Primary Structure of Type B Spherical Tank LNG Ships

Guidance on direct calculations

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Section 1: Application

1.1 The ShipRight Structural Design Assessment (SDA) procedure is mandatory for all LNG ships fitted with Independent Type B spherical cargo tanks, as defined by Lloyd's Register's Rules for Ships for Liquefied Gases.

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.

1.3 For compliance with the ShipRight SDA procedure, direct calculations are to be adopted for the determination and verification of the stress level and buckling capability of ship primary structural members, including the structure supporting the cargo tanks as specified in Lloyd's Register's Rules for Ships for Liquefied Gases.

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) are to be complied with.

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.
- Other direct calculations as applicable.

1.6 This document details the SDA procedure for the finite element analysis of the ship's hull structure including tank covers and foundation deck. The primary structure of the ship in the central and bow regions is to be verified using the procedure specified in Chapter 2.

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

1.8 A detailed report of the calculations is to be submitted and must include the information detailed in 3.1. The report must show compliance with the specified structural design criteria given in Sections 5 and 6 of Chapter 2.

1.9 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 1.3.1 of the Rules for Ships.

1.10 Lloyd's Register may require the submission of computer input and output to further verify the adequacy of the calculations carried out.

Section 2: Symbols

Section 3: Direct calculation procedures report
1.11 Ships which have novel features or unusual hull structural or tank configurations may need special consideration and additional load cases may be required.

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

## Section 2: Symbols

2.1 For the purpose of this procedure the following definitions apply:

2.1.1 ‘Hull structure supporting the cargo containment system’ includes the following structural items:
- foundation deck in way of skirts;
- underskirt support structure and all local areas of hull structure to which they are connected;
- cross tank structure;
- hopper tank inner structure in way of base of skirts; and
- side shell and inner hull between the hopper crown and the foundation deck in the forward hold.

2.1.2 ‘Hull structure not supporting the cargo containment system’ includes all structural items not listed in 2.1.1.

2.1.3 ‘Upper surface of the foundation deck’ refers to the boundary between the hull structure and cargo containment system.

2.1.4 Figs. 2.2.2 and 2.2.3 in Chapter 2 give the definitions of other structural items referred to in this document.

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

\[
L = \text{Rule length, in metres, see Pt 3, Ch 1.6 of the Rules for Ships}
\]

\[
B = \text{moulded breadth, in metres, see Pt 3, Ch 1.6 of the Rules for Ships}
\]

\[
D = \text{depth of ship, in metres, see Pt 3, Ch 1.6 of the Rules for Ships}
\]

\[
k_L, k = \text{higher tensile steel factor, see Pt 3, Ch 2.1.2 of the Rules for Ships}
\]

\[
SWBM = \text{still water bending moment}
\]

\[
VWBM = \text{design vertical wave bending moment}
\]

\[
M_w = \text{design vertical wave bending moment, including hog and sag factor, } f_2, \text{ and ship service factor, } f_1, \text{ see Pt 3, Ch 4.5 of the Rules for Ships}
\]

\[
M_{wo} = \text{vertical wave bending moment, excluding hog and sag factor and ship service factor, see Pt 3, Ch 4.5 of the Rules for Ships}
\]

\[
f_1 = \text{the ship service factor, see Pt 3, Ch 4.5 of the Rules for Ships}
\]

\[
f_2 = \text{the hogging/sagging factor, see Pt 3, Ch 4.5 of the Rules for Ships}
\]

\[
M_s = \text{Rule permissible still water bending moment, see Pt 3, Ch 4.5 of the Rules for Ships}
\]

\[
M_s = \text{design still water bending moment, see Pt 3, Ch 4.5 of the Rules for Ships}
\]
\( M_{sw} \) = 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 \( M_s \) and less than or equal to \( M_c \). 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

\( T_{sc} \) = scantling draught

\( T \) = condition draught

\( \theta \) = roll angle

\( C_b \) = block coefficient, see Pt 3, Ch 1,6 of the Rules for Ships

\( x \) = longitudinal distance from amidships to the centre of gravity of the tank, \( x \) is positive forward of amidships

\( V \) = service speed (knots)

\( g \) = gravity constant

\( \rho \) = density of sea-water (specific gravity to be taken as 1,025)

\( h \) = local head for pressure evaluation

\( \rho_c \) = density of cargo (specific gravity to be taken as 0,5)

\( P_o \) = design vapour pressure, see Ch 4,2.6 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 \( \sigma_o \geq 355 \text{ N/mm}^2 \), see Pt 3, Ch 2,1 of the Rules for Ships)

\( \sigma_L = 235/k_L \)

\( \lambda \) = factor against elastic 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

2.3 Consistent units are to be used throughout all parts

2.4 All Rule equations are to use units as defined in the Rules for Ships.
Section 3: Direct calculation procedures report

3.1 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;
- details of loads and stresses applied to the cargo tank skirts from forces acting on the cargo in the spherical tanks;
- 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;
- proposed amendments to structure where necessary, including revised assessment of stresses and buckling properties.
Analysis of Primary Structure of Type B Spherical Tank LNG Ships

Section 1: Objectives
1.1 The objectives 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 the acceptable limits.

1.2 The analysis and applied loading is to be sufficient to evaluate the loads and responses of all primary structural items including:
   • hull structure supporting the cargo containment system;
   • inner and outer hull plating and associated structure;
   • double bottom and hopper structures;
   • cross deck strips and cross tank structures; and
   • cargo tank covers and their connections to upper deck.

1.3 Adequacy of hull structure supporting the cargo containment system is to be investigated either by incorporation of fine mesh areas or by use of separate fine mesh models.

Section 2: Structural modelling
2.1 The 3-D finite element (FE) model is to cover the central and forward cargo tank regions. This is to enable the effects of changes in ship structural arrangements due to hull shape and the higher vertical accelerations in Tank No. 1 to be analysed.

2.2 The FE model is to include cargo tanks and the tank skirts, this is to ensure that the interaction between the tank and hull structure is correctly represented. The model is also to include the cargo tank covers and their connection to the upper deck.

2.3 The minimum length that the FE model is to represent is from the bow to the after bulkhead of the midship cargo hold or the mid-length of the hold aft of midships. In the former case, the bulkhead at the end of the model is to be included.

2.4 This length of FE model should enable the ship's structure over the full cargo hold region to be assessed. If the ship's structure in the after hold(s) is significantly different from the midships hold arrangements, then a full ship FE model is required.

2.5 The appropriate length of the FE model depends on the tank arrangement and is to be agreed with Lloyd's Register at an early stage. The full depth of the ship is to be modelled.

2.6 The procedures specified within this document are based on the assumption that the minimum recommended length FE model is acceptable.
2.7 Unless there is asymmetry of the ship or cargo tank primary structure about the ship's centreline, then 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.

2.8 The FE model of the ship structure is to adopt a right handed Cartesian co-ordinate system with:
- X measured in the longitudinal direction, positive forward;
- Y measured in the transverse direction, positive to port from the centreline; and
- Z measured in the vertical direction, positive upwards from the baseline.

Tank covers may be more appropriately modelled using cylindrical or spherical co-ordinate system depending on the geometry of the tank cover.

2.9 Typical arrangements representing spherical tank LNG ships are shown in Figs. 2.2.1 to 2.2.4. 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.

2.10 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 second longitudinal stiffener;
- longitudinally, one element between double bottom floors;
- vertically, one element between decks, stringers or every second stiffener; and
- three or more elements over the depth of double bottom girders, floors and side transverses in way of areas which are to be analysed in detail with adjacent structure modelled to suit.

2.11 Where the mesh size of the 3-D finite element model is insufficiently detailed to represent areas of high stress concentrations, then these areas 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 sub-modelled or subject to finer meshing are to be discussed with Lloyd's Register at an early opportunity.

2.12 The bow of the ship is to be modelled, but it is not necessary to include all the structure within the bow region. It is sufficient to model most longitudinal plating, stringers and continuous stiffeners together with sufficient transverse structure to support the modelled longitudinal material.

2.13 Areas where a fine mesh is needed include:
- mid-hold hopper tank web frames in way of the foundation deck in hold No.2 and associated structure.
- cross tank centreline web between hold Nos. 1 and 2 and associated structure.

2.14 Other areas where a fine mesh may be needed include:
- hull structure in No. 2 hold supporting the cargo containment system;
- hull structure in No. 1 hold supporting the cargo containment system;
- cargo tank covers and their connection to the upper deck and underdeck girders;
- connection of centreline double bottom girder with cross tank transverse bulkhead;
- connection of longitudinal bulkhead with foundation deck;
- structural areas anticipated to, or found to, experience high stress gradients; or
- areas where there are significantly unusual features, scantlings or constructional arrangements.

2.15 In general, the required mesh size in fine mesh areas is not to be greater than 15t x 15t or 150 x 150 mm, whichever is the lesser, where t is the main plating thickness. The mesh size is not to be less than t x t.

2.16 Secondary stiffening members are to be modelled using line elements positioned in the plane of the plating having axial and bending properties (bars), which may be grouped as necessary. The bar elements are to have:
- a cross-sectional area representing the stiffener area, excluding the area of attached plating (grouped as appropriate); and
- bending properties representing the combined attached plating and stiffener inertia (grouped as appropriate).

2.17 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 and Fig. 2.2.5.

2.18 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.
Table 2.2.1  Line element effective cross-section area

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<th>Structure represented by line element</th>
<th>Effective area, $A_e$</th>
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<td>Primary member face bars</td>
<td>Symmetrical, $A_e = 100% A_n$, Asymmetrical, $A_e = 60% A_n$</td>
</tr>
<tr>
<td>Curved bracket face bars (continuous)</td>
<td>Symmetrical, $A_e = 100% A_n$, Asymmetrical, $A_e = 60% A_n$</td>
</tr>
<tr>
<td>Straight bracket face bars (discontinuous)</td>
<td>Symmetrical, $A_e = 100% A_n$, Asymmetrical, $A_e = 60% A_n$</td>
</tr>
<tr>
<td>Straight bracket face bars (continuous around toe curvature)</td>
<td>Straight portion, Symmetrical, $A_e = 100% A_n$, Asymmetrical, $A_e = 60% A_n$</td>
</tr>
<tr>
<td>Web stiffeners - sniped both ends</td>
<td>Flat bars, $A_e = 25%$ stiffener area</td>
</tr>
<tr>
<td></td>
<td>Other sections, $A_e = \frac{A}{1 + \left(\frac{Y_0}{r}\right)^2} - A_p$</td>
</tr>
<tr>
<td>Web stiffeners - sniped one end, connected other end</td>
<td>Flat bars, $A_e = 75%$ stiffener area</td>
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<tr>
<td></td>
<td>Other sections, $A_e = \frac{A}{1 + \left(\frac{Y_0}{r}\right)^2} - A_p$</td>
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Symbols

$A =$ 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
$Y_0 =$ distance of neutral axis of stiffener and associated plating from median plane of plate
$r =$ radius of gyration $= \sqrt{\frac{I}{A}}$

2.19 Lightening holes, access openings, etc., in primary structure are to be represented in areas of interest. 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.

2.20 Lightening holes, access openings, etc., away from the areas of interest referred to in 2.1.9 may be modelled by deleting the appropriate elements or by applying a correction factor to the resulting shear stresses, see Section 5.

2.21 Modelling of the cargo tank

2.21.1 The cargo tanks are to be modelled using plate bending elements. Offset bar elements may be used to model local stiffening. Depending on the geometry of the cargo tanks, it may be more appropriate to model the cargo tanks using cylindrical or spherical co-ordinate systems.

2.21.2 The use of SPLINE elements (Nastran terminology) or generalised constraint equations to link discontinuous mesh areas is acceptable provided that these areas are clear of areas subjected to high stress gradients.

2.21.3 Full details of the discontinuous mesh areas including example models showing correct behaviour of connecting elements or constraint equations are to be supplied to Lloyd’s Register at an early opportunity.

2.21.4 The purpose of modelling the cargo tanks is for the correct transfer of cargo acceleration inertia loads to the tank supporting structure.
Fig 2.2.1

3D Finite Element model – complete model and port side only
Analysis of Primary Structure of Type B Spherical Tank LNG Ships

Chapter 2
SECTION 2

Figure 2.2.2
View of Hold No. 2 with the cargo tank, skirt and cover removed

- Cross deck bulkhead
- Cross deck strip
- Foundation deck
- Wide side tank
- Line of tank skirt
- Cross tank web
Fig 2.2.3
View of Hold No. 2 showing the internal hull structure
Fig 2.2.4 View of the lower half of Hold Nos. 1 and 2 showing the cargo tank skirt

Note: some spline elements were used to link the skirt to the foundation deck
Effective Area of Face Bars

Effective breadth ratio $\lambda_a$

Effective area of face bars $= \lambda_a b f t f$

Effective breadth ratio $\lambda_a$

Effective area of symmetrical face bars $= \lambda_a b f t f$

Effective area of asymmetric face bars $= \lambda_a b f t f$

Fig 2.2.5 Effective area of face bars
### Section 3: Boundary conditions

#### 3.1 Introduction

3.1.1 The boundary conditions to be applied to the FE model are dependent on the extent of ship modelled and 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.

3.1.3 The boundary conditions suitable for each individual sub-loadcase are shown in Table 2.4.2.

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

#### 3.2 Symmetrical boundary conditions for global loads

3.2.1 Symmetric boundary conditions suitable for the analysis of global loads are shown in Fig. 2.3.1. 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 Fig. 2.3.2. 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, only one load case needs to be considered, as the complete asymmetric load scenario can be applied to the FE model. The boundary conditions suitable for the analysis of the full-breadth are shown in Fig. 2.3.3.

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.

3.4.3 The anti-symmetric boundary conditions suitable for a half-breadth FE model are shown in Fig. 2.3.3. The symmetric boundary conditions suitable for a half-breadth model are the same as those specified for global loads described in 3.2 and shown in Fig. 2.3.1.

#### 3.5 Asymmetric boundary conditions for torsional moments

3.5.1 Asymmetric boundary conditions suitable for the analysis of torsional loads are shown in Fig. 2.3.4. These boundary conditions allow the hull to warp freely under the application of the applied torsional moments.

3.5.2 Only the anti-symmetric load case needs to be considered as there are no symmetric loads applied.
NOTE

When a different co-ordinate system is used for the modelling of the cargo tanks, pipe towers, skirts and tank covers, care should be taken in the application of the boundary condition to ensure compatibility with the co-ordinate system used for the modelling of the hull structure.

For a full-breadth model, the boundary conditions at the end plane are to be applied to both port and starboard sides. No symmetry constraints are to be applied to the centreline plane. A node on the centreline at the keel, at the aft end of the model, is to be constrained in the Y direction.

**Fig 2.3.1**

Boundary conditions for the application of symmetric global loads
Vertical forces distributed to the side shell nodes at WTBs to eliminate reactions at the vertical constraints. These forces remove the imbalance of the model caused by the applied buoyancy.

Longitudinal material, including tank structure rigidly linked to independent point in \( \delta_y \), \( \delta_z \), and \( \vartheta \) degrees of freedom.

\( \delta_y = 0 \) (Only applicable to a full breadth model)

Independent point constrained in all degrees of freedom.

Centerline planes: \( \delta_y = \theta_y = \theta_z = 0 \) (Only applicable to a half breadth model)

NOTE
When a different co-ordinate system is used for the modelling of the cargo tanks, pipe towers, skirts and tank covers, care should be taken in the application of the boundary condition to ensure compatibility with the co-ordinate system used for the modelling of the full structure.

For a full breadth model, the boundary conditions at the end planes and the vertical forces \( F \) at the side shell are to be applied to both port and starboard sides. No symmetry constraints are to be applied to the centerline planes. A node on the centerline at the keel, at the aft end of the model, is to be constrained in the Y direction.

Fig 2.3.2
Boundary conditions for the application of symmetric local loads
Longitudinal material, including tank structure, rigidly linked to the independent point in $\delta_x$, $\delta_y$, $\delta_z$ degrees of freedom.

$\delta_z = 0$
(only applicable to a full-breadth model)

Centreline plane:
Anti-symmetry constraints: $\delta_x = \delta_z = 0$
(Only applicable to a half-breadth model)

**NOTE**
For a half-breadth model, the applied loads are to be separated into symmetric and anti-symmetric components and the model run for each of these load components with the relevant boundary condition set. See Fig. 2.3.1 for the boundary condition set for the symmetric load component.

When a different co-ordinate system is used for the modelling of the cargo tanks, pipe towers, skirts and tank covers, care should be taken in the application of the boundary condition to ensure compatibility with the co-ordinate system used for the hull structure.

For a full-breadth model, the boundary conditions at the end plane are to be applied to both port and starboard sides. No anti-symmetry constraints are to be applied to the centreline plane. The nodes of the elements at the side shell and inner skin at the end of the model are to be constrained in the $z$ direction.

**Fig 2.3.3**
Boundary conditions for the application of global asymmetric loads for transverse subload cases, H1 to H4
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SECTION 3

End plane:
Anti-symmetric constraints
\[ \delta_y = \delta_z = \theta_x = 0 \]

Centreline plane:
Anti-symmetry constraints: \[ \delta_x = \delta_z = \theta_y = 0 \]

(only applicable to a full-breadth model)

(only applicable to both full and half-breadth models)

NOTE

When a different co-ordinate system is used for the modelling of the cargo tanks, pipe towers, skirts and tank covers, care should be taken in the application of the boundary condition to ensure compatibility with the co-ordinate system used for the hull structure.

For a full-breadth model, the boundary conditions at the end plane are to be applied to both port and starboard sides. No anti-symmetry constraints are to be applied to the centreline plane. A node on the centreline at the keel, at the aft end of the model, is to be constrained in the X direction. A light spring, with a stiffness in the order of 0.01 Nmm, is to be applied in the transverse and vertical directions at a point on the keel at the centreline at the forward most watertight bulkhead. The resultant load in the spring is to be checked to ensure that they are not significant.

For a half-breadth model, a light spring is to be applied in the transverse direction only.

Fig 2.3.4

Boundary conditions for the application of the torsional loads
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Section 4: Loading conditions

4.1 Introduction
4.1.1 Table 2.4.1 gives the standard load cases which are to be considered in the stress and buckling assessment. These include load components arising from static and dynamic effects.

4.1.2 Some of the standard load cases in Table 2.4.1 may not need to be examined if the ship is not to operate in such loading conditions. 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. If the ship is in an unusual configuration, then additional load cases may be required.

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, such as intermediate conditions associated with ballast water exchange at sea utilising sequential emptying and filling.

4.1.4 The standard load cases are to be generated by combining the subload cases given in Table 2.4.2 and illustrated in Fig. 2.4.1. These subload cases form the loading conditions to be applied to the structural model and are summarised in 4.2.

4.1.5 The fully loaded conditions are defined as the scantling draught condition 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.

4.2 Subload cases

4.2.1 Still water and Rule vertical bending moment
4.2.1.1 These subload cases are based on the specified ship’s operating loading conditions and include all static load components. The actual draughts and all deadweight and lightweight items are to be applied.

4.2.1.2 The Rule design wave vertical bending moment distribution and the permissible vertical still water bending moment envelope, $M_{sw}$ (see Ch 1.2), are to be applied. Explanatory notes for the application of the vertical bending moments are given in 4.3.5.

4.2.2 Vertical dynamic
4.2.2.1 These subload cases may be based on the fully loaded condition. The subload cases are to be evaluated using quasi-static techniques. The maximum downward vertical acceleration as described in 4.3.4 is applied to all deadweight and lightweight items and the resulting dynamic condition is balanced on a trimmed waterline.

4.2.2.2 The dynamic loading condition and quasi-static trimmed waterline are derived using a still water loads program. No wave profile is to be added to the trimmed waterline.

4.2.2.3 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 static pressure and dynamic pressure due to vertical and longitudinal accelerations.
- Inertia forces of structural mass and other deadweight items are to include vertical acceleration factor.
- Inertia forces of cargo tanks and skirt structure are to include longitudinal and vertical acceleration factors.
- 80% of the Rule design vertical wave bending moment distribution.

Explanatory notes for the application of the vertical bending moments is given in 4.3.5.

4.2.2.4 The generated loading condition reflects the ship at:
- maximum downward heave;
- maximum bow down pitch and hence deep draught forward; and
- maximum downwards inertial acceleration over the forward end.

4.2.2.5 If the ship structure aft of amidships is also to be analysed, then the bow pitched up vertical dynamic load cases are also to be considered.

4.2.2.6 Explanatory notes for the application of the vertical dynamic subload cases are given in 4.3.1 to 4.3.5.

4.2.3 Transverse dynamic
4.2.3.1 All loading conditions are to be reviewed to determine which gives the greatest transverse acceleration component in each of the loaded tanks. If the ship is intended to operate with one or more cargo tanks empty, it is necessary to consider alternate and single tank loading cases.
4.2.3.2 These subload cases are to be based on the following two loading conditions:

- condition that results in greatest transverse acceleration of number one cargo tank including its contents; and
- condition that results in greatest transverse acceleration of number two cargo tank including its contents.

4.2.3.3 If the structure supporting the other cargo tanks is significantly different from that of numbers one and two tanks, then further load cases may be required to verify the scantlings of this structure (see 2.4).

4.2.3.4 To simulate the dynamic transverse loads on the cargo tank structure, the cargo tank structure, including tank skirt, and its contents are to be subjected to a transverse acceleration, equal to $A_y g$, and a vertical acceleration, equal to $g$. These accelerations are relative to the ship's axes and include the effect of gravity. The value of $A_y$ is not to be taken as less than 0.58, see 4.3.2.3.

4.2.3.5 These subload cases are to be evaluated using quasi-static techniques. The ship is to be heeled to an angle, $\theta$, and the dynamic condition resulting from the accelerations given in 4.2.3.4 is balanced on a trimmed waterline using a still water loads program, see Fig. 2.4.2. The resultant external hydro-static pressure is to be based on the ship heeled waterline. No wave profile is to be added to the trimmed waterline. The heel angle, $\theta$, is to be taken as the greater of $\tan^{-1} A_y$ or 30°. The heeled waterline need not be taken beyond the upper deck at side, provided that the heel angle, $\theta$, is not less than 30°.

4.2.3.6 Normally a positive heel angle is considered to be to port. Hence transverse acceleration will be positive in the port (positive Y) direction.

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

- External hydrostatic pressures due to the heeled and trimmed waterline. The pressure head distribution is given in Fig. 2.4.2.
- Cargo pressure loads acting on the cargo tank structure. These loads are to include cargo pressure due to the transverse and vertical accelerations described in 4.2.3.4.
- Inertia forces of cargo tank and skirt structure due to the transverse and vertical accelerations described in 4.2.3.4.
- Transverse and vertical components of the ship's structural weight and other items of deadweight in the heeled condition.
- 60% of Rule design vertical wave bending moment distribution.
- Permissible vertical still water bending moment envelope, $M_{sw}$, see Ch 1.2.

Explanatory notes for the application of the vertical bending moments are given in 4.3.5.

4.2.3.8 Explanatory notes for application of the transverse dynamic load cases are given in 4.3.1 to 4.3.5.

4.2.3.9 If only half the breadth of the ship has been modelled, then these subload cases are need to be derived by combining the symmetric and anti-symmetric load components, see Appendix A.

4.2.4 Hydrodynamic torque:

4.2.4.1 A hydrodynamic torque is to be applied in conjunction with selected loading conditions to enable the adequacy of the cross deck strip, the cargo tank covers and their connections to upper deck, and other structural members to be assessed under combined torsional and bending loads.

4.2.4.2 The Rule hydrodynamic torque distribution is to be applied as subload case K in Table 2.4.2 and then combined with the results of other subload cases as specified in Table 2.4.1. The method of application of the hydrodynamic torque is given in 4.3.8.

4.2.5 Local wave effects:

4.2.5.1 The effects of local wave pressure are included by assuming a constant wave head along the full length of the FE model, see 4.3.6. Separate subload cases are required for the wave crest and trough conditions, see subload cases L and M in Table 2.4.2. These results are to be combined with results from other subload cases as specified in Table 2.4.1 before carrying out stress and buckling checks.

4.2.6 Collision

4.2.6.1 The collision subload case may be based on the fully loaded condition.

4.2.6.2 All static load components and external hydrostatic pressures due to the static waterline for this condition are to be applied.

4.2.6.3 A forward acceleration of 0.5g is to be applied in the longitudinal direction to the ship structural mass and the cargo in the tanks.

4.3 Procedures to derive subload cases

4.3.1 General

4.3.1.1 All components of a loading condition are to be included in the analysis. The lightship is to be included by adjusting the selfweight of the model to equal the required lightweight.
4.3.1.2 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.

4.3.1.3 Cargo loads and the additional acceleration factors are to be applied as pressures directly to the elements representing the tank plating. The design vapour pressure, $P_o$, may be taken as zero for the analysis of hull structure. The following equations are to be used to determine the pressure values, see also Figs. 2.4.3 to 2.4.5.

For still water:
$$ P = \rho_c g h_z + P_o $$

For vertical dynamic:
$$ P = \rho_c g h_z (1 + A_z) + \rho_c g h_x A_x + P_o $$

For transverse dynamic:
$$ P = P_{\text{sym}} + P_{\text{asym}} $$
where
$$ P_{\text{sym}} = \rho_c g h_y A_y $$
$$ P_{\text{asym}} = \rho_c g h_y (H_y - R) $$

4.3.1.4 The pressure heads in the above expressions are measured as follows:
- $h_z$ forward from the after end of the tank, for pitching bow down accelerations,
- $h_x$ transversely from the starboard tank side plating,
- $h_y$ vertically down from the highest point of the tank.

4.3.2 Selection of maximum acceleration factors

4.3.2.1 The longitudinal and transverse acceleration factors may be derived using the guidance formula in the Rules for Ships for Liquefied Gases, Ch 4.4.12. The vertical acceleration factors for the vertical dynamic subload cases are to be derived in accordance with 4.5. The block coefficient at the full load draught is to be used for all load conditions.

4.3.2.2 ShipRight program No. 20601 'LNG/LPG Acceleration Heads' may 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.

4.3.2.3 In order to comply with the IGC Code requirement that tank structures are to be able to sustain a $30^\circ$ static heel condition, the transverse acceleration factor, $A_y$, to be applied to the transverse dynamic subload cases is not to be taken as less than $\tan 30^\circ$. It is necessary to increase the transverse acceleration factor to $\tan 30^\circ$, or 0.58, if the calculated value is found to be less.

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

4.3.3 Procedure to derive the quasi-static waterline for dynamic load cases

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

4.3.3.2 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.

4.3.3.3 A vertical acceleration factor (relative to $g$) at the longitudinal centre of gravity of each section is to be calculated, in accordance with 4.3.4 and added the static gravity of $g$.

4.3.3.4 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.

4.3.3.5 The resulting quasi-static trimmed waterline is to be used to apply the external hydrostatic pressures to shell plating elements. For the dynamic transverse subload cases, the external hydrostatic pressure is to be based on the ship heeled to an angle of $\theta$ degrees, see 4.2.3.

4.3.4 Calculation of vertical acceleration factor along the length of the ship

4.3.4.1 For the dynamic vertical subload cases, the vertical acceleration factor is to be derived in accordance with this Section. The effect of gravity is not included in this vertical acceleration factor.
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### Load Still water Rule vertical Combination of Case Load case description See Notes Static wave load cases

<table>
<thead>
<tr>
<th>Load Case No.</th>
<th>Load case description</th>
<th>Still water bending moment</th>
<th>Rule vertical wave bending moment</th>
<th>Additional subload cases to apply</th>
<th>Combination of subload cases See Table 2.4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Full load + Hogging wave</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>Wave crest</td>
<td>A1 + L</td>
</tr>
<tr>
<td>S2</td>
<td>Full load + Sagging wave</td>
<td>$M_{sw}$ sagging</td>
<td>Sagging</td>
<td>Wave trough</td>
<td>A2 + M</td>
</tr>
<tr>
<td>S3</td>
<td>Alternate load odd numbered tanks full (hog) + hogging wave</td>
<td>1, 2</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>Wave crest</td>
</tr>
<tr>
<td>S4</td>
<td>Alternate load odd numbered tanks full (sag) + sagging wave</td>
<td>2</td>
<td>$M_{sw}$ sagging</td>
<td>Sagging</td>
<td>Wave trough</td>
</tr>
<tr>
<td>S5</td>
<td>Alternate load even numbered tank full (hog) + hogging wave</td>
<td>2</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>Wave crest</td>
</tr>
<tr>
<td>S6</td>
<td>Alternate load even numbered tank full (sag) + sagging wave</td>
<td>1, 2</td>
<td>$M_{sw}$ sagging</td>
<td>Sagging</td>
<td>Wave trough</td>
</tr>
<tr>
<td>S7</td>
<td>Heavy ballast + Hogging wave</td>
<td>1</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>Wave crest</td>
</tr>
</tbody>
</table>

### Hydrodynamic torque load cases

<table>
<thead>
<tr>
<th>Load Case No.</th>
<th>Load case description</th>
<th>Still water bending moment</th>
<th>Rule vertical wave bending moment</th>
<th>Additional subload cases to apply</th>
<th>Combination of subload cases See Table 2.4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>S8</td>
<td>Full load + Hogging BM + Torque</td>
<td>1</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>Wave crest</td>
</tr>
<tr>
<td>S9</td>
<td>Full load + Sagging BM + Torque</td>
<td></td>
<td>$M_{sw}$ sagging</td>
<td>Sagging</td>
<td>Wave crest</td>
</tr>
</tbody>
</table>

### Vertical dynamic load cases

<table>
<thead>
<tr>
<th>Load Case No.</th>
<th>Load case description</th>
<th>Still water bending moment</th>
<th>Rule vertical wave bending moment</th>
<th>Additional subload cases to apply</th>
<th>Combination of subload cases See Table 2.4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Full load vertical dynamic + Hogging BM</td>
<td>1</td>
<td>$M_{sw}$ hogging</td>
<td>80% Hogging</td>
<td>Additional side shell pressure</td>
</tr>
<tr>
<td>V2</td>
<td>Full load vertical dynamic + Sagging BM</td>
<td>1</td>
<td>$M_{sw}$ sagging</td>
<td>80% Sagging</td>
<td>Additional side shell pressure</td>
</tr>
</tbody>
</table>

### Transverse dynamic load cases

<table>
<thead>
<tr>
<th>Load Case No.</th>
<th>Load case description</th>
<th>Still water bending moment</th>
<th>Rule vertical wave bending moment</th>
<th>Additional subload cases to apply</th>
<th>Combination of subload cases See Table 2.4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Transverse dynamic maximum acceleration in No.1 cargo tank + Hogging BM</td>
<td>1, 3</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>None</td>
</tr>
<tr>
<td>T2</td>
<td>Transverse dynamic maximum acceleration in No.1 cargo tank + Sagging BM</td>
<td>3</td>
<td>$M_{sw}$ sagging</td>
<td>Sagging</td>
<td>None</td>
</tr>
<tr>
<td>T3</td>
<td>Transverse dynamic maximum acceleration in No.2 cargo tank + Hogging BM</td>
<td>3</td>
<td>$M_{sw}$ hogging</td>
<td>Hogging</td>
<td>None</td>
</tr>
<tr>
<td>T4</td>
<td>Transverse dynamic maximum acceleration in No.2 cargo tank + Sagging BM</td>
<td>1, 3</td>
<td>$M_{sw}$ sagging</td>
<td>Sagging</td>
<td>None</td>
</tr>
</tbody>
</table>

### Special load cases

<table>
<thead>
<tr>
<th>Load Case No.</th>
<th>Load case description</th>
<th>Still water bending moment</th>
<th>Rule vertical wave bending moment</th>
<th>Additional subload cases to apply</th>
<th>Combination of subload cases See Table 2.4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>Forward collision, full load condition</td>
<td>1</td>
<td>Actual</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

### NOTES

1. It is recommended these load cases be analysed at the early stage of the assessment.
2. These load cases may not need to be examined if the ship is not to have the corresponding degree of operational flexibility and the applicable loading conditions are not included in the Loading Manual, see 4.1.2.
3. This subload case is to be based on the loading condition that results in greatest transverse acceleration of the tank and its contents. This is likely to be a single tank loading condition.
4. Permissible still water bending moment, $M_{sw}$, see Ch 1,2.
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4.3.4.2 The guidance vertical acceleration formula given in the Rules for Ships for Liquefied Gases is modified, as shown 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.

4.3.4.3 Formula for vertical acceleration factor:

For \( x \geq -0.05L \)
\[
A_z = A_o \left[ 1 + \left( \frac{5.3 - \frac{45}{L}}{L} \right)^2 \left( \frac{x}{L} + 0.08 \right)^2 \left( \frac{0.6}{C_b} \right)^{1.5} \right]
\]

For \( x < -0.05L \)
\[
A_z = -A_o \left[ 2 - \left( \frac{5.3 - \frac{45}{L}}{L} \right)^2 \left( \frac{x}{L} + 0.08 \right)^2 \left( \frac{0.6}{C_b} \right)^{1.5} \right]
\]

where
\[ A_o = 0.2 \left( \frac{V}{L} \right) + \frac{34 - 600}{L} \]

4.3.4.4 The distribution of vertical acceleration factor is illustrated in Fig. 2.4.6. The vertical acceleration equations, given in 4.3.4.3, are based on a ship motion of heave downwards and bow pitched down.

4.3.5 Procedure to apply Rule permissible still water and design vertical wave bending moments

4.3.5.1 The vertical wave bending moment, \( \alpha M_{sw} \), and permissible vertical still water bending moment envelope, \( M_{sw} \), are to be applied to the FE model for all subload cases, with the exception of the collision subload case O1, see Tables 2.4.1 and 2.4.2, where:
\[ \alpha \] is the required portion of the Rule design vertical bending moment to be applied, \( \alpha \) equal to 0.8 for the vertical dynamic subload cases G1 and G2, \( \alpha \) equal to 0.6 for transverse dynamic subload cases H1 to H4 and the still water subload cases A3 and A4, and \( \alpha \) equal to 1.0 for other required subload cases.
\[ M_{sw}, M_{sw} \] see Ch 1,2.

4.3.5.2 The actual 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 Fig. 2.4.7. This bending moment distribution takes account of the still water bending moment created by the subload case’s loading condition. Care is to be taken in the sign convention of sagging and hogging in deriving the required bending moment distribution.

4.3.5.3 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.

4.3.5.4 The distribution of the vertical forces in 4.3.5.3 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.

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

4.3.6 Procedure to apply local wave crest or trough

4.3.6.1 An additional wave head is to be applied over the full length of the FE model using the pressure distribution shown in Fig. 2.4.8.

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

4.3.7 Procedure to apply additional side shell pressure

4.3.7.1 Additional pressure is to be applied to the side shell plating above the level of the foundation deck at midship. This pressure is to be applied over the full length of the FE model. No other loads are to be applied.

4.3.7.2 The additional side shell pressure is required in order to consider local strength, with emphasis on the structure supporting the cargo containment system.

4.3.7.3 The additional side shell pressure is to be applied as subload case N, see Table 2.4.2. The stress result is to be combined with that from the other subload cases required for the Vertical Dynamic Load Cases in Table 2.4.1.
Table 2.4.2  List of subload cases  (see continuation)

<table>
<thead>
<tr>
<th>Subload case</th>
<th>Condition</th>
<th>Boundary conditions</th>
<th>Notes</th>
</tr>
</thead>
</table>
| A1           | Full load + hogging BM  
All cargo tanks full | Symmetric global  
see Fig. 2.3.1 | • A loading condition with all cargo tanks filled and at full load draught.  
• All still water load items are to be applied.  
• External hydrostatic pressure due the static waterline are to be applied.  
• Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied. |
| A2           | Full load + sagging BM  
All cargo tanks full | As subload case A1 | As subload case A1 except as follows:  
• Rule sagging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied. |
| A3           | Full load + hogging BM  
(60% VWBM)  
All cargo tanks full | As subload case A1 | As subload case A1 except as follows:  
• 60% Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied. |
| A4           | Full load + sagging BM  
(60% VWBM)  
All cargo tanks full | As subload case A1 | As subload case A1 except as follows:  
• 60% Rule sagging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied. |
| B            | Alternate load odd  
numbered tanks full (hog) +  
hogging BM  
Nos. 1 & 3 (& 5) tanks full | Symmetric global  
see Fig. 2.3.1 | • Alternately loaded condition with all odd numbered cargo tanks full and even numbered tanks empty.  
• Ballast and fuel tanks are to be arranged to maximise the hogging vertical bending moment, see Note 1.  
• Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied.  
• Boundary conditions and other load application are similar to subload case A1. |
| C            | Alternate load odd  
numbered tanks full (sag) +  
sagging BM  
Nos. 1 & 3 (& 5) tanks full | As subload case B | As subload case B except as follows:  
• Ballast and fuel tanks are to be arranged to maximise the sagging vertical bending moment, see Note 1.  
• Rule sagging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied. |
| D            | Alternate load even  
numbered tanks full (hog) +  
hogging BM  
Nos. 2 & 4 tanks full | Symmetric global  
see Fig. 2.3.1 | • Alternately loaded condition with all even numbered cargo tanks full and odd numbered tanks empty.  
• Ballast and fuel tanks are to be arranged to maximise the hogging vertical bending moment, see Note 1.  
• Rule hogging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied.  
• Boundary conditions and other load applications are similar to subload case A1. |
| E            | Alternate holds even  
numbered tanks full (sag)  
sagging BM  
Nos. 2 & 4 tanks full | As subload case D | As subload case D except as follows:  
• Ballast and fuel tanks are to be arranged to maximise the sagging vertical bending moment and obtain a deep draft, see Note 1.  
• Rule sagging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied. |
| F            | Heavy ballast + hogging BM | Symmetrical global  
see Fig. 2.3.1 | • A deep draught ballast loading condition with most water ballast tanks filled.  
• Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied.  
• Boundary conditions and load application is similar to subload case A1. |
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**Table 2.4.2  List of subload cases** *(see continuation)*

<table>
<thead>
<tr>
<th>Subload case</th>
<th>Condition</th>
<th>Boundary conditions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dynamic subload cases</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| G1 | Full load vertical dynamic condition + hogging BM  
All cargo tanks full  
Bow pitched down | Symmetrical global  
see Fig. 2.3.1 | A loading condition with all cargo tanks filled and at full load draught  
All still water deadweight and lightweight items are to be applied and are to include the vertical acceleration factor, see 4.3.1.  
Cargo pressures are to include vertical and longitudinal acceleration factors, see 4.3.1.  
External hydrostatic pressures due to the quasi-static trimmed waterline are to be applied, see 4.3.3.  
80% Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied. |
| G2 | Full load vertical dynamic condition + sagging BM  
All cargo tanks full | As subload case G1 | As subload case G1 except as follows:  
80% Rule sagging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied. |
| H1 | Transverse dynamic maximum acceleration in No. 1 cargo tank + hogging BM | Full breadth model  
Asymmetric case  
see Fig. 2.3.3  
Half breadth model  
Symmetric case  
see Fig. 2.3.1  
Anti-symmetric case  
see Fig. 2.3.1 | The loading condition which generates maximum transverse acceleration in No.1 cargo tank and its contents is to be chosen. This is usually a single tank loading condition.  
Ballast and fuel tanks are to be arranged to maximise the hogging vertical bending moment, see Note 1.  
The subload case is to be based on the ship heeled at an angle of $\theta$, see 4.2.3.  
All still water deadweight and lightweight items are to be applied.  
Cargo tank structure and its contents are to be subjected to the transverse and vertical accelerations specified in 4.2.3. These accelerations include the effect of gravity.  
Cargo pressures are to include effect of the transverse and vertical accelerations specified in 4.2.3.  
External hydrodynamic pressures due to the quasi-static trimmed waterline are to be applied, see Fig. 2.4.2.  
60% Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied. |
| H2 | Transverse dynamic maximum acceleration in No. 1 cargo tank + sagging BM | As subload case H1 | As subload case H1 except as follows:  
Ballast and fuel tanks are to be arranged to maximise the sagging vertical bending, see Note 1.  
60% Rule sagging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied. |
| H3 | Transverse dynamic maximum acceleration in No.2 cargo tank + hogging BM | As subload case H1 | The loading condition which generates maximum transverse acceleration in No.2 cargo tank and its contents is to be chosen. This is usually a single tank loading condition.  
Ballast and fuel tanks are to be arranged to maximise the hogging vertical bending moment, see Note 1.  
The subload case is to be based on the ship heeled at an angle of $\theta$, see 4.2.3.  
60% Rule hogging vertical design wave bending moment distribution and permissible hogging still water bending moment envelope, $M_{sw}$, are to be applied.  
Boundary conditions and other load applications are similar to subload case H1. |
| H4 | Transverse dynamic maximum acceleration in No.2 cargo tank + sagging BM | As subload case H1 | As subload case H3 except as follows:  
Ballast and fuel tanks are to be arranged to maximise the sagging vertical bending moment, see Note 1.  
60% Rule sagging vertical design wave bending moment distribution and permissible sagging still water bending moment envelope, $M_{sw}$, are to be applied. |
Table 2.4.2  List of subload cases  (conclusion)

<table>
<thead>
<tr>
<th>Subload case</th>
<th>Condition</th>
<th>Boundary conditions</th>
<th>Notes</th>
</tr>
</thead>
</table>
| K            | Hydrodynamic torque case | Asymmetric torsion see Fig. 2.3.5 | • Torsional moments are to be applied to transverse bulkhead positions to generate the Rule hydrodynamic torque distribution as given in Pt 4, Ch 8, 1.5.1 of the Rules for Ships, see 4.3.8 and Fig. 2.4.10.  
• No other load components are to be applied. |
| L            | Local wave crest | Symmetric local see Fig. 2.3.2 | • Only the pressure due to a local wave crest is to be applied, see 4.3.6.  
• It is to be assumed that the wave crest acts over the full length of the FE model.  
• The ship’s scantling draught may be used for deriving the pressure head distribution. |
| M            | Local wave trough | Symmetric local see Fig. 2.3.2 | • Only the pressure due to a local wave trough is to be applied, see 4.3.6.  
• It is to be assumed that the wave crest acts over the full length of the FE model.  
• The ship’s scantling draught may be used for deriving the pressure head distribution. |
| N            | Additional side shell pressure | Symmetric global see Fig. 2.3.1 | • Only side pressure defined in 4.3.7 is to be applied to the side shell.  
• This pressure is to be applied over the full length of the FE model. |
| O1           | Forward collision | Symmetric global as in Fig. 2.3.1, except that δx constraint is to be removed from the end plane and added to a point at the forward of the bow | • A fully loaded condition with all cargo tanks filled and at full load draught acceleration in No.2 cargo tank and its contents is to be chosen.  
• All still water items to be applied.  
• External hydrostatic pressures due to the static waterline for this condition to be applied.  
• A forward acceleration of 0.5g is to be applied in the longitudinal direction to all LNG cargo and tank structure and the self-weight of the model. |

**NOTES**

1. These subload cases are to include ballast in the wide side tanks, narrow side wing tanks and or cross ballast tanks if it is considered that:
   (i) the loading of these tanks is likely to occur with this cargo arrangement; and  
   (ii) the loading of these tanks would result in higher stresses in primary members or the structure supporting the containment system.  
2. Permissible still water bending moment, $M_{SW}$, see Ch 1.2.
### S1 Full load + hogging wave

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully loaded</td>
<td></td>
</tr>
<tr>
<td>External pressure</td>
<td>Hydrostatic due to static waterline</td>
</tr>
<tr>
<td>Cargo pressure</td>
<td>Cargo pressure due to gravity</td>
</tr>
<tr>
<td>Additional applied BM</td>
<td>SWBM: $M_{sw}$ hogging – actual VWBM: Rule hogging</td>
</tr>
<tr>
<td>External pressure</td>
<td>Local wave crest (to be applied to full length of FE model)</td>
</tr>
</tbody>
</table>

### S2 Full load + sagging wave

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully loaded</td>
<td></td>
</tr>
<tr>
<td>External pressure</td>
<td>Hydrostatic due to static waterline</td>
</tr>
<tr>
<td>Cargo pressure</td>
<td>Cargo pressure due to gravity</td>
</tr>
<tr>
<td>Additional applied BM</td>
<td>SWBM: $M_{sw}$ sagging – actual VWBM: Rule sagging</td>
</tr>
<tr>
<td>External pressure</td>
<td>Local wave trough (to be applied to full length of FE model)</td>
</tr>
</tbody>
</table>

### S3 Alternate load odd numbered tanks full (hogs) + hogging wave

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternate holds 1 &amp; 3 (hoggling condition)</td>
<td></td>
</tr>
<tr>
<td>External pressure</td>
<td>Hydrostatic due to static waterline</td>
</tr>
<tr>
<td>Cargo pressure</td>
<td>Cargo pressure due to gravity</td>
</tr>
<tr>
<td>Additional applied BM</td>
<td>SWBM: $M_{sw}$ hogging – actual VWBM: Rule hogging</td>
</tr>
<tr>
<td>External pressure</td>
<td>Local wave crest (to be applied to full length of FE model)</td>
</tr>
</tbody>
</table>

---

**Fig 2.4.1**

Illustration of load cases – Part 1
Fig 2.4.1
Illustration of load cases – Part 2
<table>
<thead>
<tr>
<th>Subload cases</th>
<th>Loading condition</th>
<th>External pressure</th>
<th>Cargo pressure</th>
<th>Additional applied BM</th>
<th>Hydrodynamic torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7</td>
<td>Heavy ballast</td>
<td>Hydrostatic due to static waterline</td>
<td>Cargo pressure due to gravity</td>
<td>SWBM: ( M_{\text{sw}} ) hogging – actual ( M_{\text{sw}} ) hogging – applied actual ( M_{\text{sw}} )</td>
<td>Rule hydrodynamic torque distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VWBM: 60% Rule hogging</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>Fully loaded</td>
<td>Hydrostatic due to static waterline</td>
<td>Cargo pressure due to gravity</td>
<td>SWBM: ( M_{\text{sw}} ) hogging – actual ( M_{\text{sw}} )</td>
<td>Rule hydrodynamic torque distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VWBM: 60% Rule hogging</td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>Fully loaded</td>
<td>Hydrostatic due to static waterline</td>
<td>Cargo pressure due to gravity</td>
<td>SWBM: ( M_{\text{sw}} ) sagging – actual ( M_{\text{sw}} )</td>
<td>Rule hydrodynamic torque distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VWBM: 60% Rule sagging</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.4.1
Illustration of load cases – Part 3
### Analysis of Primary Structure of Type B Spherical Tank LNG Ships

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**T1 Transverse dynamic maximum acceleration in No.1 tank + hogging BM**

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Pressure and Cargo pressures</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1 tank loaded, ship heeled to port, at an angle specified in 4.2.3 (see Note 2)</td>
<td>Hydrostatic due to heel and quasi-static trimmed waterline, Cargo pressure due to gravity, vertical and longitudinal accelerations, SWBM: ( M_{SW} ) hogging – actual, VWBM: 60% Rule hogging</td>
<td>H1</td>
</tr>
</tbody>
</table>

**V1 Full load vertical dynamic + hogging BM cases**

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Pressure and Cargo pressures</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully loaded (vertical acceleration factor applies), see Note 1</td>
<td>Hydrostatic due to quasi-static trimmed waterline, Cargo pressure due to gravity, vertical and longitudinal accelerations</td>
<td>G1</td>
</tr>
</tbody>
</table>

**External Hydrostatic due to heel and \( H_1 \) pressure quasi-static trimmed waterline**

**Cargo pressure induced by pressure transverse and vertical accelerations**

**Additional SWBM:**

- Actual \( M_{SW} \) hogging
- 60% Rule hogging

**Additional SWBM:**

- Actual \( M_{SW} \) sagging
- 80% Rule sagging

**V2 Full load vertical dynamic + sagging BM cases**

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Pressure and Cargo pressures</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully loaded (vertical acceleration factor applies), see Note 1</td>
<td>Hydrostatic due to quasi-static trimmed waterline, Cargo pressure due to gravity, vertical and longitudinal accelerations</td>
<td>G2</td>
</tr>
</tbody>
</table>

**External Hydrostatic due to quasi-static \( G_1 \) pressure trimmed waterline**

**Cargo pressure due to gravity, pressure vertical and longitudinal accelerations**

**External Additional pressure on side shell above foundation deck level at midship**

**V1 Full load vertical dynamic + hogging BM cases**

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Pressure and Cargo pressures</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully loaded (vertical acceleration factor applies), see Note 1</td>
<td>Hydrostatic due to quasi-static trimmed waterline, Cargo pressure due to gravity, vertical and longitudinal accelerations</td>
<td>G1</td>
</tr>
</tbody>
</table>

**External Hydrostatic due to heel and \( H_1 \) pressure quasi-static trimmed waterline**

**Cargo pressure induced by pressure transverse and vertical accelerations**

**Additional SWBM:**

- Actual \( M_{SW} \) hogging
- 60% Rule hogging

**External Additional pressure on side shell above foundation deck level at midship**

**Illustration of load cases – Part 4**

**Notes:**

1. Vertical dynamic load cases: Cargo tank and skirt structures are to include vertical and longitudinal accelerations
2. Transverse dynamic load cases: Maximum transverse acceleration in a tank is usually achieved by a single tank loading condition. Cargo tank and skirt structures are to include vertical and transverse accelerations, see 4.2.3
### Analysis of Primary Structure of Type B Spherical Tank LNG Ships

#### Section 4

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Subload cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>Transverse dynamic maximum acceleration in No.1 tank + sagging BM</td>
<td><img src="T2.png" alt="Image" /></td>
</tr>
<tr>
<td>T3</td>
<td>Transverse dynamic maximum acceleration in No.2 tank + hogging BM</td>
<td><img src="T3.png" alt="Image" /></td>
</tr>
<tr>
<td>T4</td>
<td>Transverse dynamic maximum acceleration in No.2 tank + sagging BM</td>
<td><img src="T4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Fig 2.4.1**

**Illustration of load cases – Part 5**

**NOTE:**
1. Transverse dynamic load cases: Maximum transverse acceleration in a tank is usually achieved by a single tank loading condition. Cargo tank and skirt structures are to include vertical and transverse accelerations, see 4.2.3.

**NOTE:**
- Transverse dynamic load cases: Maximum transverse acceleration in a tank is usually achieved by a single tank loading condition. Cargo tank and skirt structures are to include vertical and transverse accelerations, see 4.2.3.
- **External pressure**: Hydrostatic due to heel and quasi-static trimmed waterline.
- **Additional applied BM**: SWBM: $M_{sw}$ sagging – actual WWBM: 60% Rule sagging.
- **Cargo pressure**: Cargo pressure induced by transverse and vertical accelerations.
Fig 2.4.1
Illustration of load cases – Part 6

- O1 Forward Collision, full load condition
- Loading condition
- External pressure
- Cargo pressure due to gravity and longitudinal forward accelerations of 0.5g

NOTE: Forward accelerations of 0.5g are to be applied to the cargo and model structural mass.
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, measures at the centreline
- $y$ = transverse distance from centreline, positive to port

**Fig 2.4.2**

Hydrostatic pressure distribution in heeled condition for transverse dynamic loadcase, see 4.2.3.5

**Fig 2.4.3**

Symmetric pressure load distribution $P_{sym}$ for transverse dynamic subload cases
Fig 2.4.4
Asymmetric pressure load distribution $P_{\text{asym}}$ for transverse dynamic subload cases
($P_{\text{asym}}$ to be calculated in accordance with 4.3.1.3)

Symmetric and anti-symmetric pressure load distribution $P_{\text{sym}}$ and $P_{\text{anti-sym}}$ for applying asymmetric pressure load distribution to a half-breadth FE model
4.3.7.4 At any hull section along the length of the ship where $\text{WL}_1 > \text{WL}_2$, additional side shell pressure is to be applied in accordance with 4.3.7.5. No side pressure needs to be applied if $\text{WL}_1 \leq \text{WL}_2$, where:
- $\text{WL}_1$ is a waterline corresponding to a constant draught $T_{\text{WL1}}$
- $\text{WL}_2$ is the quasi-static trimmed waterline of the vertical dynamic loadcase $G_1$ or $G_2$
- $T_{\text{WL1}}$ in metres, is to be calculated as follows:
  - For ships less than 250 m in length:
    $$T_{\text{WL1}} = 0.056 L - 3 + 0.68 T_{\text{sc}}(L)$$
  - For ships of 250 m in length and above:
    $$T_{\text{WL1}} = 7.136 C_{\text{bl}} + 0.68 + 3 + T_{\text{sc}}$$

For ships of 250 m in length and above:

4.3.7.5 For side shell between the waterlines $\text{WL}_1$ and $\text{WL}_2$, pressure is to be applied as $\rho gh$ to the shell elements, where $h$ is the vertical distance from the centre of the element to the waterline $\text{WL}_1$. For side shell below the waterline $\text{WL}_2$ and above the level of the foundation deck at midship, a constant pressure, $\rho gd$, is to be applied to the shell elements, where $d$ is the vertical distance between the waterlines $\text{WL}_1$ and $\text{WL}_2$. See 4.3.7.4 and Fig. 2.4.9.

4.3.8 Procedure to apply Rule hydrodynamic torque moment

4.3.8.1 The Rule hydrodynamic torque distribution, $M_T$, as given in Pt 4, Ch 8.1.5.1 of the Rules for Ships, may be modelled by applying torsional moments at each transverse bulkhead position. This results in a stepwise torque distribution as shown in Fig. 2.4.10.

4.3.8.2 For ships with usual form and structural arrangement, the position of the shear centre at midship may be taken at the centre line, at the level of the inner bottom. Alternatively, a direct calculation method may be used to derive the shear centre after consultation with Lloyd’s Register.

4.3.8.3 The torsional moment, $T_m$, required at each bulkhead position can be calculated from:

$$T_m = M_{T_F} - M_{T_A}$$

where

- $M_{T_F}$ is the Rule hydrodynamic torque value at the mid-length of the forward hold
- $M_{T_A}$ is the Rule hydrodynamic torque value at the mid-length of the aft hold

4.3.8.4 Other proposed methods of modelling the Rule hydrodynamic torque distribution will be specially considered.
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Rule vertical design wave bending moment $M_w$

Permissible still water bending moment envelope $M_{sw}$

Actual still water bending moment of loading condition

Additional vertical bending moment to be applied to FE model

Fig 2.4.7

Procedure to derive required vertical bending moment distribution for applying to FE model
Analysis of Primary Structure of Type B Spherical Tank LNG Ships

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Pressure head distribution for local wave crest or trough

(a) Wave crest
\[ P_{WL} = H_W + h \]
\[ P_H = H_W \left( 1 - (1 - k_z) \frac{h}{T} \right) \]

(b) Wave trough
\[ P_{WL} = H_W - h \]
\[ P_H = H_W \left( 1 - (1 - k_z) \frac{h}{T} \right) \]

where
\[ H_W = 0.046L e^{-0.0044L} \text{ m} \quad \text{for } L < 227 \text{ m} \]
\[ e = 3.846 \text{ m} \quad \text{for } L \geq 227 \text{ m} \]
\[ h = \text{distance below the still waterline, m} \]
\[ k_z = e^{-d} \]
\[ d = \frac{2\pi}{T} \]
\[ T = \text{ship draught, may be taken as scantling draught of ship} \]
Analysis of Primary Structure of Type B Spherical Tank LNG Ships

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Fig 2.4.9
Side pressure distribution for subload case N
Fig 2.4.10
Application of Rule hydrodynamic torque distribution to FE model
Section 5: Permissible stresses

5.1 The stresses resulting from the application of the loadcases are not to exceed the maximum permissible values given in Table 2.5.1. 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 1.1.4.

5.2 The permissible stress criteria in Table 2.5.1 are based on the recommended mesh size indicated in Section 2.

5.3 The structural items indicated in Table 2.5.1 are provided for guidance as to the most likely critical areas. All stresses for all parts of the model, however, are to be examined for high values.

5.4 Where openings are not represented in the structural model, both the mean shear stress, $\tau$, and the element shear stress, $\tau_{xy}$, are 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.
### Table 2.5.1 Maximum permissible membrane stresses

<table>
<thead>
<tr>
<th>Structural item</th>
<th>Load cases</th>
<th>Combined stress $\sigma_e$</th>
<th>Direct stress $\sigma$</th>
<th>Shear stress $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Double bottom structure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom shell plating</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Inner bottom plating</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
<td>0.46 $\sigma_L$</td>
</tr>
<tr>
<td>Hopper tank sloping plating</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td><strong>Double bottom girders</strong></td>
<td>Dynamic cases, Static wave cases</td>
<td>1.00 $\sigma_L$</td>
<td>0.92 $\sigma_L$</td>
<td>0.46 $\sigma_L$</td>
</tr>
<tr>
<td>Double bottom floors</td>
<td>Dynamic cases, Static wave cases</td>
<td>0.92 $\sigma_o$</td>
<td>–</td>
<td>0.46 $\sigma_o$</td>
</tr>
<tr>
<td>Hopper tank web plating</td>
<td>Dynamic cases, Static wave cases</td>
<td>0.75 $\sigma_o$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td><strong>Side structure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side shell plating</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
<td>0.46 $\sigma_L$</td>
</tr>
<tr>
<td>Inner side plating (longitudinal)</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td>Side strings</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td>Side transverse webs</td>
<td>All cases</td>
<td>0.75 $\sigma_o$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td><strong>Deck structure and tank covers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper deck, outboard the line of openings</td>
<td>All cases</td>
<td>0.92 $\sigma_L$</td>
<td>0.92 $\sigma_L$</td>
<td>–</td>
</tr>
<tr>
<td>Cross deck structure, including cross deck strips</td>
<td>All cases</td>
<td>0.92 $\sigma_o$</td>
<td>0.75 $\sigma_o$</td>
<td>Transverse direction 0.46 $\sigma_o$</td>
</tr>
<tr>
<td><strong>Tank covers</strong></td>
<td>All cases</td>
<td>0.92 $\sigma_o$</td>
<td>0.92 $\sigma_o$</td>
<td>0.46 $\sigma_o$</td>
</tr>
<tr>
<td><strong>Transverse bulkhead structure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulkhead plating</td>
<td>All cases</td>
<td>0.75 $\sigma_o$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td>Bulkhead vertical webs</td>
<td>All cases</td>
<td>0.75 $\sigma_o$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td>Bulkhead stringers</td>
<td>All cases</td>
<td>0.75 $\sigma_o$</td>
<td>–</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td><strong>Structure supporting containment system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundation deck in way of skirts</td>
<td>Static wave cases</td>
<td>0.75 $\sigma_o$</td>
<td>0.75 $\sigma_o$</td>
<td>0.35 $\sigma_o$</td>
</tr>
<tr>
<td>Underskirt supporting structure</td>
<td>Dynamic cases</td>
<td>0.92 $\sigma_o$</td>
<td>0.92 $\sigma_o$</td>
<td>0.46 $\sigma_o$</td>
</tr>
<tr>
<td>Cross tank structure hopper tank inner structure in way of base of skirts</td>
<td>Collision case</td>
<td>1.00 $\sigma_o$</td>
<td>0.95 $\sigma_o$</td>
<td>0.55 $\sigma_o$</td>
</tr>
<tr>
<td><strong>Fine mesh regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average combined stress, $\sigma_{average}$ and Average shear stress, $\tau_{average}$</td>
<td>All cases</td>
<td>1.0 $\sigma_o$</td>
<td>–</td>
<td>0.46 $\sigma_o$</td>
</tr>
<tr>
<td>See Note 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual element, see 5.2</td>
<td>All cases</td>
<td>&lt; 1.2 $\sigma_{average}$</td>
<td>–</td>
<td>&lt; 1.2 $\tau_{average}$</td>
</tr>
</tbody>
</table>

**NOTES**

1. Static load cases are load cases S1 to S9. Dynamic load cases are load cases V1, V2, T1 to T4 and the collision load case is load case O1.
2. $\sigma_{average}$ and $\tau_{average}$ are the average combined stress and shear stress respectively 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.
Section 6: Buckling acceptance criteria

6.1 The buckling criteria are given in Table 2.6.1. 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. 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 1,1.4.

6.2 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.

6.3 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.

6.4 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.

6.5 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 6.4.

6.6 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.

6.7 When the calculated elastic critical buckling stress 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:

$$\sigma_{cr} = \sigma_o \left(1 - \frac{\sigma_o}{4\sigma_c}\right)$$

where

- $\sigma_{cr}$ = critical buckling stress corrected for plasticity effects
- $\sigma_c, \sigma_o$ = see Ch 1,2
Section A1: Procedure to apply transverse asymmetric loads to a half-breadth FE model

A1.1 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:

1. The symmetric load case. This case applies symmetric loading components and boundary conditions to the FE model, see Fig. A1.1.
2. The anti-symmetric load case. This case applies anti-symmetric loading components and boundary conditions to the FE model, see Fig. A1.1.

A1.2 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.

A1.3 Using the above two load cases, the different structural response of both sides of the ship to the transverse loads can be derived as follows:

port asymmetric = symmetric plus anti-symmetric
starboard asymmetric = symmetric minus anti-symmetric

This is illustrated in Fig. A1.1.

A1.4 Application of the external hydrostatic pressure corresponding to the heeled waterline for symmetric and anti-symmetric load cases is illustrated in Fig. A1.1 and described as follows:

1. 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 Fig. A1.1 to satisfy the symmetric load definition stated above.
2. The anti-symmetric load component for the external hydrostatic pressure is applied as half the difference of pressure on the port and starboard sides.

A1.5 The cargo tank pressure loadings for the symmetric and anti-symmetric load cases are specified in Ch 2.4.3.1.

A1.6 The boundary conditions for the symmetric load case and the anti-symmetric load are as follows:

1. Symmetric load case: See Ch 2, Fig. 2.3.1.
2. Anti-symmetric load case: See Ch 2, Fig. 2.3.3.
Procedure to Apply Transverse Asymmetric Loads to a Half-Breadth FE Model

Primary Structure of Type B Spherical Tank LNG Ships May 2004

Appendix A

SECTION A1

Full Ship Asymmetric Load Case

Where

\[ H_1 = B \sin \theta \]

\[ H_2 = T \cos \theta + \frac{B}{2} \sin \theta \]

\[ H_3 = T \cos \theta - \frac{B}{2} \sin \theta \]

Analysis of Port Side Structure using a Port Half-Breadth Model

Analysis of Starboard Side Structure using a Port Half-Breadth Model

Derivation of the asymmetric load cases for a half-breadth model from the symmetric and anti-symmetric load cases

Fig. A1.1