Internal and external loads are to be calculated based on the heeled/trimmed condition. All lightweight items are to be included.

2. No additional vertical bending moment is required to be applied to the FE model, i.e., the vertical bending moment in the model is equal to the still water bending moment generated by the loads when the model is heeled. However, if the actual hull girder bending moment achieved in the model exceeds $M_{SW} + 0.6M_W$, then correcting the bending moment in the model to $M_{SW} + 0.6M_W$ is permitted.

3. Static tank pressure due to 30° heel condition is to be applied for the cargo tanks.

4. Alternately loaded condition with odd number tanks full and even number tanks empty. Figure shown is a ship with four cargo tanks.

5. Alternately loaded condition with even number tanks full and odd number tanks empty. Figure shown is a ship with four cargo tanks.

6. Full ballast tanks are shown in way of empty cargo tanks. If the ship’s Loading Manual contains conditions in which ballast tanks in way of empty cargo tanks are empty or have reduced filling level, then these conditions are to be analysed. If only conditions in which full ballast tanks in way of empty cargo tanks are analysed, the ship’s Loading Manual is to state clearly that, if the fill level of a cargo tank is less than or equal to its lower filling limit in a sea-going condition, the double bottom ballast tanks in way are to be at least 95 per cent filled. See also Ch 2, 4.1 Introduction 4.1.3 and Ch 2, 4.2 Wave load cases 4.2.7.

7. If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, a full load condition can be used for the analysis.

**Table 2.4.4 Transverse dynamic load cases**

<table>
<thead>
<tr>
<th>Load case</th>
<th>SWBM</th>
<th>VWBM</th>
<th>Draught</th>
<th>External pressure</th>
<th>Internal pressure</th>
<th>Tank loading pattern</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternate 1, see 8, 11, 12</td>
<td>T1-P1, see 1</td>
<td>See 7</td>
<td>See 7</td>
<td>Heeled/ trimmed waterline, see 5</td>
<td>$a_0$, $a_1$, $a_2$, $g$, $P_o$, see Ch 2, 4.7 Application of loads 4.7.3 and Notes 4, 6, 10</td>
<td>See Table 2.4.6 Tank loading pattern, 3</td>
<td>An inertia relief solution is recommended. If the FE package being used does not provide this facility then alternative boundary conditions given in Figure 2.3.3 Alternative boundary conditions for transverse cases for a full-breadth model if an inertial relief solution cannot be applied may be used. See Ch 2, 3.4 Asymmetric boundary conditions for transverse loads</td>
</tr>
<tr>
<td></td>
<td>T1-P2, see 3</td>
<td>See 7</td>
<td>See 7</td>
<td>Hydrostatic pressure under heeled/ trimmed condition, see 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1-P3, see 3</td>
<td>See 7</td>
<td>See 7</td>
<td>Hydrostatic pressure under heeled/ trimmed condition, see 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternate 2, see 9, 11, 12</td>
<td>T2-P1, see 1</td>
<td>See 7</td>
<td>See 7</td>
<td>Heeled/ trimmed waterline, see 5</td>
<td>$a_0$, $a_1$, $a_2$, $g$, $P_o$, see Ch 2, 4.7 Application of loads 4.7.3 and Notes 4, 6, 10</td>
<td>See Table 2.4.6 Tank loading pattern, 4</td>
<td>An inertia relief solution is recommended. If the FE package being used does not provide this facility then alternative boundary conditions given in Figure 2.3.3 Alternative boundary conditions for transverse cases for a full-breadth model if an inertial relief solution cannot be applied may be used. See Ch 2, 3.4 Asymmetric boundary conditions for transverse loads</td>
</tr>
</tbody>
</table>
NOTES

1. Dynamic condition P1: maximum pressure at the corners A or D of cargo tank, see Ch 2, 4.5 Transverse dynamic load cases 4.5.8 and Figure 2.4.3 Definition of corner points of tank A through F. See also Note 4.

2. Dynamic condition P2: maximum pressure at the corners B or E of cargo tank, see Ch 2, 4.5 Transverse dynamic load cases 4.5.8 and Figure 2.4.3 Definition of corner points of tank A through F. See also Note 4.

3. Dynamic condition P3: maximum pressure at the corners C or F of cargo tank, see Ch 2, 4.5 Transverse dynamic load cases 4.5.8 and Figure 2.4.3 Definition of corner points of tank A through F. See also Note 4.

4. The combination of longitudinal, transverse and vertical acceleration components is to be in accordance with the acceleration ellipsoid concept, see Figure 2.4.2 Acceleration ellipsoid.

5. The ship is to be heeled at the required angle specified in Ch 2, 4.5 Transverse dynamic load cases 4.5.11 and balanced vertically on a trimmed waterline. External pressure applied to the FE model is to be based on the hydrostatic pressure due to the heeled and trimmed waterline.

6. All lightweight and deadweight items are to be applied and to include acceleration factors. In general, the acceleration vectors $a_x$, $a_y$ and $a_z$ applied to each cargo tank are different, to maximise the tank pressure at the tank boundary, see Ch 2, 4.7 Application of loads 4.7.3. An average acceleration factor, $a_{average}$, may be applied to lightship mass and deadweight items other than for the contents in cargo tanks, see Ch 2, 4.5 Transverse dynamic load cases 4.5.12.

7. The analysis may be based on the actual bending moment generated by the applied loads. No additional hull girder bending moment is to be applied. If, however, the actual bending moment exceeds $M_{SW} + 0.6M_{W}$, then correcting the bending moment in the model to $M_{SW} + 0.6M_{W}$ is permitted.

8. Alternate loaded condition with odd number tanks full and even number tanks empty. Figure shown is a ship with four cargo tanks.

9. Alternate loaded condition with even number tanks full and odd number tanks empty. Figure shown is a ship with four cargo tanks.

10. Single cargo tank conditions are to be considered to determine the maximum transverse acceleration for each tank unless it is specifically stated in the ship’s Loading Manual that single tank loading conditions are prohibited.

11. Full ballast tanks are shown in way of empty cargo tanks. If the ship’s Loading Manual contains conditions in which ballast tanks in way of empty cargo tanks are empty or have reduced filling level, then these conditions are to be analysed. If only conditions in which full ballast tanks in way of empty cargo tanks are analysed, the ship’s Loading Manual is to state clearly that, if the fill level of a cargo tank is less than or equal to its lower filling limit in a sea-going condition, the double bottom ballast tanks in way are to be at least 95 per cent filled. See also Ch 2, 4.1 Introduction 4.1.3 and Ch 2, 4.2 Wave load cases 4.2.7.

12. If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, a full load condition can be used for the analysis.

### Table 2.4.5 Collision load cases

<table>
<thead>
<tr>
<th>Load case</th>
<th>SWBM</th>
<th>WWBM</th>
<th>Draft</th>
<th>External pressure</th>
<th>Internal pressure</th>
<th>Tank loading pattern</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>Actual see 4, 6</td>
<td>—</td>
<td>Balanced waterline</td>
<td>Hydrostatic pressure due to balanced waterline</td>
<td>$a_x = 0.5g$ $a_z = g, P_o$</td>
<td>See Table 2.4.6 Tank loading pattern, 3</td>
<td>See Ch 2, 3.2 Symmetrical boundary conditions for global loads and Figure 2.3.1 Boundary conditions for the application of symmetric global loads</td>
</tr>
<tr>
<td>O2</td>
<td>Actual see 3</td>
<td></td>
<td>Balanced waterline</td>
<td>Hydrostatic pressure due to balanced waterline</td>
<td>$a_x = 0.5g$ $a_z = g, P_o$</td>
<td>See Table 2.4.6 Tank loading pattern, 4</td>
<td>See Ch 2, 3.2 Symmetrical boundary conditions for global loads and Figure 2.3.1 Boundary conditions for the application of symmetric global loads</td>
</tr>
</tbody>
</table>

NOTES
1. Forward longitudinal acceleration of 0.5g is to be applied to the lightship mass and cargo in tanks.

2. Vertical downward acceleration of 1g is to be applied to all lightweight and deadweight items.

3. The analysis is based on the actual bending moment generated by the applied loads. No additional hull girder bending moment is to be applied.

4. Alternately loaded condition with odd number tanks full and even number tanks empty. Figure shown is a ship with four cargo tanks.

5. Alternately loaded condition with even number tanks full and odd number tanks empty. Figure shown is a ship with four cargo tanks.

6. If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, a full load condition can be used for the analysis.

Table 2.4.6 Tank loading pattern

<p>| | | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

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Chapter 2

Section 4
4.4 Static heel load cases

4.4.1 The static heel load cases to be analysed are specified in Table 2.4.3 Static heel load cases. These load cases are for the compliance of ICG Code requirement that tank structures are to be able to sustain a 30° static heel condition. The analysis is to be carried out based on two ship loading configurations, i.e., Alternate load 1 (odd numbered cargo tank loaded, even numbered cargo tanks empty, and Alternate load 2 (even numbered cargo tanks loaded, odd numbered cargo tanks empty). If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, then a full load condition can be used for the analysis.

4.4.2 Static load due to all deadweight and lightweight items is to be applied. The ship is to be heeled at an angle of 30° and balanced vertically on a trimmed waterline.

4.4.3 The Rule design vertical wave bending moment and the permissible vertical still water bending moment envelope need not be applied. If, however, the actual hull girder bending moment achieved in the model exceeds $M_{SW} + 0.6M_W$, then correcting the bending moment in the model to $M_{SW} + 0.6M_W$ is permitted.

4.5 Transverse dynamic load cases

4.5.1 The following loads are to be applied to the FE model:

- External hydrostatic pressures due to the trimmed and heeled waterline. The pressure head distribution is given in Figure 2.4.4 Hydrostatic pressure distribution for asymmetric load cases using a full-breadth model.
- Cargo pressure loads acting on the cargo tank structure. These loads are to include design cargo vapour pressure, static pressure and dynamic pressure due to vertical and transverse accelerations.
Inertia forces of lightship mass and other deadweight items are to include transverse and vertical acceleration factors, see Ch 2, 4.5 Transverse dynamic load cases 4.5.12.

Components shown are acceleration factors based on acceleration 1g.

Bending moment correction, if required, see Ch 2, 4.5 Transverse dynamic load cases 4.5.14. Explanatory notes regarding the derivation and application of these load components are given in Ch 2, 4.10 Application of assigned permissible still water and design vertical wave bending moment envelope.

Figure 2.4.2 Acceleration ellipsoid
4.5.2 The transverse dynamic load cases to be analysed are specified in Ch 2, 4.3 Vertical dynamic load cases 4.3.8. The analysis is to be carried out based on two ship loading configurations, i.e., Alternate load 1 (odd numbered cargo tanks loaded, even numbered cargo tanks empty) and Alternate load 2 (even numbered cargo tanks loaded, odd numbered cargo tanks empty). If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, then a full load case analysis can be used for the analysis.

4.5.3 The transverse acceleration (i.e. \( \alpha_y \) at point I of the acceleration ellipsoid in Figure 2.4.2 Acceleration ellipsoid) to be used to derive the resultant acceleration of a given tank is to be the maximum transverse acceleration for that tank from all the loading conditions in the ship’s Loading Manual, including any single tank loading condition. When calculating the transverse acceleration factors, \( \alpha_y \) for a given tank, the maximum \( GM \) from the ship’s loading conditions, which will result in the maximum transverse acceleration component, is to be used. Therefore, the \( GM \) of a given tank used for the calculation of \( \alpha_y \) for application to the FE analysis may be related to different loading conditions in the loading manual. This \( GM \) is to be selected by reviewing all alternate tank and single tank loading conditions in the Loading Manual. For example, the \( GM \) for the Alternate 1 loading condition may be less than the \( GM \) for the No.1 or No.3 tank single loading condition, in which case the higher value should be used for the Alternate 1 load case analysis. Similarly, the \( GM \) for the Alternate 2 loading condition may be less than the \( GM \) for the No.2 or No.4 tank single loading condition, in which case the higher value should be used in the Alternate 2 load case analysis. Single tank loading conditions are to be considered unless it is specifically stated in the ship’s Loading Manual that single tank loading conditions are prohibited.

4.5.4 For each loading configuration, the vertical and longitudinal accelerations (i.e. \( \alpha_z \) at point II and \( \alpha_x \) at point III of the acceleration ellipsoid in Figure 2.4.2 Acceleration ellipsoid) to be used to derive the resultant acceleration of a given tank is to be the maximum vertical downward acceleration and maximum longitudinal acceleration of each tank for the same loading configuration, as determined in accordance with Ch 2, 4.3 Vertical dynamic load cases.

4.5.5 The combination of longitudinal, transverse and vertical acceleration components is to be in accordance with the acceleration ellipsoid concept as described in Ch 4.28.1 of the Rules for Ships for Liquefied Gases. This acceleration ellipsoid is shown in Figure 2.4.2 Acceleration ellipsoid.

4.5.6 Depending on the phase relationship between longitudinal, transverse and vertical acceleration components, the resultant acceleration vector, \( a_r \), will have varying magnitude and direction \( \beta \). These relationships are given by the acceleration ellipsoid, see Figure 2.4.2 Acceleration ellipsoid. The acceleration ellipsoid can be represented by the following equation:

\[
\frac{a_x^2}{A_x^2} + \frac{a_y^2}{A_y^2} + \frac{(a_z - 1)^2}{A_z^2} = 1
\]

where \( a_x, a_y \) and \( a_z \) are instantaneous longitudinal, transverse and vertical acceleration factors on the surface of the acceleration ellipsoid.

- Point I represents the maximum transverse acceleration factor \( a_y = A_y \) when \( a_x = 0 \) and \( a_z = 1 \),
- Point II represents the maximum vertical acceleration factor \( a_z = (1 + A_y) \) when \( a_y = 0 \) and \( a_x = 0 \),
- Point III represents the maximum longitudinal acceleration factor \( a_x = A_x \) when \( a_y = 0 \) and \( a_z = 1 \).

4.5.7 The pressures calculated from Ch 2, 4.7 Application of loads 4.7.3 gives the instantaneous pressures at the tank boundary. The maximum pressure acting at individual points on the tank boundary in general does not occur simultaneously, thus, the combination of \( a_x, a_y \) and \( a_z \) that generates the maximum pressure at individual points on the tank boundary may vary. Whilst this pressure should be used for the design of the local structure, the primary structure, e.g., transverse web, transverse bulkheads, stringers girders, inner hull plating, deck and shell plating, requires to be designed also to meet the most onerous condition in which the pressure acts simultaneously. A number of load cases needs to be investigated to show compliance with relevant stress and buckling criteria when the tanks are subjected to a combination of \( a_x, a_y \) and \( a_z \); the derivation of these cases is described in the following paragraphs.
Figure 2.4.3 Definition of corner points of tank A through F
The pressure head, $h$, for any point around the hull is as follows:

$$h = z \cos \theta + y \sin \theta$$

where

- $z$ = vertical distance below the mean waterline, measured at the centreline
- $y$ = transverse distance from centreline, positive to port
- $\theta$ = heel angle
- $P$ = pressure $= \rho gh$
- $T$ = local draught

**Figure 2.4.4 Hydrostatic pressure distribution for asymmetric load cases using a full-breadth model**
4.5.8 The following design conditions, which maximise pressures on the tank boundary, are to be considered, see Figure 2.4.3 Definition of corner points of tank A through F:

P1: condition in which an internal pressure distribution is calculated using a combination of $\alpha_x$, $\alpha_y$, and $\alpha_z$, resulting in a maximum pressure at any section along the length of the tank at knuckle point A or point D, whichever is the higher.
P2: condition in which an internal pressure distribution is calculated using a combination of $a_x$, $a_y$, and $a_z$; resulting in a maximum pressure at any section along the length of the tank at knuckle point B or point E, whichever is the higher.

P3: condition in which an internal pressure distribution is calculated using a combination of $a_x$, $a_y$, and $a_z$; resulting in a maximum pressure at any section along the length of the tank at knuckle point C or point F, whichever is the higher.

4.5.9 For a tank with uniform cross section, where the maximum pressure at forward and aft sections of the tank is equal, the points at the forward section are to be considered. For each of these conditions, there is a specific set of values of $a_\beta$ and angle $\beta$ to be applied to generate the maximum pressure at the point considered on the boundary of each tank, where

- $a_\beta$ is the resultant acceleration vector of $a_x$, $a_y$, and $a_z$, and
- $\beta$ is the angle of the resultant acceleration vector as shown in Figure 2.4.2 Acceleration ellipsoid.

4.5.10 The design conditions described in Ch 2, 4.5 Transverse dynamic load cases 4.5.8 are to be considered for each loading configuration specified in Ch 2, 4.5 Transverse dynamic load cases 4.5.2.

4.5.11 External sea pressure applied to the model is to be taken as hydrostatic pressure calculated based on the ship heeled at an angle equal to the lesser of the following angles and vertically balanced on a trimmed waterline:

- $\beta_{\text{average}}$ (see Ch 2, 4.5 Transverse dynamic load cases 4.5.13);
- 30° (or lifetime roll angle if transverse acceleration is obtained from direct calculation method, see Ch 2, 4.8 Calculation on acceleration factors 4.8.6 and Ch 2, 4.8 Calculation on acceleration factors 4.8.7);
- Angle of heel equivalent to upper deck edge immersion at zero trim.

4.5.12 Inertia loads due to lightship mass and other deadweight items, other than contents in cargo tanks, are to be included by applying the following vertical and transverse acceleration factors

- $a_z = a_{\text{average}} \cos(\beta_{\text{average}})$
- $a_y = a_{\text{average}} \sin(\beta_{\text{average}})$

These acceleration factors include the effect of gravity.

4.5.13 The value of $a_{\text{average}}$ and $\beta_{\text{average}}$ is to be calculated as follows:

$$a_{\text{average}} = \frac{1}{n} \left( \sum_{i=1}^{n} a_{\beta_{0,j} \cos \beta_{0,i}} \right)^2 + \left( \sum_{i=1}^{n} a_{\beta_{0,j} \sin \beta_{0,i}} \right)^2$$
\[
\tan(\beta_{\text{average}}) = \frac{\sum_{i=1}^{n} a_{0i} \sin \beta_{0i}}{\sum_{i=1}^{n} a_{0i} \cos \beta_{0i}}
\]

where

\[n = \text{is the number of loaded cargo tanks}\]
\[a_{0i} = \text{is the resultant vertical and transverse acceleration factor that generates the maximum pressure at the point considered on the boundary of loaded cargo tank } i, \text{ see Figure 2.4.2 Acceleration ellipsoid}\]
\[\beta_{0i} = \text{is the angle of the resultant acceleration factor } a_{0i}, \text{ see Figure 2.4.2 Acceleration ellipsoid}\]

4.5.14 The analysis of the transverse dynamic load cases may be based on the actual bending moment resulting from the application of loads to the FE model. If, however, the actual hull girder bending moment exceeds \(M_{SW} + 0.6 M_{w}\), then correcting the bending moment in the model to \(M_{SW} + 0.6 M_{w}\) is permitted.

4.6 Collision load cases

4.6.1 The collision load cases to be analysed are specified in Table 2.4.5 Collision load cases. These load cases are to be based on two ship loading configurations, i.e., Alternate load 1 (odd numbered cargo tank loaded, even numbered cargo tanks empty) and Alternate load 2 (even numbered cargo tanks loaded, odd numbered cargo tanks empty). If it is clearly stated in the ship’s Loading Manual that alternate loading conditions and single tank loading conditions are prohibited in a sea-going condition, a full load condition can be used for the analysis.

4.6.2 All static load components and external hydrostatic pressures due to the static waterline for these conditions are to be applied. The cargo design vapour pressure is to be applied.

4.6.3 A forward acceleration of 0.5g is to be applied in the longitudinal direction to the lightship mass and the cargo in the tanks.

4.6.4 No additional vertical bending moment is required to be applied to the FE model, i.e., the vertical bending moment in the model is equal to the still water bending moment generated by the applied loads.

4.6.5 The pressure at the tank boundary is to be calculated according to Ch 2, 4.7 Application of loads 4.7.3.

4.7 Application of loads

4.7.1 All components of a loading condition are to be included in the analysis. The lightship is to be included by adjusting the self-weight of the model to equal the required lightweight and LCG position. Acceleration factors are to be applied to lightship mass items, including the ship’s engine, in the case of dynamic load cases. See also Ch 2, 2.1 Structural Modelling 2.1.14.
4.7.2 Buoyancy loads are to be applied as pressures, $\rho gh$, to wetted shell elements, where $h$ is the vertical distance from the waterline to the centre of the element.

Figure 2.4.7 Distribution of vertical acceleration factor $A_z$
Figure 2.4.8 Procedure to derive required vertical bending moment distribution for applying to FE model
4.7.3 Cargo loads, including the design vapour pressure, static and dynamic loads due to additional acceleration factors, are to be applied as pressures directly to the elements representing the tank plating. The following equations are to be used to determine the pressure values:

For still water cases:

\[ P = \rho c \Lambda p g h_z + P_o \]

For vertical dynamic cases:

\[ P = P_o + \rho c \Lambda p g h_z \left( 1 + A_z \right) + \rho c \Lambda p g I_x A_x \]

For transverse dynamic cases:

\[ P = P_o + \rho c \Lambda p g Z_y \]

For collision cases:

\[ P = P_o + \rho c \Lambda p g h_z + \rho c \Lambda p 0.5g I_x \]

where

\[ I_x = \text{is the horizontal distance from the aft end of tank to centre of element (for bow pitched down vertical dynamic cases) or the horizontal distance from the forward end of tank to centre of element (for bow pitched up vertical dynamic cases)} \]

\[ l_x = \text{is the horizontal distance from the aft end of tank to centre of element for collision cases} \]
\( h_z = \) is the vertical distance from the highest point of a tank to centre of element, see Figure 2.4.6 Static pressure load distribution \( P \) for cargo tanks.

\( a_{\beta} = \) is the resultant acceleration factor vector (at angle \( \beta_0 \)) that generate the maximum pressure at a required point on the tank boundary, see Ch 2, 4.5 Transverse dynamic load cases 4.5.7 and Ch 2, 4.5 Transverse dynamic load cases 4.5.8. The acceleration vectors required to maximise the pressure at a given point on the tank boundary depend on tank geometry, hence they are in general different for each cargo tank. These maximum pressures may be determined using LR’s RulesCalc software.

\( Z_\beta = \) is the largest liquid height above the point where the pressure is to be determined measured from the tank shell in the \( \beta \) direction, see Figure 2.4.5 Internal tank pressure for transverse dynamic load cases.

\( \Lambda_P = \leq 1.0, \) a factor to account for the difference in cargo tank volume measured from the primary barrier and that measured to the ship structure.

4.7.4 Tank domes considered to be part of the accepted total tank volume shall be taken into account when determining \( Z_{\beta} \), unless the total volume of tank domes \( V_d \) does not exceed the following value:

\[ V_d = V_t \left( \frac{100 - FL}{FL} \right) \]

where

\( V_t = \) tank volume without any domes; and

\( FL = \) filling limit in accordance with Ch 15, 15.1 of LR’s Rules for Liquefied Gases.

4.8 Calculation on acceleration factors

4.8.1 The maximum longitudinal and transverse acceleration factors may be obtained using the following guidance formulae given in the Rules for Liquefied Gases:

\[ A_x = A_0 \sqrt{0.06 + A^2 - 0.25A} \]

\[ A_y = A_0 \sqrt{0.6 + 2.5 \left( \frac{X}{L} + 0.05 \right)^2 + K \left( 1 + 0.6K \frac{Z^2}{B} \right)^2} \]

\[ A = \left( 0.7 - \frac{L}{1200} + 5 \frac{Z}{L} \left( 0.6 \frac{Z}{C_B} \right) \right) \]

where

\( Z = \) is the vertical distance, in meters, from the ship’s actual waterline to the gravity of the tank with contents; \( Z \) is positive above and negative below the waterline.

\( X = \) is the longitudinal distance, in meters, from amidships to the centre of gravity of the tank with contents; \( X \) is positive forward of amidships, negative aft of amidships.

\( B = \) is the greatest moduled breadth of the ship, in meters.

\( K = 13 \frac{GM}{B} \)

where

\( K \geq 1 \) and \( GM \) is the metacentric heigth, in meters.

\( A_0 = \) see Ch 2, 4.8 Calculation on acceleration factors 4.8.3

\( C_B = \) is the block coefficient, see Ch 2, 4.8 Calculation on acceleration factors 4.8.5

4.8.2 LR’s RulesCalc software can be used to calculate the longitudinal and transverse accelerations at the centre of each cargo tank and also at the selected positions along the ship length.

4.8.3 The guidance vertical acceleration formula given in the Rules for Ships for Liquefied Gases is modified, as below, to maintain a consistent acceleration curve over the model length. This modification takes account of the fact that the pitch motion in the aft end of the ship results in a vertical acceleration component acting in the opposite direction to that at the forward end of the ship. The following formulae may be used to obtain the vertical acceleration factors.
For heave downward and bow pitch down case:

- For \( x \geq -0.05L \):
  \[
  A_z = A_0 \left( 1 + \left( \frac{5.3 - 45x}{L} \right)^2 \left( \frac{x}{L} + 0.05 \right)^2 \right)^{1.5} + \left( \frac{0.6yK}{B} \right)^2 \]

- For \( x < -0.05L \):
  \[
  A_z = A_0 \left( 1 + \left( \frac{0.6yK}{B} \right)^2 \right) - \left( 1 + \left( \frac{5.3 - 45x}{L} \right)^2 \left( \frac{x}{L} + 0.05 \right)^2 \right)^{1.5} + \left( \frac{0.6yK}{B} \right)^2 \]

For heave downward and bow pitch up case:

- For \( x \geq -0.05L \):
  \[
  A_z = A_0 \left( 1 + \left( \frac{5.3 - 45x}{L} \right)^2 \left( \frac{x}{L} + 0.05 \right)^2 \right)^{1.5} + \left( \frac{0.6yK}{B} \right)^2 \]

- For \( x < -0.05L \):
  \[
  A_z = A_0 \left( 1 + \left( \frac{5.3 - 45x}{L} \right)^2 \left( \frac{x}{L} + 0.05 \right)^2 \right)^{1.5} + \left( \frac{0.6yK}{B} \right)^2 \]

where

\[
A_0 = 0.2 \frac{V}{\sqrt{L}} + \frac{34 - 600}{L} \]

\( x \) = as defined in Ch 2, 4.8 Calculation on acceleration factors 4.8.1

\( y \) = is the transverse distance, in meters, from the ship’s centreline to the centre of gravity of the tank with contents

\( C_b \) = is the block coefficient, see Ch 2, 4.8 Calculation on acceleration factors 4.8.5

\( A_z \) = is the vertical acceleration factor (positive downwards).

4.8.4 The distribution of vertical acceleration factor for the case of ship motion of heave downwards/bow pitched down and heave downwards/bow pitched up are illustrated in Figure 2.4.7 Distribution of vertical acceleration factor \( A_z \).

4.8.5 The block coefficient based on the summer draught or the scantling draught, whichever is greater, may be used for the calculation of the acceleration factors.

4.8.6 Alternatively, direct calculation procedures using an appropriate ship motion program may be used to derive the acceleration factors after consultation with Lloyd’s Register.

4.8.7 Direct calculation approach is recommended for the determination of transverse acceleration for membrane tank LNG ships with a capacity greater than 150 000 \( m^3 \). It is considered that ships of this size exceed the range of ship parameters for which the guidance formulae were originally developed; however, the guidance formulae are considered to be conservative for ships exceeding 150 000 \( m^3 \). Guidance on the use of direct calculations for the determination of lifetime transverse acceleration is given in Ch 6 Appendix B: Guidance procedure to determine long-term transverse accelerations.

4.9 Pressure to derive the quasi-static waterline for dynamic load cases

4.9.1 This procedure may be used to calculate the static and dynamic loads acting on all deadweight and lightweight items to determine the resulting quasi-static external pressure distribution acting on the shell plating.

4.9.2 The longitudinal weight distribution is to be broken down into convenient longitudinal sections for all lightweight and deadweight items in a similar way to that required for a still water loads analysis.

4.9.3 A vertical acceleration factor (relative to \( g \)) at the longitudinal centre of gravity of each section is to be calculated and added to the static gravity of \( g \).

4.9.4 Each section of lightweight and deadweight is to be multiplied by its corresponding vertical acceleration factor to give the combined static and dynamic weight distribution, and this is to be balanced on a suitable waterline using a still water loads program. This waterline should not include any added wave profile.
4.9.5 The resulting quasi-static trimmed waterline is to be used to apply the external hydrostatic pressures to shell plating elements.

4.9.6 For static heel and dynamic transverse cases, the external hydrostatic pressure is to be based on the ship heeled at the required angle and balanced vertically on a trimmed waterline. This position may be obtained by first achieving the vertical balance of the upright ship and then the ship is heeled at the required heel angle.

4.10 Application of assigned permissible still water and design vertical wave bending moment envelope
4.10.1 Where required the vertical wave bending moment and permissible vertical still water bending moment envelope are to be applied to the FE model.

4.10.2 The additional bending moment distribution that is required to be applied to the FE model to generate the permissible still water and Rule design vertical wave bending moments is illustrated in Figure 2.4.8 Procedure to derive required vertical bending moment distribution for applying to FE model. This bending moment distribution takes account of the bending moment generated by the loading condition of the FE load case. The total bending moment, i.e. the sum of the applied additional bending moment and the still water bending moment from the FE load case, need not exceed the required value. Care is to be taken in the sign convention of sagging and hogging in deriving the required bending moment distribution.

4.10.3 The vertical load distribution that is required to produce the bending moment distribution can be obtained by numerical differentiation method. The load distribution calculated is to be approximated by a series of vertical forces acting along the length of the FE model. These vertical forces are to be applied as a series of nodal forces at the side shell and inner skin in proportion to the projected vertical cross-sectional area. The distribution of the vertical forces is to be such that the required bending moment distribution can be closely reproduced. It is recommended that the nodal forces be applied to every frame position.

4.10.4 Other proposed methods of applying the Rule vertical wave bending moment distribution and permissible vertical still water bending moment envelope will be specially considered.

4.11 Procedure to apply local wave crest or trough
4.11.1 For the wave load cases, an additional wave head is to be applied over the full length of the FE model using the pressure distribution shown in Ch 2, 4.7 Application of loads 4.7.2.

4.11.2 The ship’s scantling draught may be used for deriving the pressure head distribution.

Section 5
Permissible stresses

5.1 Permissible stresses
5.1.1 The stresses resulting from the application of all load cases, with the exception of load cases O1 and O2, are not to exceed the maximum permissible values given in Table 2.5.1 Maximum permissible membrane stresses. The structural items indicated in Table 2.5.1 Maximum permissible membrane stresses are provided for guidance as to the most likely critical areas. All stresses for all parts of the model are to be examined.

5.1.2 The maximum permissible stresses applicable for load cases O1 and O2, the collision cases, are given in Table 2.5.2 Maximum permissible membrane stresses (collision load cases).

5.1.3 In addition, it should be noted that the longitudinal hull girder elements should comply, as a minimum, with the requirements in Pt 3, Ch 4 of the Rules for Ships, see Ch 1, 1.1 Introduction 1.1.4.

5.1.4 The permissible stress criteria in Table 2.5.1 Maximum permissible membrane stresses and Table 2.5.2 Maximum permissible membrane stresses (collision load cases) are based on the recommended mesh size indicated in Ch 2, 2 Structural modelling.

5.1.5 In addition to the criteria given in Table 2.5.1 Maximum permissible membrane stresses, design requirements imposed by the containment system manufacturer are to be complied with, see Ch 1, 1.1 Introduction 1.1.4.
### Table 2.5.1 Maximum permissible membrane stresses

<table>
<thead>
<tr>
<th>Structural item (see Note 1)</th>
<th>Load cases</th>
<th>Permissible stresses</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Combined stress, $\sigma_c$</td>
<td>Direct stress, $\sigma$</td>
</tr>
<tr>
<td><strong>Double bottom structure</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Bottom shell plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Inner bottom plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Hopper tank slope plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Double bottom girders</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Double bottom floors</td>
<td>All cases</td>
<td>0.75$\sigma_0$</td>
<td>–</td>
</tr>
<tr>
<td><strong>Side structure</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Side shell plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Inner side plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Side stringers</td>
<td>All cases</td>
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</tr>
<tr>
<td>Upper deck plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
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</tr>
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<td>Upper wing tank plating</td>
<td>All cases</td>
<td>0.92$\sigma_L$</td>
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<td>Side transverse webs</td>
<td>All cases</td>
<td>0.75$\sigma_0$</td>
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<td>Upper wing tank web plating</td>
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<tr>
<td><strong>Deck structure</strong></td>
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<td>Inner trunk deck plating</td>
<td>All cases</td>
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<td>–</td>
</tr>
<tr>
<td>Trunk deck plating</td>
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<td>(see Note 6)</td>
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<tr>
<td>Trunk deck girders</td>
<td>All cases</td>
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</tr>
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<td>Trunk deck transverses</td>
<td>All cases</td>
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<td><strong>Bulkhead structure</strong></td>
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<tr>
<td>Bulkhead plating</td>
<td>All cases</td>
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<td>Bulkhead vertical webs</td>
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<tr>
<td>Bulkhead stringers</td>
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<tr>
<td><strong>Face plate of web structure</strong></td>
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</tr>
<tr>
<td>Transverse structure face plate</td>
<td>All cases</td>
<td>–</td>
<td>0.75$\sigma_0$</td>
</tr>
</tbody>
</table>

### NOTES

1. Additional design requirements imposed by the containment system manufacturer are to be complied with, see Ch 2, 5.1 Permissible stresses 5.1.5.

2. Stress criteria relate to the coarse mesh described in Ch 2, 2.1 Structural Modelling 2.1.5 and Ch 2, 2.1 Structural Modelling 2.1.6.
3. All cases include wave load cases, vertical dynamic load cases, static heel load cases and transverse dynamic load cases. The stress criteria for the collision load cases are to be in accordance with Table 2.5.2 Maximum permissible membrane stresses (collision load cases).

4. If a finer mesh size is used, stresses may be 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 discontinuity or abutting structure.

5. For girders, stringers, vertical webs and floors the specified values 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 FE element.

6. The average stress across the trunk deck plating is to be limited to the permissible value indicated.

<table>
<thead>
<tr>
<th>Table 2.5.2 Maximum permissible membrane stresses (collision load cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural item</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Bulkhead structure and immediate areas of integration</td>
</tr>
<tr>
<td>Plating, vertical webs, stringers and girders</td>
</tr>
</tbody>
</table>

NOTES
1. Stress criteria are based on the coarse mesh described in Ch 2, 2.1 Structural Modelling 2.1.5 and Ch 2, 2.1 Structural Modelling 2.1.6.

3. Immediate areas of integration are to include side, bottom and deck structures from one web frame aft of the bulkhead to one web frame forward of the bulkhead.

4. For girders, stringers, vertical webs and floors the specified values 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 FE element.

5.1.6 Where openings are not represented in the structural model, the element shear stress, $\tau_{xy}$, is to be increased in direct proportion to the modelled web shear area divided by the actual web area. The revised $\tau_{xy}$ is to be used to calculate the combined equivalent stress, $\sigma_e$. Where the resulting stresses are greater than 90 per cent of the maximum permitted, a more detailed analysis using a fine mesh representing the opening may be required or the scantlings increased accordingly.

### Section 6

#### Buckling acceptance criteria

6.1 Buckling acceptance criteria

6.1.1 For all load cases, with the exception of the collision load cases O1 and O2, the buckling criteria are given in Table 2.6.1 Local plate panel required factor against buckling (see Note). Plate buckling is to be investigated for all areas of primary structure, but particular attention is to be paid to the areas specified in Table 2.6.1 Local plate panel required factor against buckling (see Note).

6.1.2 The buckling criteria applicable for load cases O1 and O2, the collision cases, are given in Table 2.6.2 Local plate panel required factor against buckling (collision load cases).

6.1.3 In addition, it should be noted that the longitudinal hull girder elements should comply, as a minimum, with the requirements in Pt 3, Ch 4,7 of the Rules for Ships, see Ch 1, 1.1 Introduction 1.1.4.
6.1.4 The combined effects of bi-axial compressive stress, shear stress and ‘in-plane’ bending stress are to be included in the buckling calculation. In general, the average stresses acting within the plate panel are to be used for the buckling calculation.

Table 2.6.1 Local plate panel required factor against buckling (see Note)

<table>
<thead>
<tr>
<th>Structural item</th>
<th>Factor against buckling $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double bottom structure</td>
<td></td>
</tr>
<tr>
<td>Bottom shell plating</td>
<td>1,0</td>
</tr>
<tr>
<td>Double bottom girders</td>
<td>1,0</td>
</tr>
<tr>
<td>Inner bottom plating</td>
<td>1,0</td>
</tr>
<tr>
<td>Hopper tank plating</td>
<td>1,0</td>
</tr>
<tr>
<td>Double bottom floors</td>
<td>1,1</td>
</tr>
<tr>
<td>Hopper tank web plating</td>
<td>1,1</td>
</tr>
<tr>
<td>Side structure</td>
<td></td>
</tr>
<tr>
<td>Side shell</td>
<td>1,0</td>
</tr>
<tr>
<td>Inner side plating</td>
<td>1,0</td>
</tr>
<tr>
<td>Side stringers</td>
<td>1,0</td>
</tr>
<tr>
<td>Side transverse webs</td>
<td>1,1</td>
</tr>
<tr>
<td>Upper wing tank plating</td>
<td>1,1</td>
</tr>
<tr>
<td>Deck structure</td>
<td></td>
</tr>
<tr>
<td>Inner trunk deck plating</td>
<td>1,0</td>
</tr>
<tr>
<td>Trunk deck plating</td>
<td>1,0</td>
</tr>
<tr>
<td>Trunk deck girder</td>
<td>1,0</td>
</tr>
<tr>
<td>Trunk deck transverse webs</td>
<td>1,1</td>
</tr>
<tr>
<td>Transverse bulkhead structure</td>
<td></td>
</tr>
<tr>
<td>Bulkhead plating</td>
<td>1,1</td>
</tr>
<tr>
<td>Vertical web diaphragms</td>
<td>1,1</td>
</tr>
<tr>
<td>Stringers</td>
<td>1,1</td>
</tr>
</tbody>
</table>

NOTE

Applicable to wave load cases, vertical dynamic load cases, static heel load cases and transverse dynamic load cases.

Table 2.6.2 Local plate panel required factor against buckling (collision load cases)

<table>
<thead>
<tr>
<th>Structural item</th>
<th>Factor against buckling $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulkhead structure and immediate areas of integration</td>
<td></td>
</tr>
<tr>
<td>Plating, vertical webs, stringers and girders</td>
<td>1,0</td>
</tr>
</tbody>
</table>

NOTE

Immediate areas of integration are to include side, bottom and deck structure from one web frame aft of the bulkhead to one web frame forward of the bulkhead.
6.1.5 Panel buckling calculations are to be based on the proposed thickness of the plating reduced by a thickness deduction for corrosion. A corrosion deduction of 1 mm is to be made for all structural items for each surface in contact with ballast water. No deduction is to be made for other surfaces.

6.1.6 In general, the applied stresses for buckling assessment are to be increased by a factor equal to the original thickness divided by the thickness after corrosion.

6.1.7 For the direct stress component which includes hull girder bending stress, it is permissible to adjust only the local stress component by the corrosion deduction. All other stress components are to be applied in accordance with Ch 2, 6.1 Buckling acceptance criteria 6.1.6.

6.1.8 In calculating the factors against buckling, the edge restraint factor ‘c’ defined in Pt 3, Ch 4,7 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 edge of the panel. The edge restraint factor ‘c’ is not to be used in the calculation of the critical buckling stress for compression applied on the short edges.

6.1.9 When the calculated elastic critical buckling stress, \( \sigma_c \), 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 formula, given below:

- when \( \sigma_c \leq 0.5 \sigma_o \)
  \[ \sigma_{cr} = \sigma_c \]
- when \( \sigma_c > 0.5 \sigma_o \)
  \[ \sigma_{cr} = \sigma_c \left(1 - \frac{\sigma_o}{4\sigma_c}\right) \]

where \( \sigma_{cr} \) = critical buckling stress corrected for plasticity effects \( \sigma_c, \sigma_o \), see Ch 1, 2 Symbols.

---

Section 7

Primary member deflections

7.1 Primary memeber deflections

7.1.1 It should be ascertained that the deflections of primary members including angular deflections (i.e., relative deflection between joining primary members and deflections of secondary structural members relative to primary structure) are compatible with the containment system. The requirements or guidance of the containment system designer should be followed in this matter.
Contents

CHAPTER 1 INTRODUCTION
CHAPTER 2 ANALYSIS OF PRIMARY STRUCTURE OF MEMBRANE TANK LNG SHIPS
CHAPTER 3 ANALYSIS OF TRUNK DECK SCARPHING ARRANGEMENTS WITH THE AFT END
  SECTION 1 OBJECTIVES
  SECTION 2 STRUCTURAL MODELLING
  SECTION 3 BOUNDARY CONDITIONS
  SECTION 4 LOADING CONDITIONS
  SECTION 5 PERMISSIBLE STRESSES
  SECTION 6 BUCKLING ACCEPTANCE CRITERIA
CHAPTER 4 ANALYSIS OF STRUCTURAL DETAILS
CHAPTER 5 APPENDIX A: ALTERNATIVE PROCEDURE FOR TRANSVERSE LOAD CASES (HALF-BREADTH FE MODEL)
CHAPTER 6 APPENDIX B: GUIDANCE PROCEDURE TO DETERMINE LONG-TERM TRANSVERSE ACCELERATIONS
Section 1

Objectives

1.1 Objectives

1.1.1 The objective of this Chapter of this SDA procedure is to ensure that the structural arrangement of the transition from the cargo tank region to the aft end structure is satisfactory.

1.1.2 In particular, this analysis is to enable the distribution of loads from the trunk deck structure into the deckhouse and main deck structure at the aft end to be accurately modelled.

1.1.3 The analysis is to be sufficient to enable the effect of all critical openings and structural discontinuities (i.e., doors, windows, access openings, end of trunk deck and scarphing brackets, etc.) to be determined.

1.1.4 The structural analysis described in this Chapter is not to be used to verify the minimum required scantlings of the aft part of aftmost cargo tank including its aftmost bulkhead. These areas are to be verified using the analysis specified in Ch 2 Analysis of primary structure of membrane tank LNG ships.

IMPORTANT NOTE
The objective of this procedure is to assess the strength of the ship primary structure to withstand the design loads. The ability of the containment system to accommodate the global or local deformations of the ship structure is not considered in this procedure. Therefore it is necessary for the designers to consider and demonstrate separately that the containment system design in terms of strength and fatigue capability can withstand the global and local deformations of the ship structure. Additional design requirements with respect to the ship structure specified by the containment system supplier are to be complied with. It is recommended that the designer consult the containment system supplier early on in the design cycle.

Section 2

Structural modelling

2.1 Structural modelling

2.1.1 The 3-D finite element model of the aft end is to extend from the transom to the middle of the aft cargo hold. The model is to include all primary structure.

2.1.2 The model is to include the deckhouses and all internal structure, especially where the internal structure will form part of the load path from the trunk decks to the main deck. Similarly, in cases where the longitudinal bulkheads of the cargo region are not continuous through the engine room, the scarphing arrangements of the longitudinal bulkheads are to be adequately represented in the model.

2.1.3 If structural symmetry about the ship’s centreline exists then a half-breadth model may be used.

2.1.4 The model of this area developed for the Ch 2 Analysis of primary structure of membrane tank LNG ships analysis may be used for this investigation, provided that it complies with the meshing arrangements described in this Chapter.
2.1.5 The basic (coarse) mesh size is to comply with the requirements of Ch 2, 2.1 Structural Modelling 2.1.5. This basic mesh is to be applied to:

- deckhouse external and internal walls and decks from one deck below the main deck to one deck above the trunk deck. The window and door openings are to be represented.
- longitudinal bulkheads of the hull in way of scarphing areas.

2.1.6 Fine mesh regions are to be introduced, as described in Ch 3, 2.1 Structural modelling 2.1.7 to Ch 3, 2.1 Structural modelling 2.1.8, at likely areas of high stress concentrations. These will include:

- the ends of the trunk deck to main deck scarphing brackets;
- areas around doors and windows on the side and main longitudinals walls of the deckhouse structure, between the main deck and the top of the trunk deck;
- scarphing areas of longitudinal bulkheads and inner trunk deck.

2.1.7 The structural geometry, particularly in areas of concern, is to be accurately represented. The level of refinement and mesh size chosen is to be such as to enable stress concentrations to be identified.

2.1.8 The element mesh size in the fine mesh zones should comply with the following:

- Between closely spaced openings: a minimum of 9 elements should be arranged between openings.
- Elsewhere, a minimum of 9 elements should be arranged between longitudinals. This mesh should extend at least 9 elements in all directions from the point of interest.
- Aspect ratio of approximately one should be used.

2.1.9 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 are likely to be high stresses or a high stress gradient.

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

2.1.11 The proposed scantlings, excluding Owner’s extras and any additional thicknesses to comply with the ShipRight ES Procedure, are to be used throughout the model.

2.1.12 Secondary stiffening may be represented by line elements having appropriate bending and axial geometric properties.

2.1.13 A suitable model of the aft end structure is shown in Figure 3.2.1 3-D FE model of aft end showing typical mesh arrangements on deckhouse and Figure 3.2.2 Details of fine mesh in way of trunk deck scarphing brackets and deckhouse side opening.
Figure 3.2.1 3-D FE model of aft end showing typical mesh arrangements on deckhouse
Section 3

Boundary conditions

3.1 Boundary conditions

3.1.1 The grid points of all longitudinal elements at the model end section in way of the middle of the aft cargo hold are to be constrained in $\delta_x$, $\delta_y$, $\delta_z$, $\theta_x$, $\theta_y$, and $\theta_z$ degrees of freedom.

When using a half-breadth model, symmetry constraint, i.e., $\delta_y = 0$, $\theta_x = 0$ and $\theta_z = 0$, is to be applied to all nodes on the centreline.
### Section 4

#### Loading conditions

4.1 Loading conditions

4.1.1 Two load cases are required to be considered for the aft end model. These load cases relate to the application of the following bending moments and shear forces to the aft end model:

**Case 1**

Combined permissible hogging still water plus design hogging wave bending moment and combined Rule positive permissible still water plus design positive wave shear force, see Pt 3, Ch 4.5 and Ch 4.6 of the Rules for Ships.

**Case 2**

Combined permissible sagging still water plus design wave sagging bending moment and combined Rule negative permissible still water plus design negative wave shear force, see Pt 3, Ch 4.5 and Ch 4.6 of the Rules for Ships.

4.1.2 The permissible hogging and permissible sagging still water bending moments are to be taken as the maximum hogging and sagging $M_{SW}$ of all loaded and ballast conditions, see Ch 2, 4.1 Introduction 4.1.5.

4.1.3 The values of the combined still water plus wave bending moment and the combined still water plus wave shear force are to be derived for the longitudinal location where the trunk deck terminates.

4.1.4 A vertical force equal to the shear force is to be applied at the aft end of the model so that the required bending moment is generated at the longitudinal location where the trunk deck terminates, see Figure 3.4.1 Shear force applied to aft end FE model.

4.1.5 The vertical force is to be applied as a series of nodal forces at the side shell in proportion to the projected vertical cross-sectional plate area.

4.1.6 The model may be considered weightless and no other load components are to be applied to the model.
Section 5

Permissible stresses

5.1 Permissible stresses

5.1.1 The stresses resulting from the application of the load case specified in Section 4 are not to exceed the criteria given in Table 3.5.1 Permissible stress criteria – Basic (coarse) mesh and Table 3.5.2 Permissible stress criteria – Basic (coarse) mesh.

5.1.2 The basic (coarse) mesh criteria are given in Table 3.5.1 Permissible stress criteria – Basic (coarse) mesh and the fine mesh stress criteria are given in Table 3.5.2 Permissible stress criteria – Basic (coarse) mesh. The coarse mesh criteria are based on the element size given in Ch 2, 2.1 Structural Modelling 2.1.5 and the fine mesh criteria are based on the element size indicated in Ch 3, 2 Structural modelling.

Figure 3.4.1 Shear force applied to aft end FE model
5.1.3 The shear stress at any longitudinal position may be corrected by the ratio of the required shear force at that position, based on the Rule combined permissible still water plus design wave shear force distribution, to the applied shear force. The combined stress may be recalculated using the corrected shear stress prior to comparison with the permissible stress values.

Table 3.5.1 Permissible stress criteria – Basic (coarse) mesh

<table>
<thead>
<tr>
<th>Structural item</th>
<th>Permissible stresses</th>
<th>von Mises stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single element criteria for elements clear of the fine mesh regions</td>
<td>Longitudinal material</td>
<td>$0.80\sigma_L$</td>
</tr>
<tr>
<td>See Note</td>
<td>Transverse material</td>
<td>$0.80\sigma_o$</td>
</tr>
</tbody>
</table>

NOTE
Criteria for the fine mesh regions are given in Table 3.5.2 Permissible stress criteria – Basic (coarse) mesh.

Table 3.5.2 Permissible stress criteria – Basic (coarse) mesh

<table>
<thead>
<tr>
<th>Load case</th>
<th>Location</th>
<th>Stress criterion</th>
<th>Allowable stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined still water and wave, see Ch 3, 4.1 Loading conditions 4.1.1</td>
<td>Between openings</td>
<td>Average Von Mises stress between openings</td>
<td>$0.94\sigma_o$ (see Note 2)</td>
</tr>
<tr>
<td>Scarphing brackets, corners of openings and other structural details</td>
<td>Average shear stress between openings</td>
<td>$0.47\sigma_o$ (see Note 2)</td>
<td></td>
</tr>
<tr>
<td>Scarphing brackets, corners of openings and other structural details</td>
<td>Average Von Mises stress</td>
<td>$1.0\sigma_o$ (see Note 1)</td>
<td></td>
</tr>
<tr>
<td>Scarphing brackets, corners of openings and other structural details</td>
<td>Average shear stress</td>
<td>$0.47\sigma_o$ (see Note 1)</td>
<td></td>
</tr>
<tr>
<td>Scarphing brackets, corners of openings and other structural details</td>
<td>Individual element Von Mises stress</td>
<td>$1.2\sigma_o$</td>
<td></td>
</tr>
</tbody>
</table>

NOTES:
1. The average stress from the element being assessed and the elements directly connected to its boundary nodes. Averaging is not to be taken across or include abutting structural boundaries, discontinuities or members.
2. Average stress is to be calculated independently of the sign of the individual stress levels.

Section 6
Buckling acceptance criteria

6.1 Buckling acceptance criteria

6.1.1 A buckling assessment is to be carried out for aft end analysis in accordance with Ch 2, 6 Buckling acceptance criteria.
A factor against buckling, $\lambda$, of 1.0 is to be achieved for all areas of the structure.
<table>
<thead>
<tr>
<th>CHAPTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>
Section 1

Objectives

1.1 Objectives

1.1.1 The objective of the structural analysis is to verify that the stress level in structural components and details under the applied static and dynamic loads are within acceptable limits.

Structural components and details in the following locations are to be investigated:

- Connection of the inner bottom to hopper side.
- Connection of the hopper side to inner side.
- Connection of the transverse bulkhead to the inner hull.
- Significant deck dome opening including coamings and girders in way, see Ch 4, 2.1 Structural modelling 2.1.2(f).
- Other locations where the mesh size of the 3-D full ship FE model is insufficiently detailed to represent areas of high stress concentrations.

IMPORTANT NOTE

The objective of this procedure is to assess the strength of the ship primary structure to withstand the design loads. The ability of the containment system to accommodate the global or local deformations of the ship structure is not considered in this procedure. Therefore it is necessary for the designers to consider and demonstrate separately that the containment system design in terms of strength and fatigue capability can withstand the global and local deformations of the ship structure. Additional design requirements with respect to the ship structure specified by the containment system supplier are to be complied with. It is recommended that the designer consult the containment system supplier early on in the design cycle.

Section 2

Structural modelling

2.1 Structural modelling

2.1.1 Areas of high stress concentration in way of structural components and details are to be investigated by incorporating local fine meshed zones into the main model. Alternatively, separate local fine mesh models with boundary conditions derived from the main model may be used. Clear of areas to be analysed in detail, a coarse mesh arrangement may be adopted. The areas to be submodelled or subjected to finer meshing are to be discussed with Lloyd’s Register at the earliest opportunity.

2.1.2 Areas where a fine mesh is needed include:

(a) the inner bottom to hopper side connection at midhold, including local floor and hopper web plating;
(b) the hopper side to inner side connection at mid-hold, including local hopper web and side transverse plating;
(c) transverse bulkhead to inner bottom connection, including local vertical webs and girders;
(d) transverse bulkhead to inner trunk deck connection, including local vertical webs and girders;
(e) transverse bulkhead to inner side structure connection, including horizontal girders; and
(f) for designs which have a significant dome opening in the outer and inner trunk deck, such as the GTT MARK III design, these deck dome openings include coamings and girders in way.
2.1.3 For the fine mesh areas specified in Ch 4, 2.1 Structural modelling 2.1.2(c), (d) and (e), the fine mesh FE analysis may be waived, provided that:

- the coarse mesh criteria are satisfied; and
- a fatigue investigation is carried out in accordance with ShipRight FDA level 3 procedures or equivalent.

2.1.4 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 x 15t or 150 x 150 mm, whichever is the lesser, where t is the main plating thickness. In some locations a finer mesh may be necessary to represent the structural geometry. The mesh size need not be less than t x t unless adequate representation of the structural geometry requires a finer mesh. Triangular plate elements are to be avoided.

2.1.5 The element mesh size in way of dome openings is to comply with Ch 4, 2.1 Structural modelling 2.1.4 and, additionally, at the radius corner the element size should be smaller than R/10, where R is the radius of the corner. However, the mesh size need not be less than the thickness of the plating. For analysis codes in which reliable nodal stresses are not given, a line element of nominal (small) area should be arranged at the radius free edge. The stresses from this line element should be compared to the peak stress criteria given in Table 4.4.1 Maximum permissible stresses in fine mesh regions in way of stress concentrations.

2.1.6 Typical examples of fine mesh areas are shown in Figure 4.2.1 Typical fine mesh area in way of hopper connections to inner bottom and inner side and Figure 4.2.2 Typical fine mesh area in way of a dome opening.
Figure 4.2.1 Typical fine mesh area in way of hopper connections to inner bottom and inner side
Section 3

Loading and boundary conditions

3.1 Loading and boundary conditions

3.1.1 Load cases specified in Ch 2, 4 Loading condition are to be analysed. The collision load cases are only required to be considered for areas specified in Ch 4, 2.1 Structural modelling 2.1.2 (c), (d) and (e).

3.1.2 Where a separate local fine mesh model is used, enforced displacements obtained from the full ship FE model in Ch 2 Analysis of primary structure of membrane tank LNG ships are to be applied to the boundaries of the fine mesh model. All local loadings are to be applied to the fine mesh model.

Section 4

Permissible stresses

4.1 Permissible stresses

4.1.1 The stresses resulting from the application of the load cases referenced in Table 2.4.1 Wave load cases to Table 2.4.4 Transverse dynamic load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships are not to exceed the maximum permissible values given in Table 4.4.1 Maximum permissible stresses in fine mesh regions in way of stress concentrations.
4.1.2 The stresses resulting from the application of the collision load cases, referenced in Table 2.4.5 Collision load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships, are not to exceed the criteria given in Table 4.4.2 Maximum permissible stresses in fine mesh regions in way of stress concentrations (Collision load cases).

Table 4.4.1 Maximum permissible stresses in fine mesh regions in way of stress concentrations

<table>
<thead>
<tr>
<th>Load cases</th>
<th>Permissible stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined stress $\sigma_e$</td>
</tr>
<tr>
<td>Fine mesh regions with mesh size in accordance with Ch 4, 2.1 Structural modelling 2.1.4</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{coarse}}$, see Note 1</td>
<td></td>
</tr>
<tr>
<td>Average combined stress $\sigma_{\text{average}}$, see Note 2</td>
<td></td>
</tr>
<tr>
<td>Individual element, see Ch 4, 2.1 Structural modelling 2.1.4</td>
<td></td>
</tr>
<tr>
<td>Cases as in Table 2.4.1 Wave load cases to Table 2.4.4 Transverse dynamic load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships</td>
<td></td>
</tr>
<tr>
<td>$1.0\sigma_0$</td>
<td>$-\sigma_0$</td>
</tr>
<tr>
<td>Cases as in Table 2.4.1 Wave load cases to Table 2.4.4 Transverse dynamic load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships</td>
<td></td>
</tr>
<tr>
<td>$1.2\sigma_0$</td>
<td>$-\sigma_0$</td>
</tr>
<tr>
<td>In way of dome openings, see Ch 4, 2.1 Structural modelling 2.1.5</td>
<td></td>
</tr>
<tr>
<td>Peak stress in radius: clear of welds</td>
<td></td>
</tr>
<tr>
<td>Cases as in Table 2.4.1 Wave load cases to Table 2.4.4 Transverse dynamic load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships</td>
<td></td>
</tr>
<tr>
<td>$-\sigma_0$</td>
<td>$1.5\sigma_0$</td>
</tr>
<tr>
<td>Peak stress in radius: in way of welds</td>
<td></td>
</tr>
<tr>
<td>Cases as in Table 2.4.1 Wave load cases to Table 2.4.4 Transverse dynamic load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships</td>
<td></td>
</tr>
<tr>
<td>$-\sigma_0$</td>
<td>$1.2\sigma_0$</td>
</tr>
</tbody>
</table>

NOTES

1. $\sigma_{\text{coarse}}$ 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, see Figure 4.4.1 Mesh area for the calculation of $\sigma_{\text{coarse}}$. 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 discontinuity or abutting structure.

2. $\sigma_{\text{average}}$ is the average combined stress from the element being assessed and the elements connected to its boundary nodes. However, averaging is not to be carried across structural discontinuity or abutting structure.

Table 4.4.2 Maximum permissible stresses in fine mesh regions in way of stress concentrations (Collision load cases)
### Fine mesh regions

with mesh size in accordance with Ch 4, 2.1 Structural modelling 2.1.4

<table>
<thead>
<tr>
<th>$\sigma_{\text{coarse}}$, see Note 1</th>
<th>Cases as in Table 2.4.5 Collision load cases in Ch 2 Analysis of primary structure of membrane tank LNG ships</th>
<th>See Table 2.5.2 Maximum permissible membrane stresses (collision load cases) in Ch 2 Analysis of primary structure of membrane tank LNG ships</th>
<th>See Table 2.5.2 Maximum permissible membrane stresses (collision load cases) in Ch 2 Analysis of primary structure of membrane tank LNG ships</th>
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#### NOTES

1. $\sigma_{\text{coarse}}$ 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, see Figure 4.4.1 Mesh area for the calculation of $\sigma_{\text{coarse}}$. 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 discontinuity or abutting structure.

2. $\sigma_{\text{average}}$ is the average combined stress from the element being assessed and the elements connected to its boundary nodes. However, averaging is not to be carried across structural discontinuity or abutting structure.
Figure 4.4.1 Mesh area for the calculation of $\sigma_{\text{coarse}}$
CHAPTER 1 INTRODUCTION

CHAPTER 2 ANALYSIS OF PRIMARY STRUCTURE OF MEMBRANE TANK LNG SHIPS

CHAPTER 3 ANALYSIS OF TRUNK DECK SCARPHING ARRANGEMENTS WITH THE AFT END

CHAPTER 4 ANALYSIS OF STRUCTURAL DETAILS

CHAPTER 5 APPENDIX A: ALTERNATIVE PROCEDURE FOR TRANSVERSE LOAD CASES (HALF-BREADTH FE MODEL)

SECTION 1 PROCEDURE TO APPLY TRANSVERSE ASYMMETRIC LOADS TO HALF-BREADTH FE MODEL

CHAPTER 6 APPENDIX B: GUIDANCE PROCEDURE TO DETERMINE LONG-TERM TRANSVERSE ACCELERATIONS
Section 1

Procedure to apply transverse asymmetric loads to half-breadth FE model

1.1 Procedure to apply transverse asymmetric loads to half-breadth FE model

1.1.1 The preferred method for analysing the transverse load cases is to use a full-breadth model as described in Ch 2 Analysis of primary structure of membrane tank LNG ships. If, however, the analyst chooses to use a half-breadth model for the transverse cases, the procedure described in this Section may be used.

1.1.2 In order to generate a transverse asymmetric load case for a half-breadth model, it is necessary to apply the transverse loads by combining two separate load cases. These two load cases consist of:

(a) The symmetric load case.

This case applies symmetric loading components and boundary conditions to the FE model, see Figure 5.1.2 Boundary conditions for the application of the symmetric loads to a half-breadth model.

(b) The anti-symmetric load case.

This case applies anti-symmetric loading components and boundary conditions to the FE model, see Figure 5.1.3 Boundary conditions for the application of the anti-symmetric loads to a half-breadth model

1.1.3 If any of the loads do not conform to the above description, or if the structure is not symmetric about the centreline, then this technique is not strictly valid and a full-breadth FE model is required. In this case, it may also be necessary to consider an additional transverse dynamic load case which is heeled in starboard direction with negative transverse acceleration factors.

1.1.4 Using the two load cases shown in Ch 5, 1.1 Procedure to apply transverse asymmetric loads to half-breadth FE model 1.1.2, the different structural response of both sides of the ship to the transverse loads can be derived as follows:

• port asymmetric = symmetric + anti-symmetric
• starboard asymmetric = symmetric - anti-symmetric

This is illustrated in Figure 5.1.1 Derivation of the asymmetric load cases for a half-breadth model from the symmetric and anti-symmetric load cases.

1.1.5 Application of the external hydrostatic pressure corresponding to the heeled waterline for symmetric and anti-symmetric load cases is illustrated in Figure 5.1.1 Derivation of the asymmetric load cases for a half-breadth model from the symmetric and anti-symmetric load cases and is described as follows:

• The symmetric load component for the hydrostatic pressure is applied as half the sum of the pressures on the port and starboard sides. Note it is necessary to modify the side shell pressure distribution as shown in Figure 5.1.1 Derivation of the asymmetric load cases for a half-breadth model from the symmetric and anti-symmetric load cases to satisfy the symmetric load definition stated above.

• The anti-symmetric load component for the external hydrostatic pressure is applied as half the difference of pressure on the port and starboard sides.

1.1.6 The cargo tank pressure loadings are specified in Ch 2, 4.7 Application of loads. If a half-breadth model is used to analyse the transverse cases then, in a similar method as indicated in Ch 5, 1.1 Procedure to apply transverse asymmetric loads to half-breadth FE model 1.1.4, it is necessary to express this pressure distribution as symmetric and anti-symmetric pressure cases.

The total pressure at a point in the tank is given by:

\[ P = p_0 + \rho c \Lambda_p a_\beta g Z_\beta \]

The pressure is to be applied to the symmetrical load case, \( P_{\text{symmetric}} \), and the anti-symmetric load case, \( P_{\text{anti-symmetric}} \), are given by:

\[ P_{\text{symmetric}} = p_0 + 0.5 \cdot \rho c \cdot \Lambda_p \cdot a_\beta \cdot g \cdot \left( Z_{\beta,\text{port}} + Z_{\beta,\text{stbd}} \right) \]
\[ p_{\text{anti-symmetric}} = 0.5 \cdot \rho_c \cdot \Lambda \cdot g \cdot (Z_{\beta, \text{port}} - Z_{\beta, \text{stbd}}) \]

where

\( \mathbf{a}_\beta \) = is resultant acceleration vector at angle \( \beta \), see Ch 2, 4.7 Application of loads 4.7.3 and Figure 2.4.5

Internal tank pressure for transverse dynamic load cases.

\( Z_\beta \) = is the largest liquid height above the point where the pressure is to be determined.

\( Z_{\beta, \text{port}} \) = is the height, \( Z_\beta \) measured to a point on the tank boundary at the port side of the ship.

\( Z_{\beta, \text{stbd}} \) = is the height, \( Z_\beta \) measured to the point on the tank boundary at the starboard side of the ship corresponding to the point used for \( Z_{\beta, \text{port}} \).

See Ch 2, 4.7 Application of loads 4.7.3 for definition of other symbols.

1.1.7 The boundary conditions for the symmetric load case and the anti-symmetric load case are as follows:

- Symmetric load case: See Figure 5.1.2 Boundary conditions for the application of the symmetric loads to a half-breadth model.
- Anti-symmetric load case: See Figure 5.1.3 Boundary conditions for the application of the anti-symmetric loads to a half-breadth model.

1.1.8 The FE model is to be analysed as follows:

- Sub-load case 1: Symmetric condition comprising symmetric loads and symmetric boundary conditions.
- Sub-load case 2: Anti-symmetric condition comprising antisymmetric loads and anti-symmetric boundary conditions.

1.1.9 The load cases to be compared with the stress and buckling criteria given in Ch 2 Analysis of primary structure of membrane tank LNG ships are obtained as follows:

- For the port side of the ship: Sub-load case 1 + sub-load case 2.
- For the starboard side of the ship: Sub-load case 1 − sub-load case 2.

In carrying out these combinations, direct and shear stresses should be combined as indicated above and von Mises stress is to be recalculated from the values of direct and shear stress resulting from the required combination. Buckling factor of safety is to be calculated based on the combined stresses.
Figure 5.1.1 Derivation of the asymmetric load cases for a half-breadth model from the symmetric and anti-symmetric load cases.
**Appendix A: Alternative procedure for transverse load cases (half-breadth FE model)**

*Figure 5.1.2 Boundary conditions for the application of the symmetric loads to a half-breadth model*

*Figure 5.1.3 Boundary conditions for the application of the anti-symmetric loads to a half-breadth model*
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CHAPTER 2 ANALYSIS OF PRIMARY STRUCTURE OF MEMBRANE TANK LNG SHIPS
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CHAPTER 6 APPENDIX B: GUIDANCE PROCEDURE TO DETERMINE LONG-TERM TRANSVERSE ACCELERATIONS

SECTION 1 WAVE SCATTER DIAGRAM AND WAVE SPECTRUM
SECTION 2 MAXIMUM LIFETIME ROLL ANGLES
SECTION 3 MAXIMUM LIFETIME TRANSVERSE ACCELERATIONS
Appendix B: Guidance procedure to determine long-term transverse accelerations

Section 1

1 Wave scatter diagram and wave spectrum
2 Maximum lifetime roll angles
3 Maximum lifetime transverse accelerations

Section 1

Wave scatter diagram and wave spectrum

1.1 Wave scatter diagram and wave spectrum

The IACS recommended wave scattered diagram for the North Atlantic is to be considered for delivering the lifetime maximum roll angle and transverse acceleration. The scatter diagram is shown in Table 6.1.1 IACS recommended wave scatter diagram for the North Atlantic.

Table 6.1.1 IACS recommended wave scatter diagram for the North Atlantic

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Section 2

Maximum lifetime roll angles

2.1 Maximum lifetime roll angles

2.1.1 The lifetime maximum roll angle of the ship is considered to occur in a wave condition lying on the contour of the scatter diagram corresponding to a return period of one wave event in the expected lifetime of the ship. The contour corresponding to a wave event with probability of occurrence equal to once in 20 years for the scatter diagram in Table 6.1.1 IACS recommended wave scatter diagram for the North Atlantic is given in Table 6.2.1 Significant wave height and zero crossing period for 20-year return wave in North Atlantic based on each sea state event of 3 hours’ duration.

2.1.2 Short-term roll responses are to be determined for each sea state given in Table 6.2.1 Significant wave height and zero crossing period for 20-year return wave in North Atlantic. Short-term responses are to be determined based on long crested sea for each wave heading from 0° (head sea) to 180° (following sea) in 15° intervals. ISSC (Bretschneider or two parameter Pierson-Moskowitz) spectrum for fully developed sea is to be used. The ship’s speed variation with significant wave height as given in Table 6.2.2 Variation of ship’s speed against significant wave height is to be considered. A duration of 3 hours is to be considered for the calculation of most probable maximum roll response.

2.1.3 Hydrodynamic software is to be used to calculate the motions in irregular waves for each combination of significant wave height, zero crossing period, ship speed and wave heading. The Ikeda roll damping method or equivalent should be used to determine the equivalent linear damping coefficient for each combination of wave condition, ship speed and wave heading.

2.1.4 The most probable maximum roll angle during the 3 hour period may be determined as follows:

\[ \text{Roll}_{\text{max}} = 2 \times E_0 \times \ln \left( \frac{3 \times 60 \times 60}{ZUC} \right) \]

where

- \( \text{Roll}_{\text{max}} \) = is the most probable maximum roll angle
- \( E_0 \) = is the variance of response
- \( ZUC \) = is the zero up-crossing period of the motion response[s]

2.1.5 The lifetime maximum roll angle of the ship is to be taken as the maximum of the most probable maximum roll angles determined for all combinations of significant wave height, zero cross period, ship speed and wave heading.

Table 6.2.1 Significant wave height and zero crossing period for 20-year return wave in North Atlantic

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Symbols:
- \( T_z \) zero up-crossing period
- \( H_s \) Significant wave height

Table 6.2.2 Variation of ship’s speed against significant wave height

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<th>Significant wave height ( (H_s) )</th>
<th>Ship speed</th>
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<td>75% service speed</td>
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<td>( H_s \leq 5 \text{ m} )</td>
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Section 3

Maximum lifetime transverse accelerations

3.1 Maximum lifetime transverse accelerations

3.1.1 Long-term probability analysis is to be based on equal wave heading probability and variation of ship's speed against significant wave height specified in Table 6.2.2 Variation of ship's speed against significant wave height. ISSC (Bretschneider or two parameter Pierson-Moskowitz) spectrum for fully developed sea with cosine square wave spreading function is to be used for long-term probability analysis.

3.1.2 The roll damping coefficient to be used for the calculation of the ship's long-term transverse accelerations is to be determined by matching the roll angle response (at $10^{-8}$ probability level) obtained by long-term probability analysis with the lifetime maximum roll angle determined in accordance with Ch 6, 2 Maximum lifetime roll angles. This process may take several iterations as it will require calculating a number of long-term roll response curves for a range of assumed roll damping coefficients, see Figure 6.3.1 Determination of linear roll damping coefficient for use in long-term probability analysis of transverse accelerations.

![Figure 6.3.1 Determination of linear roll damping coefficient for use in long-term probability analysis of transverse accelerations](image)

3.1.3 The roll damping coefficient used to derive the long-term roll response that matches the lifetime maximum roll angle determined in accordance with Ch 6, 2 Maximum lifetime roll angles at $10^{-8}$ probability level should be used for long-term probability analysis of transverse accelerations. The long term transverse acceleration determined at $10^{-8}$ probability level is to be used in the transverse dynamic load cases specified in Ch 2 Analysis of primary structure of membrane tank LNG ships.