2025

Guideline for Direct Strength Analysis of Liquefied Gas Carriers with Independent Type C Tanks

GL-0049-E

KR

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(서식번호 : FI-03-05) (20.01.2025)

APPLICATION OF

“Guideline for DSA of Liquefied Gas Carriers with Independent Cylindrical Type C Tanks”

1. Unless expressly specified otherwise, the requirements in the Guideline apply to ships for which are contracted for construction are signed on or after 1 July 2025.

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Chapter 1

General Principles

Section 1 – Application

Section 1 – Application

1. Scope of application

1.1. General

1.1.1.

This **Guideline** applied to the following ships:

a) Ships intended to be registered and classed as "Liquefied Gas Carrier" with independent Cylindrical Type C Tanks having a length *L* of 150 m above and:

b) Being self-propelled ships with unrestricted navigation.

c) Cargo holds region as defined in **Pt 15, Ch 1, Sec 1, [2.4] of Rules for the Classification of Steel Ships.**

1.1.2. Relation with Part 15 of Rules for the Classification of Steel Ships

Ships are to comply with the principles and requirements of **Part 15 of Rules for the Classification of Steel Ships** except for the requirements specified in this **Guideline.**

1.1.3. Relation with Part 3 of Rules for the Classification of Steel Ships

Ships are to comply with the principles and requirements of **Part 3 of the Rules for the Classification of Steel Ships** except for the requirements specified in this **Guideline**.

1.1.4. Novel designs

Ships with novel features or unusual hull design are to comply with **Pt 15, Ch 1, Sec 3, [6.2] of Rules for the Classification of Steel Ships.**

1.2. Structure parts not covered by this Guideline

1.2.1.

Designers should take care that parts of the structure that this **Guideline** does not cover comply with the relevant requirements of the Society's Rules.

1.3. Application and implementation of this Guideline

1.3.1.

This Guideline addresses the hull structural aspects of classification and does not include requirements related to the verification of compliance with the Rules during construction and operation.

1.3.2.

The Society verifies compliance with the classification requirements and the applicable international regulations when authorized by a Nation Administration during design, construction and operation of the ship.

Chapter 2

Finite element analysis to assess yielding, buckling and fatigue strength of type C tanks

Section 1 – Yielding strength assessment

1. General

1.1.

This guideline provides general information and recommendations for the finite element analysis of single cylinder and multi-lobe shape type C tanks of **Pt 7 Ch 5 of the Rule** (IGC Code).

The corrosion allowance is excluded in this guideline and can be considered by the Classification Society as needed.

1.2.

Finite element analysis of a type C tank may be required as a supplementary assessment where the structural strength cannot be duly assessed by the prescriptive requirements of the Society, i.e. stress concentration locations such as structural discontinuities in way of tank supports, Y-connections of multi-lobe tanks and tanks of novel design or configuration.

2. Modelling

2.1.

The entire tank and supporting saddle structures should be modelled including any discontinuities which might affect the stress distribution significantly. The FE model should include the tank shell, ring stiffeners, internal bulkheads and all major components attached to the tank. Examples are shown in **Figure 1**.

Both 2D shell elements and solid 3D elements are acceptable for the analysis and subsequent stress calculations. In principle, elements of second order which are with additional internal degrees of freedom for improved in plane element behavior are recommended. Also, the limitations of shell elements in assessing secondary / peak / hot spot stresses should be considered.

2.2.

For the local areas of structural discontinuity where it is intended to evaluate result including secondary stress:

- It is recommended to use 8-node shell elements or 4-nodes shell elements with additional internal degree of freedom, and with the mesh size of $1.0\ t$ up to $50\ mm$ in principle, where t denotes the plate thickness.
- Alternatively, the element mesh size may be established by sensitivity checks in accordance with recognized standards to represent the bending deflection of tank structure and local stresses in way of the structural discontinuities.

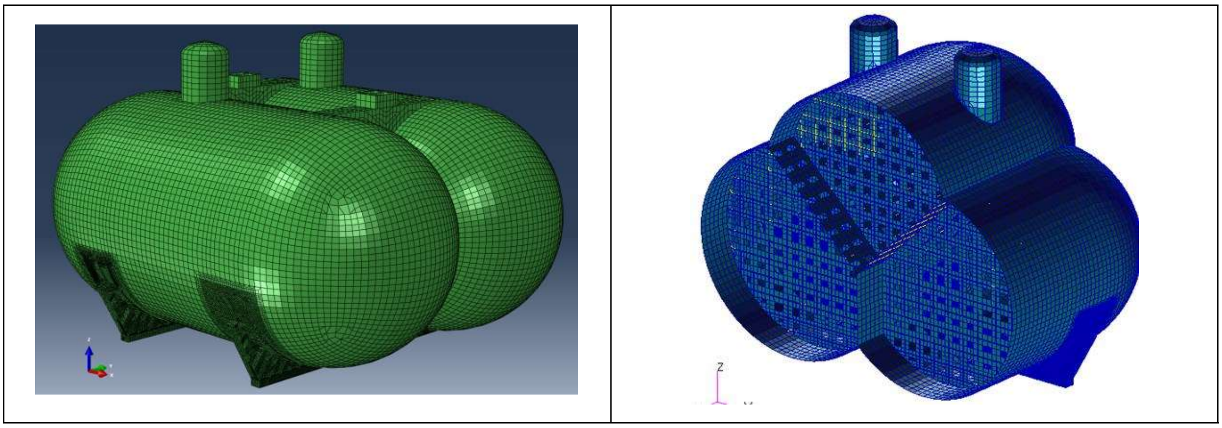


Figure 1 Finite element model of type C tanks (bi-lobe and tri-lobe)

- For other areas, coarser mesh may be used as considered appropriate to simulate realistic structural response including local bending. e.g. the lesser of cylindrical radius R/30 or 200 mm in shell mesh size. Consideration should be given to the smooth transition to coarse mesh to get appropriate stress distribution. Stiffening rings are recommended to be modelled as shell elements.

2.3.

Solid elements may be necessary in order to represent the steep stress gradient distribution in the plate thickness direction in way of the local area of complex geometry, e.g. Y-connections of the bi-lobe tank, etc.

It is recommended to use iso-parametric 20-node elements with a size of plate thickness t. For 8-node solid elements, at least four elements in the thickness direction $\left(t \times t \times \frac{t}{4}\right)$ should be used. When solid elements are used, it is normally required to extrapolate stresses to surfaces. The membrane and bending stress components may be obtained according to the stress linearization method determined by the recognized standards.

2.4.

Attention should be given to the transition area between solid elements and shell elements, if integrated, to ensure that the structural response is correctly transferred between the two types of elements. The transition area between two types of elements should be kept away from the areas with high stresses. An example is shown in **Figure 2.**

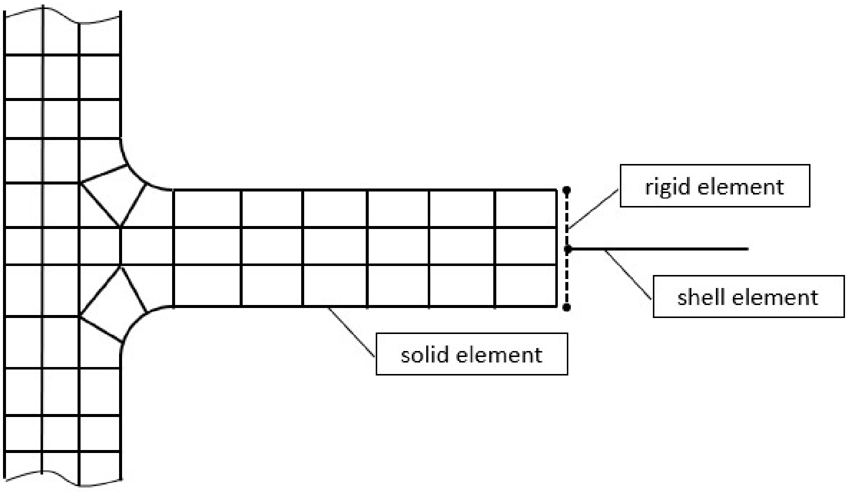


Figure 2 Transition area between solid and shell elements

2.5.

If the tank is placed on supports that can be considered as contact surfaces, the relative deflections between the tank and supports should be correctly considered, especially for low temperature applications or for large diameter tanks.

Examples are shown in **Figure 3.** The relative deflections between the tank and the supports may significantly affect the stress distribution and so the contact surface conditions should be correctly modelled.

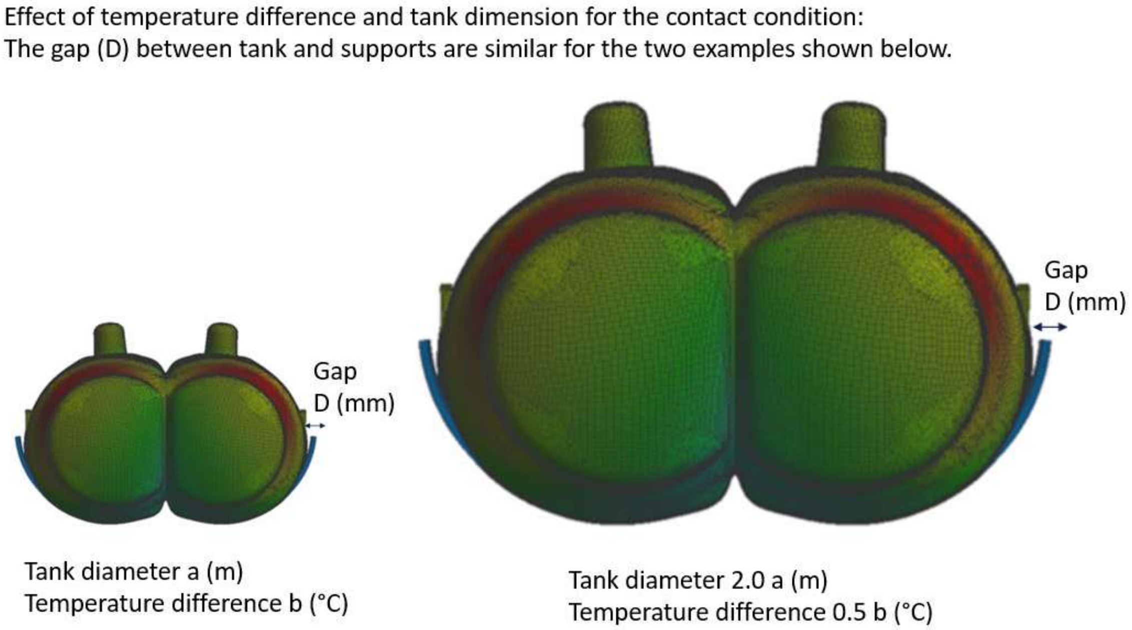


Figure 3 Modelling of contact surfaces between tank and support

2.6.

The contact surfaces may be modelled in several different ways subject to the capabilities of the applied FE analysis program.

Deflection plots should be reviewed to ensure that the physics of the tank and supports are appropriately modelled where the tank is allowed to deflect relatively to the saddle shape due to the relative shrinkage between tank and saddle structure, see **Figure 4** for illustration.

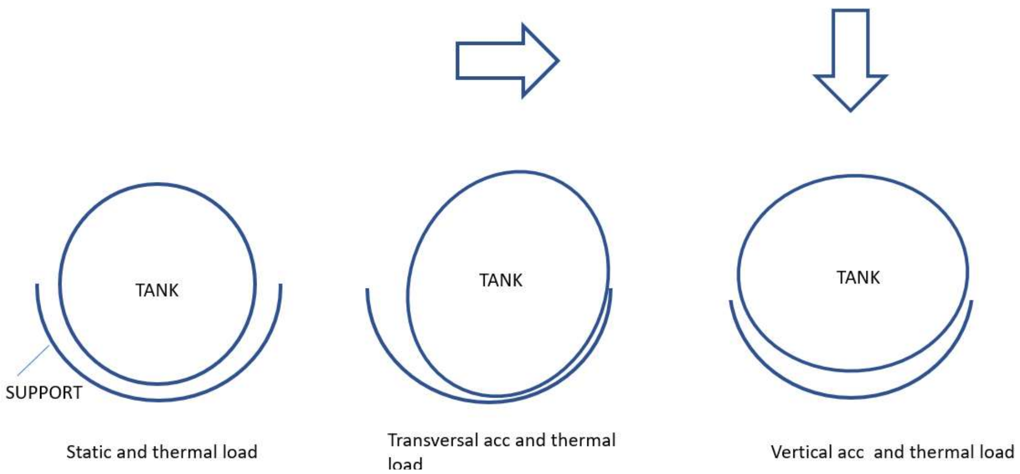


Figure 4 Contact conditions between tank and support need to allow for the relative deflection due to thermal contraction and inertial loads

2.7.

For the doubler plate fitted in way of tank support and where the two independent plates are considered to influence the local stresses critically, the weld and contact conditions between doubler plate and tank body is recommended to be modelled with solid elements as shown in **Figure 5.**

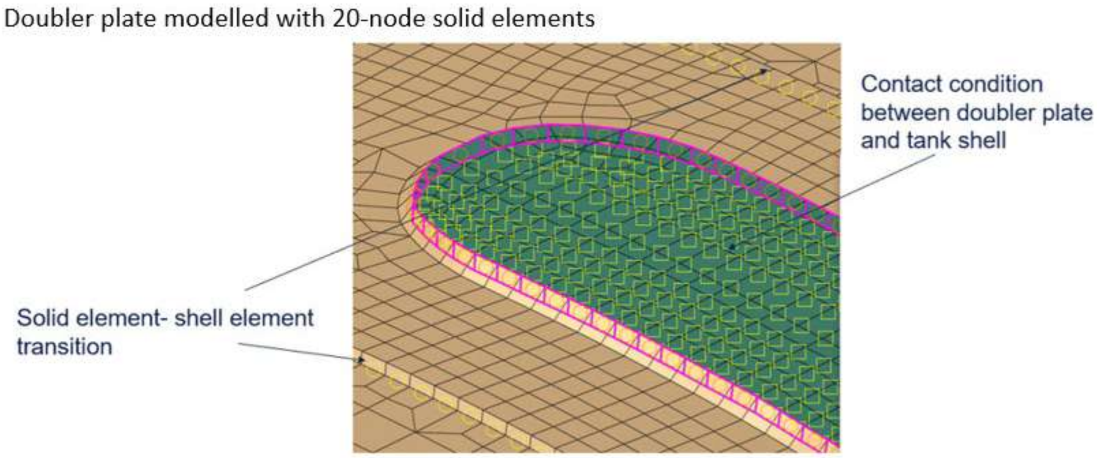


Figure 5 Recommended modelling for the doubler plate and the weld in way of tank support

3. Design load

3.1.

The ultimate, accident and testing design conditions should be assessed as outlined in **Table 1**. These conditions should be combinations of permanent, functional, environmental, accidental and testing loads as outlined in **Table 2** as per the Code.

The design conditions and load cases shown on following tables should be considered for the finite element analysis.

Table 1 Design conditions and load cases

Design conditions	Description	Load case
Ultimate	For the maximum load-carrying capacity or, in some cases, to the maximum applicable strain, deformation or instability in structure resulting from buckling and plastic collapse under intact (undamaged) conditions	Longitudinal dynamic
		Transverse dynamic
		Vertical dynamic
Accident	For the ability of the structure to resist accidental situations	Static heel 30° 1)
		Collision
		Floatation
Testing	For hydrostatic test of each pressure vessel	Tank testing
1) The condition can also be considered to cover an ultimate limit state (ULS) condition with small GM values, which cannot be assessed by the other ULS conditions. This condition may correspond to large roll angles and consequently provide large transverse inertial loads due to the gravity component.		

3.2.

The load combinations defined in **Tables 2** to **6** should be considered for each load case.

Table 2 Load combinations for considering dynamic load cases

Load case ID	Description	Permanent loads	Functional loads			Enviroment loads
			Filling level	Internal pressure	Thermal load	Load due to ship motion
LD	Longitudinal acceleration	Gravity	Full	P_{eq} 1)	Minimum design cargo temperature 3)	$+a_x$ 2)
TD	Transverse acceleration	Gravity	Full	P_{eq} 1)	See above	$+a_y$ 2)
VD	Vertical acceleration	Gravity	Full	P_{eq} 1)	See above	$-a_z$ 2)

1) Internal pressure as defined in Pt 7 Ch 5 413. 2 (4) of the Rule (IGC Code 4.13.2.4). See 'Environmental loads' column for applicable acceleration component for the calculation of internal pressure.
2) Maximum dimensionless accelerations in longitudinal, transverse and vertical directions as defined in Pt 7 Ch 5 428. 2 (1) of the Rule (IGC Code 4.28.2.1). Direct calculation may be considered in accordance with Pt 7 Ch 5 414. 1 (3) of the Rule (IGC Code 4.14.1.3).
3) Minimum design cargo temperature is given for tank. Applicable temperature gradient for the saddle supports can be separately considered.

Table 3 Load combinations for static heel load case

Load case ID	Description	Permanent loads	Functional loads		
			Filling level	Internal pressure	Thermal load
SH1	Static heel	Gravity	Full	30° static heel pressure P_0 1)	Minimum design cargo temperature for tank 2)

1) Design vapor pressure as defined in Pt 7 Ch 5 412 of the Rule (IGC Code 4.1.2)
2) Minimum design cargo temperature is given for tank. Applicable temperature gradient for the cradle supports can be separately considered.

Table 4 Load combinations for collision load cases

Load case ID	Description	Permanent loads	Functional loads			Accidental loads
			Filling level	Internal pressure	Thermal load	Load due to ship motion
CL1	Collision forward direction	Gravity	Full	Collision pressure P_0 1)	Minimum design temperature	0.5g forward acceleration
CL2	Collision aft direction	Gravity	Full	Collision pressure P_0 1)	Minimum design temperature	0.25g faft acceleration

1) Design vapor pressure as defined in Pt 7 Ch 5 412 of the Rule (IGC Code 4.1.2)

Table 5 Load combinations for floatation load case

Load case ID	Description	Permanent loads	Functional loads		Accidental loads
			Filling level	Thermal load	
FL1	Tank floatation	Gravity	Empty	Not applicable	Loads caused by the buoyancy of an empty tank in a hold space flooded to the summer load draught

Table 6 Load combinations for tank testing load case

Load case ID	Description	Permanent loads	Functional loads	
			Test load	Thermal load
TT1	Tank Testing	Gravity	1.5 P_0 1)	Not applicable
1) Design vapor pressure as defined in Pt 7 Ch 5 412 of the Rule (IGC Code 4.1.2)				

3.3.

The sloshing loads should be examined separately by a procedure acceptable to the Classification Society in order to verify arrangement and strength of swash bulkheads, if fitted.

4. Acceptance criteria

4.1.

The permissible stresses of the tank structures should not exceed that given in **Pt 7 Ch 5 423.3**.

4.2.

Bending and local stresses may be read from the top and bottom surfaces of elements. The allowable stresses for FE stress check of type C tank may be simplified using the following equations for the local area of structural discontinuities:

- $\sigma_{eL\_membrane} \leq 1.5f$
- $\sigma_{eL\_surface} \leq 1.5f$
- $\sigma_{eL\_surface} \leq 3.0f$ (for containing self-limiting stresses, such as thermal stress)

In addition, for tank testing condition, using the following equation:

- $\sigma_{e\_membrane} \leq 0.9R_e$ (for tank testing condition only)

Where

- $\sigma_{eL\_membrane}$: is element equivalent stress derived from the stress components of the membrane Stress for the local area of structural discontinuities.
- $\sigma_{e\_surface}$: is element equivalent stress derived from the stress components of the top and bottom surfaces for the local area of structural discontinuities, whichever is greater.
- $\sigma_{e\_membrane}$: is element equivalent stress derived from the stress components of the membrane stress at any point. See Pt 7 Ch 5 423. 6 (1) of the Rule (IGC Code 4.23.6.1).
- f : See Pt 7 Ch 5 423. 3 (1) (Pt 7 Ch 5 423. 3 (1) of the Rule (IGC code 4.23. 3. 1))
- R_e : Yield stress of the material considered, See Pt 7 Ch 5 418. 1 (3) Pt 7 Ch 5 418. 1 (3) of the Rule (IGC code 4.18. 1. 3)
- Note: For solid elements, the membrane and surface stress components are taken as [2.3]

Section 2 – Buckling strength assessment by non-linear finite element analysis

1. General

1.1.

The cylindrical and spherical parts of single-cylinder or multi-lobe shaped tanks, which are not influenced by structural discontinuities such as Y-connections, should be as follows:

$$\frac{P_c}{P_e} \geq 4 \text{ for cylindrical shell}$$

$$\frac{P_c}{P_e} \geq 3 \text{ for spherical shell}$$

where:
P_c : critical buckling pressure, in MPa
P_e : external design pressure, in MPa

1.2.

The critical buckling pressure may also be determined by bifurcation buckling analysis using linear elastic stress analysis without geometric non-linearities and imperfections. In such cases, the cylindrical and spherical parts of single cylinder or multi-lobe shape tanks which are not influenced by structural discontinuities should be as

$$\frac{P_{c\_EI}}{P_e} \geq 4 \text{ for cylindrical shell}$$

$$\frac{P_{c\_EI}}{P_e} \geq 15 \text{ for spherical shell}$$

where:
P_{c_EI}: critical buckling pressure obtained from eigenvalue analysis, in MPa
P_e : external design pressure, in MPa
Buckling strength assessments of the remaining parts should be specially considered further. When applicable, all the possible load cases including axisymmetric and non-axisymmetric load scenarios should be considered.

1.3.

Alternatively, non-linear finite element analysis may be carried out for further assessment of the entire tank using elastic-plastic material behavior with explicit imperfections (see 3.4 below), and with the criteria given below.

$$\frac{P_{c\_NL}}{P_e} \geq 2 \text{ for cylindrical shell}$$

$$\frac{P_{c\_NL}}{P_e} \geq 3 \text{ for spherical shell}$$

where:
P_{c_NL} : critical buckling pressure obtained from nonlinear analysis, in MPa
P_e : external design pressure, in MPa

* For spherical shell, a lower safety factor but not less than 2 is to be agreed by the Society. In such a case, a lower safety factor can be used, provided it is proven by the benchmark study deemed appropriate by the Society.

2. Procedure for non-linear finite element analysis

2.1.

Figure 6 shows an overview of the non-linear analysis process. The detailed procedure should be ascertained in advance in consultation by the Society.

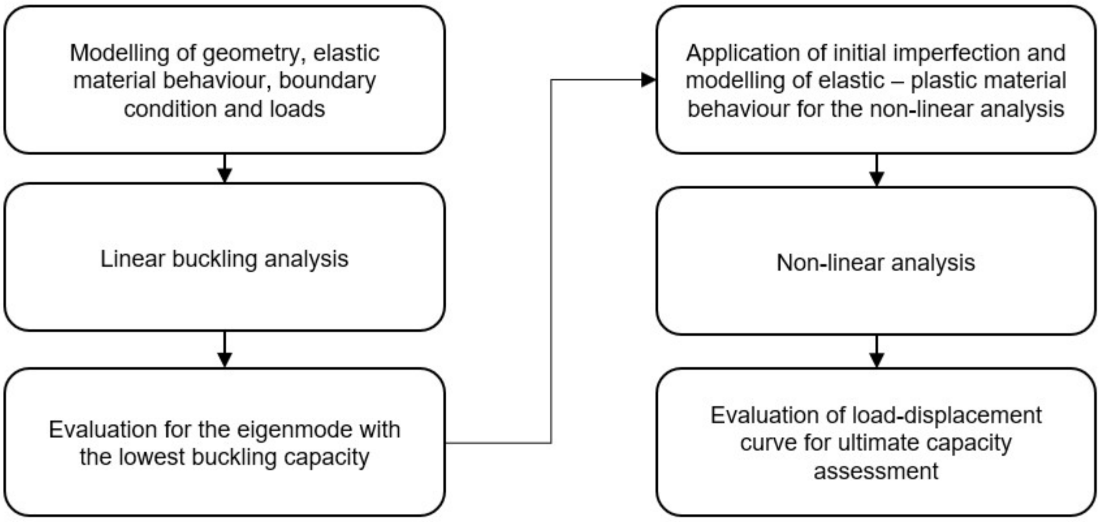


Figure 6 Flow chart for non-linear finite element analysis

3. Modelling

3.1.

The mesh size should be fine enough to simulate the relevant localized deformation of failure mode appropriately. Also, 2D shell elements are acceptable for analysis. It is recommended as much as possible to use 4-node elements with aspect ratio not greater than 2. Examples are shown in **Figure 7** and **Figure 8**.

3.2.

Type C tanks are generally made up of a combination of a cylindrical body with stiffening rings and spherical shells. It is recommended to evaluate the buckling capacity using the full model including both cylindrical and spherical shell components as well as stiffening rings. Simply supported ends are acceptable as a boundary condition.
However, if the location of the buckling is away from the boundary conditions and the distorted stresses induced by the boundary conditions are proven negligible, then it is possible to evaluate it through a partial model.

3.3.

In general, as the spherical shell has a higher buckling capacity than the cylindrical shell, most of the vulnerable parts appear in the cylindrical shell when evaluating the buckling capacity using the entire model. In addition, the openings, which are initially designed with a sufficiently large strength compared to the tank itself, and saddle structures are not required to be modelled in the buckling evaluation

4. Initial imperfection

4.1.

For conventional type C tanks generally made of cylindrical body with stiffening rings and spherical shells, initial imperfections such as out of roundness occur due to mechanical processing or welding in the manufacturing process. The maximum allowable imperfection should be considered in the assessment in accordance with the Classification Society's requirement or recognized standard such as **EN 13445.**

4.2.

Where the shape and size of the initial imperfection may not be available, the buckling mode of nth order with the lowest buckling capacity should be used as an initial imperfection shape as shown in **Figure 6**. The magnitude of imperfection should take into account the manufacture and workmanship tolerances specified by Classification Societies or accepted manufacture standard.

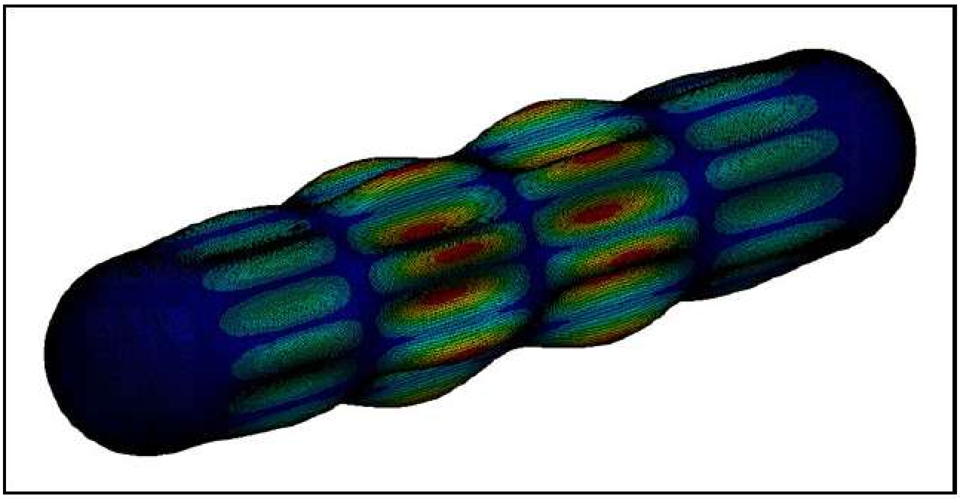


Figure 7 Linear buckling mode of typical single cylinder tank

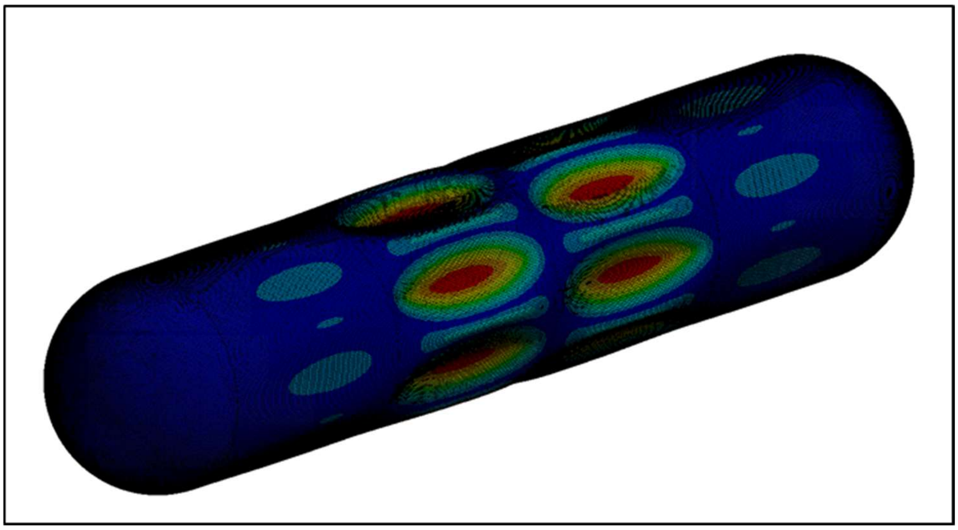


Figure 8 Deformation of typical single cylinder tank under collapse pressure

5. Load−displacement curve for assessment

5.1.

In order to obtain the maximum buckling capacity, the load−displacement curve from the non−linear finite element analysis should be evaluated. The buckling capacity should be conservatively determined considering the stable capacity level, which may be below the highest, yet unstable, limit point as shown in **Figure 9.**

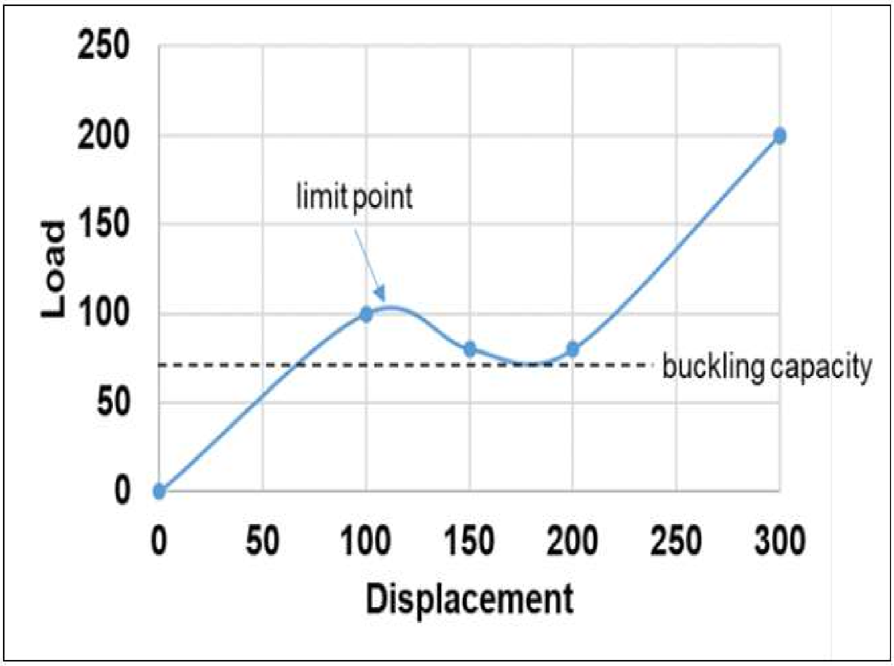


Figure 9 Load-displacement curve

Section 3 – Fatigue strength assessment

1. Objectives and scope

1.1.

The prescriptive formula for design vapor pressure as defined in **Pt 7 Ch 5 423. 1 (2) of the Rule (IGC Code 4.23.1.2)** is intended to provide a simple design method to ensure sufficient fatigue strength capacity without further detailed finite element analysis. However, for larger tanks or tanks with more complex designs, the prescriptive formula does not take into account the stresses that occurred at local hot spots and support interactions. It may be required to document the tank design with finite element analysis for such cases.

1.2.

The following locations of multi-lobe tank should be evaluated for fatigue performance. **Figure 10** to **12** shows the location where high dynamic stresses may be expected.

- Tank shell in way of supports
- Tank joint connections between cylinders and their longitudinal bulkhead (Y-joint)
- Support ring frames
- High stressed locations identified by the ULS FE calculation

1.3.

This document offers basic guidelines for a simplified fatigue assessment. Alternative methods also may be applied in consultation by the Society.

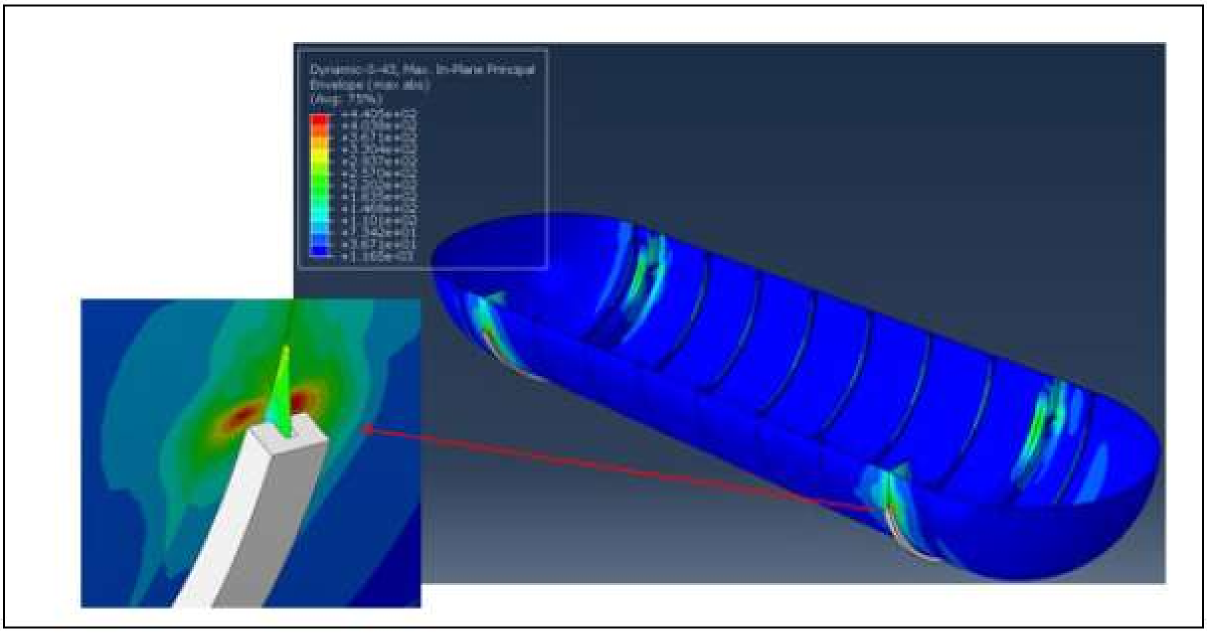


Figure 10 High dynamic stress at the interface with saddle support

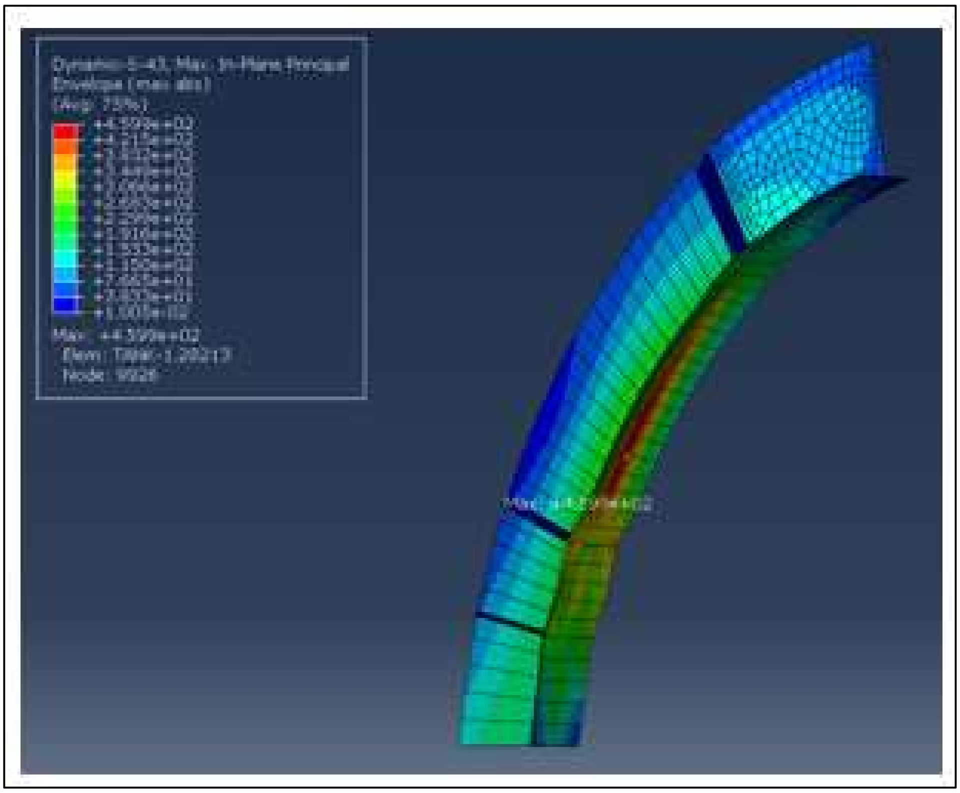


Figure 11 High dynamic stress at the stiffening ring frame

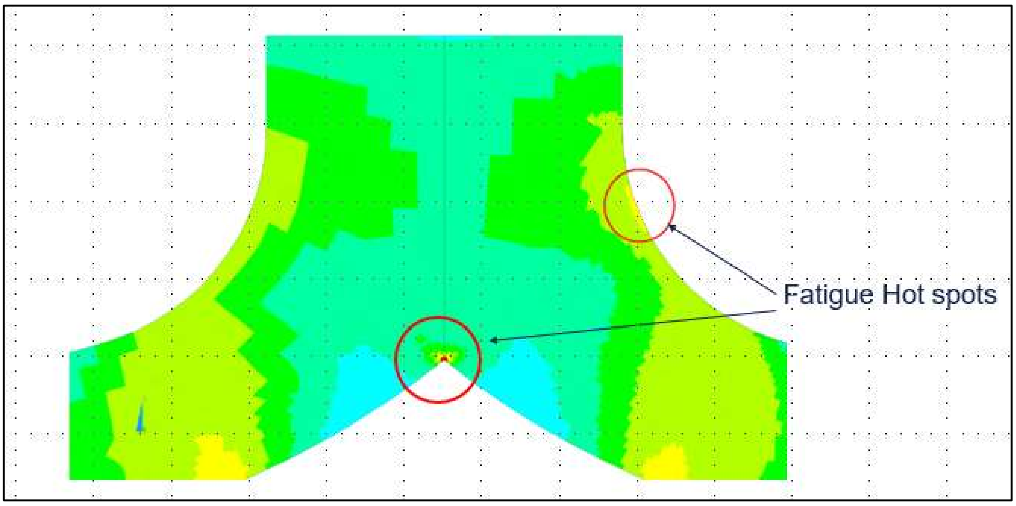


Figure 12 High dynamic stress at the Y-connection of bi-lobe tank

2. Modelling

2.1.

The finite element model will depend on configuration and arrangement of tanks and supports. In addition, the design temperature of the tank may affect the way how the tank is modelled. A few typical tank design applications are as follows:

- Single cylinder tanks on a typical saddle support with arrangement of wooden block between tank and saddle
- Single cylinder tanks with arrangement of vacuum insulated outer jacket – the support between inner tank and outer jacket is a fully welded type design

- Single cylinder tanks with arrangement of vacuum insulated outer jacket – the support between inner tank and outer jacket is made by contact blocks
- Multi-lobe tanks

2.2.

Finite element model should in principle be in accordance with Section 2.2. However, fatigue calculations require a finer mesh than normally required by the ULS calculations.

2.3.

The local finite element models should include fine mesh zones for the evaluation of hot spot stresses in way of areas of stress concentration. The fine mesh zones should cover all potential fatigue check areas.
The mesh size in way of the fine mesh zone should be taken as close to tt x tt as possible, where tt is the thickness of the plate where crack is likely to initiate. The extent of the fine mesh zone, in the principal direction of the stress leading to maximum stress concentration at the detail, should be in order of at least 10 times the plate thickness, so that a realistic stress gradient toward the hotspot is correctly and realistically modelled.

2.4.

It is recommended to use 8-node shell element or 4-node shell elements with additional internal degree of freedom, and with the mesh size of t x t in the high stressed area, where t denotes plate thickness.

2.5.

The welding geometry can be modelled in local areas to investigate the hot spot stress. If necessary, 20 node quadratic solid elements are recommended to be used.
It is recommended that also the fillet weld is modelled to achieve proper local stiffness and geometry (See **Figure 13**). In such cases, the dimensions of the first two or three elements in front of the weld toe should be chosen as follows.

The element length may be selected to correspond to the plate thickness (See 4.2.6). In the perpendicular direction, the plate thickness may be chosen again for the breadth of the plate elements.
However, the breadth should not exceed the attachment width, i.e. the thickness of the attached plate plus two times the weld leg length. The length of the elements should be limited to 2.0 t (See **Figure 14**).

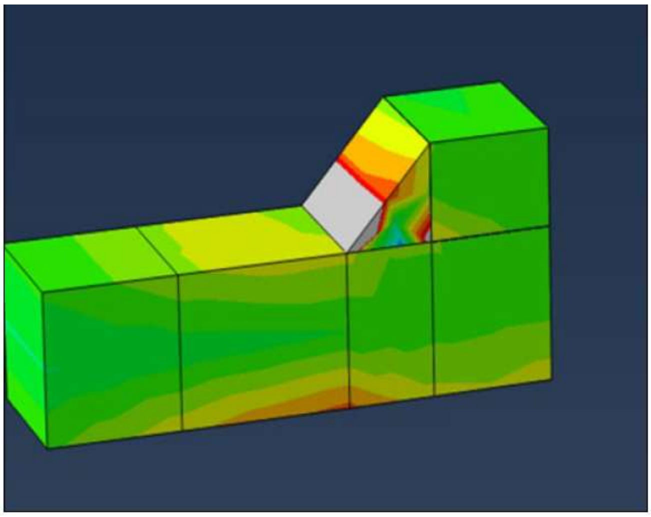


Figure13 A section of a plate, weld and an attachment modelled by 20-node solid elements

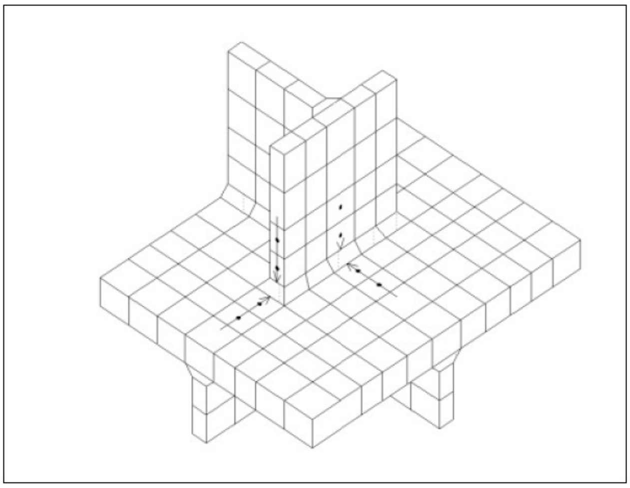


Figure 14 Example of a meshed geometry close to hotspot area based on 20-node solid elements

2.6.

Mesh around hot spots: The mesh size should be maintained within the hot spot mesh zone (see **Figure 14**), extending over at least 10 elements in all directions from the fatigue hot spot position.

The transition of element size between the coarser mesh and the hot spot mesh zone should be done gradually and an acceptable mesh quality should be maintained. This transition mesh should be such that a uniform mesh with regular shape gradually transitions from smaller elements to larger ones. As a guidance mesh incremental size should be about 1:2.

3. Design load

3.1.

The load cases defined in **Table 7** should be considered to determine dynamic stress range for the high cycle fatigue utilization. The stress response is advised to be determined based on the accelerations at 10^{-4} probability level. For fatigue evaluations the dynamic stress range at the local hotspot is to be determined based on the load cases defined in **Table 7**.

As the stress response for a type C tank is often non-linear due to contact elements and affected by deflections from static loads and thermal effects, the load cases will need to include all these effects correctly. However, the static stresses will need to be deducted or filtered away to extract the dynamic stress range. Load cases in **Table 7** shall, in addition to the dynamic load component, include all static load components including relative shrinkage due to thermal loads.

It should also be noted that the recommended acceleration probability level of 10^{-4} is selected primarily based on the relative deflexions between tank and supports (geometrical non-linearity) to define a stress response that is representative of the fatigue utilization.

3.2.

A fully loaded condition and empty tank condition cycle, including a complete pressure and thermal cycle should be assumed for low cycle fatigue utilization. The number of stresses cycles due to loading and unloading should be taken as a minimum of 1000.

Table 7 Load combinations for high cycle fatigue load cases

Load case ID	Description	Permanent loads	Functional loads	Environment loads

			Filling level	Internal pressure	Thermal load3)	Loads due to ship motion
LD1	Positive longitudinal acceleration	Gravity	Full	P_{eq} 1)	Minimum design temperature	$+a_x$
LD2	Negative longitudinal acceleration	Gravity	Full	P_{eq} 1)	Minimum design temperature	$-a_x$
TD1	Positive transverse acceleration	Gravity	Full	P_{eq} 1)	Minimum design temperature	$+a_y$
TD2	Negative transverse acceleration	Gravity	Full	P_{eq} 1)	Minimum design temperature	$-a_y$
VD1	Positive vertical acceleration	Gravity	Full	P_{eq} 1)	Minimum design temperature	$+a_z$
VD2	Negative vertical acceleration	Gravity	Full	P_{eq} 1)	Minimum design temperature	$-a_z$
1) Internal pressure as defined in Pt 7 Ch 5 413. 2 (4) of the Rule (IGC Code 4.13.2.4). 2) Accelerations at 10^{-4} probability level in longitudinal, transverse and vertical directions. Accelerations may be determined based on the IGC Code 4.28.2.1. Direct calculation may be considered in accordance with Pt 7 Ch 5 414. 1 (3) of the Rule (IGC Code 4.14.1.3). 3) Minimum design cargo temperature is given for tank. IGC condition may be assumed as it is a more representative ambient temperature for normal operation. Applicable temperature gradient for the saddle supports can be separately considered.						

4. Stress calculation

4.1.

Linear extrapolation to stress at hotspots should be based on stress evaluation points located at distances t/2 and 3·t/2 away from the hot spot, where t is the plate thickness at the weld toe (See **Figure 15**).

These locations are also denoted as stress read out points. The extrapolation method is regarded as the basic method but reading out at t/2 with stress correction is often regarded as more convenient for many standard details (See **Figure 15)**.

For read out at 0.5t from hotspot an additional stress concentration should be considered to be added to compensate for use of this method. A commonly used stress concentration factor is 1.12, unless other value is documented.

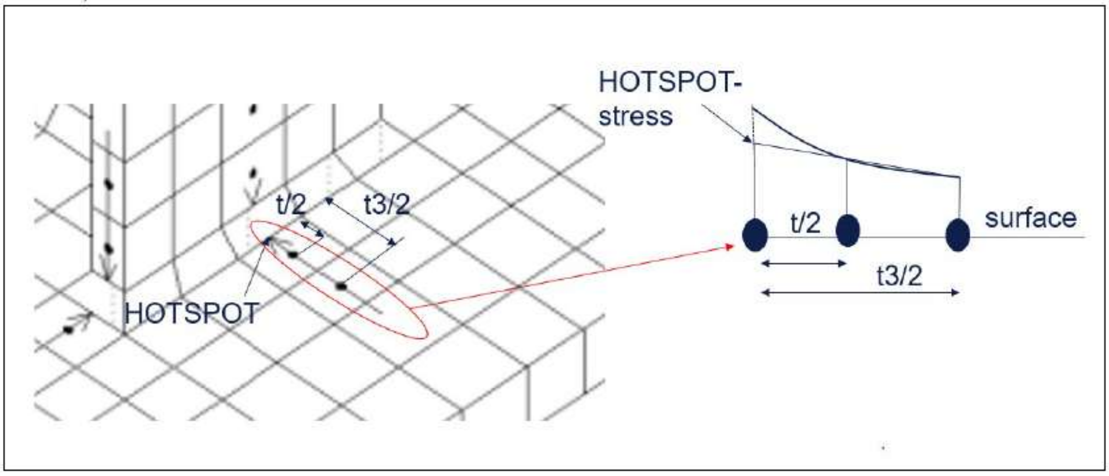


Figure 15 Illustration of stress interpolation for solid elements

4.2.

The stresses at the location where the fatigue performance is evaluated should first be extrapolated to the surface of the plate then to the hot spot.

The extrapolation technique should be used with care as it can be non-conservative with large local stress variation. The extraction of principal stress range which is selected within +/−45° of the normal to the weld toe should be used for the analysis.

5. Determination of stress range from load cases

5.1.

The stress ranges for longitudinal, transverse and vertical load cases should be calculated from the hot spot stress response described in 4.4.1 and 4.4.2 of the six load cases as defined in **Table 7.**

$$\Delta\sigma x = \sigma(+x) - \sigma(-x)$$

where:
Δσx : Stress range for accelerations in longitudinal direction
σ(+x) : Principal stress amplitude from load case LD1
σ(-x) : Principal stress amplitude from load case LD2

$$\Delta\sigma y = \sigma(+y) - \sigma(-y)$$

where:
Δσy : Stress range for accelerations in transverse direction
σ(+y) : Principal stress amplitude from load case TD1
σ(-y) : Principal stress amplitude from load case TD2

$$\Delta\sigma z = \sigma(+z) - \sigma(-z)$$

where:
Δσz : Stress range for accelerations in vertical direction
σ(+z) : Principal stress amplitude from load case VD1
σ(-z) : Principal stress amplitude taken from load case VD2

5.2.

The combined stress range ($\Delta\sigma_A$) determined based on all three load directions can be calculated as a root square summation based on the assumption that each stress component is statistically independent of the other load components. The combined stress range can accordingly be determined as:

$$\Delta\sigma_{A} = \sqrt{\Delta\sigma_{LD}{}^{2} + \Delta\sigma_{TD}{}^{2} + \Delta\sigma_{VD}{}^{2}}$$

5.3.

Where appropriate, additional stress concentration factors to account for construction qualities and plate thickness effects may need to be applied.

5.4.

For simplified fatigue assessment, long term distribution of stress may be assumed to follow a two-parameter Weibull distribution. The stress range may be distributed over 10^8 cycles according to Weibull probability function with shape factor 1,0.

6. S-N Curves

6.1.

The fatigue damage should be calculated using S-N curves and the Miner-Palmgren linear cumulative fatigue damage law.

6.2.

In principle, the fatigue S-N curves should be derived from experimental data obtained from tests. **Pt 7 Ch 5 418. 2 of the Rule** (IGC Code 4.18.2) Fatigue Design Condition requires that the S-N curves used in the analysis shall be applicable to the materials and weldments, construction details, fabrication procedures and applicable stress envisioned.

The curves also shall be based on 97.6% probability of survival corresponding to the mean-minus-two-standard-deviation curves of relevant experimental data up to final failure. The S-N curves complying with these requirements should be used as design S-N curves.

6.3.

The design S-N curve for concerned materials should be taken in accordance with recognized standards or equivalent acceptable to each Classification Society.

7. Acceptance criteria

7.1.

If a fatigue analysis is required, the cumulative effect of the load should comply with:

$$\sum \frac{n_i}{N_i} + \frac{n_{Loading}}{N_{Loading}} \le C_w$$

Where

n_i : number of stress cycles at each stress level during the life of the tank.

N_i : number of cycles to fracture for the respective stress level according to the Wohler (S-N) curve.

$n_{Loading}$: number of loading and unloading cycles during the life of the tank, not to be less than 1000. Loading and unloading cycles include a complete pressure and thermal cycle.

$N_{Loading}$: number of cycles to fracture for the fatigue loads due to loading and unloading.

C_w : maximum allowable cumulative fatigue damage ratio.

⚓

Chapter 3

Direct Strength Analysis for Cargo Holds

Section 1 – Strength Assessment

1. General

1.1. Application

1.1.1.

This section provides requirements applicable to verify the scantlings of the hull structure using finite element analysis.

1.1.2.

The finite element analysis consists of two parts:

a) Global analysis to assess the strength of longitudinal hull girder structural members, primary supporting structural members and bulkheads.
b) Fine mesh analysis to assess detailed stress levels in local structural details.

1.1.3.

Strength assessment based on finite element analysis is applicable for the structural members.

The analysis is to verify the following:

a) Stress levels are within the acceptance criteria specified in this guideline for yielding.
b) Buckling capability of plates and stiffened panels are within the acceptance criteria for bucking.

2. Finite element types

2.1. Used finite element types

2.1.1.

The structural assessment is to be based on linear finite element analysis of three-dimensional structural models. The general types of finite elements to be used in the finite element analysis are given in Table 8.

Table 8 Types of finite element

Type of finite element	Description
Rod (or truss) element	Line element with axial stiffness only and constant cross-sectional area along the length of the element.
Beam element	Line element with axial, torsional and bi-directional shear and bending stiffness and with constant properties along the length of the element.
Shell (or plate) element	Shell element with in-plane stiffness and out-of-plane bending stiffness with constant thickness.

2.1.2.

Two node line elements and four node shell elements are, in general, considered sufficient for the representation of the hull structure. The mesh requirements provided in this section assume that these elements are used in the finite element models. However, higher order elements may also be used.

3. Submission of results

3.1. Detailed report

3.1.1.

A detailed report of the structural analysis is to be submitted by the designer/builder to demonstrate compliance with the specified structural design criteria. This report is to include the following information:

a) The list of plans should include dates and versions.
b) Detailed description of structural modelling including all modelling assumptions and any deviations in geometry and arrangement of structure compared with plans.
c) Plots to demonstrate correct structural modelling and assigned properties.
d) Details of material properties, plate thickness, beam properties used in the model.
e) Details of boundary conditions.
f) Details of all loading conditions reviewed with calculated hull girder shear force, bending moment and torsional moment distributions.
g) Details of applied loads and confirmation that individual and total applied loads are correct.
h) Plots and results that demonstrate the correct behavior of the structural model under the applied loads.
i) Summaries and plots of global and local deflections.
j) Summaries and sufficient plots of stresses to demonstrate that the design criteria are not exceeded in any member.
k) Plate and stiffened panel buckling analysis and results.
l) Tabulated results showing compliance, or otherwise, with the design criteria.
m) Proposed amendments to structure where necessary, including revised assessment of stresses, buckling and fatigue properties showing compliance with design criteria.
n) Reference of the finite element computer program, including its version and date.

4. Computer programs

4.1. Use of computer programs

4.1.1.

Any finite element computation program may be employed to determine the stress and deflection of the hull structure, provided that the combined effects of bending, shear, axial and torsional deformations are considered.

Section 2 – Cargo Hold Structural Strength Analysis

Symbols

T_{SC} : Scantling draught, in m, at which the strength requirements for the scantlings of the ship are met and represent the full load condition. The scantling draught is to be not less than that corresponding to the assigned freeboard.

T_{BAL} : Minimum design normal ballast draught amidships, in m, at which the strength requirements for the scantlings of the ship are met. This normal ballast draught is the minimum draught of ballast conditions including ballast water exchange operation, if any, for any ballast conditions in the loading manual including both departure and arrival conditions.

T_{LC} : Draught, in m, amidships for the considered load case.

ρ : Density of seawater, taken equal to 1.025 t/m^3.

ρ_L : Density of liquid in the tank, in t/m^3.

g : Gravity acceleration, taken equal to 9.81 m/s^2.

X, Y, Z : X, Y and Z coordinates, in m, of the load point with respect to the reference coordinate system defined in **Sec 2, [4.2]**.

1. Objective and scope

1.1. General

1.1.1.

The cargo hold structural strength analysis is for the assessment of structural strength of longitudinal hull girder structural members, primary supporting members and bulkheads within the cargo hold region including transition areas to engine room and fore end. This section describes the analysis methodology and load application for cargo hold structural strength analysis.

1.1.2.

Cargo holds structural strength analysis is mandatory within the cargo hold region including cofferdam structure i.e. aft bulkhead of the aftmost cargo hold and fore bulkhead of the foremost cargo hold. The evaluation areas are defined in [5.1.1].

1.1.3.

For the FE structural assessment and load application, at least three cargo holds are to be assessed:

a) Midship cargo hold region

Holds in the midship cargo hold region are defined as holds with their longitudinal center of gravity position at or forward of 0.3L from AE and at or aft of 0.7L from AE, as defined in

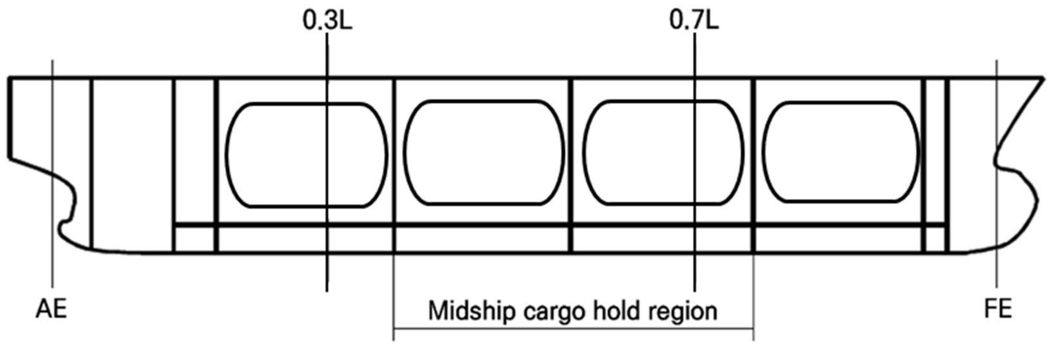


Figure 16:

Figure 16 Definition of cargo hold region for FE structural assessment

1.2. Cargo holds structural strength analysis procedure

1.2.1. Procedure description

The structural FE analysis is to be performed in accordance with the following:

a) Model: Three cargo hold model with:

• Extent as given in [2.2]

• Finite element types as given in [2.3]

• Structural modelling as defined in [2.4]

b) Boundary conditions as defined in [2.5]

c) FE load combinations as defined in [3]

d) Load application as defined in [4.1]

e) Evaluation area as defined in [5]

f) Strength assessment as defined in [5.2] and [5.3]

1.2.2. Mid-hold definition

For the FE analysis, the mid-hold is defined as the middle hold(s) of the three cargoes hold length FE model. In case of foremost and aftmost cargo hold assessment, the mid-hold represents the foremost and aftmost cargo hold respectively.

2. Structural model

2.1. Members to be modelled

2.1.1.

All main longitudinal and transverse structural elements are to be modelled. These include:

- Inner and outer shell,
- Upper deck,
- Double bottom floors and girders,
- Transverse and vertical web frames,
- Cargo tank dome openings,
- Stringers,
- Transverse and longitudinal bulkhead structures,
- Other primary supporting members,
- Other structural members which contribute to hull girder strength.

All plates and stiffeners on the structure, including web stiffeners, are to be modelled. Brackets which contribute to primary supporting member strength and the size of which is not less than the typical mesh size (s-by-s) described in [2.3], are to be modelled.

2.2. Extent of model

2.2.1. Longitudinal extent

Generally, the longitudinal extent of the cargo hold FE model is to cover three cargo hold lengths.

2.2.2. Hull form modelling

In general, the finite element model is to represent the geometry of the hull form. In the midship cargo hold region, the finite element model may be prismatic provided the mid-hold has a prismatic shape.

When the hull form is modelled by extrusion, the geometrical properties of the transverse section located at the middle of the considered space are copied along the simplified model. The transverse web frames are to be considered along this extruded part with the same properties as ones in the fore part or in the machinery space.

2.2.3. Transverse extent

Both port and starboard sides of the ship are to be modelled.

2.2.4. Vertical extent

The full depth of the ship is to be modelled including primary supporting members above the upper deck, trunks and forecastle, if any.

The superstructure or deck house in way of the machinery space and the bulwark are not required to be included in the model.

2.3. Finite element types

2.3.1.

Shell elements are to be used to represent plates.

2.3.2.

All stiffeners are to be modelled with beam elements having axial, torsional, bi-directional shear and bending stiffness. The eccentricity of the neutral axis is to be modelled.

2.3.3.

Face plates of primary supporting members and brackets are to be modelled using rod or beam elements.

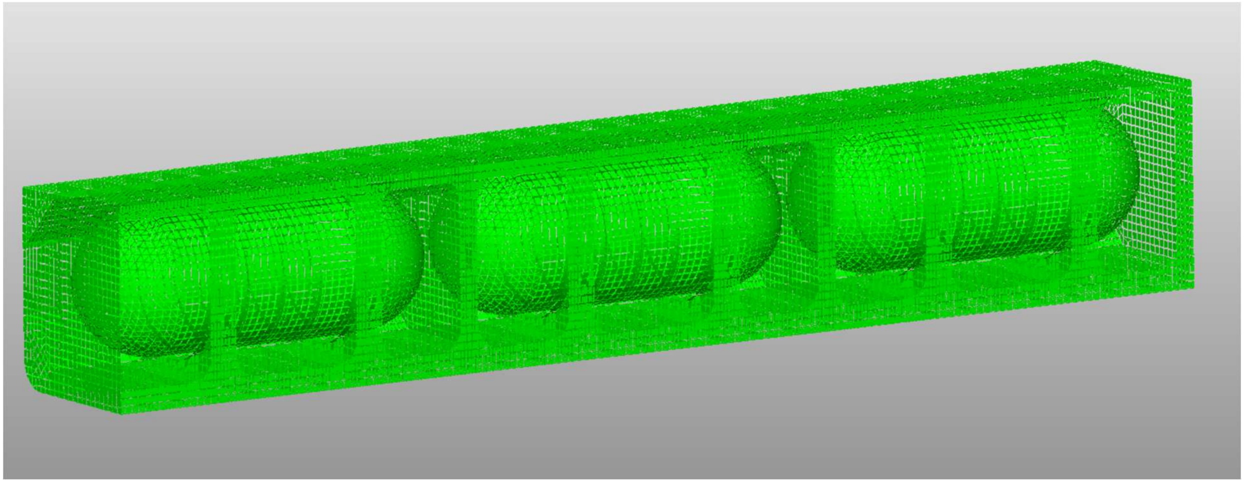


Figure 17 Example of 3 cargo hold model within midship region

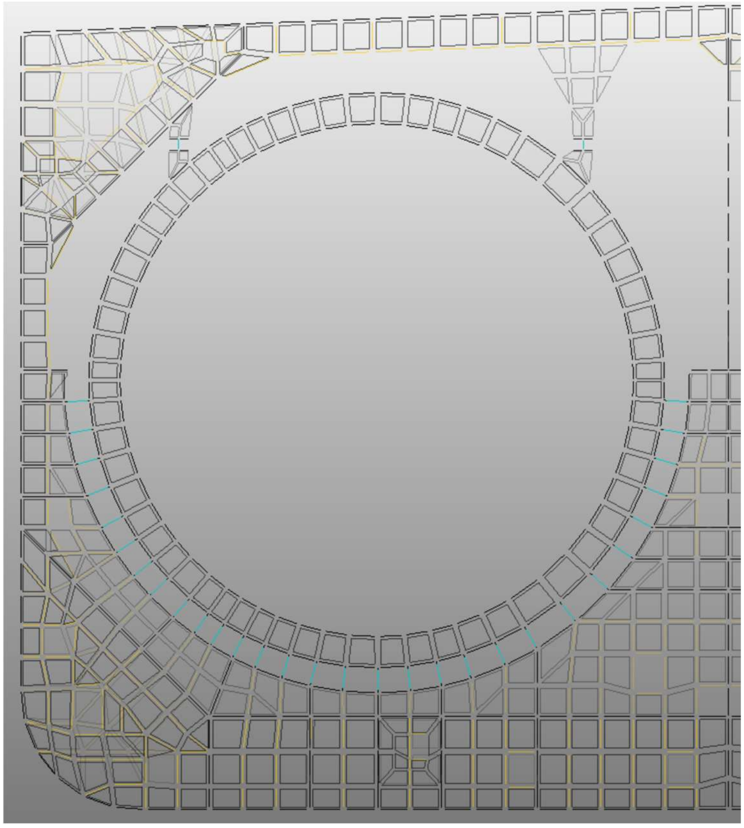


Figure 18 Typical finite element mesh on web frame

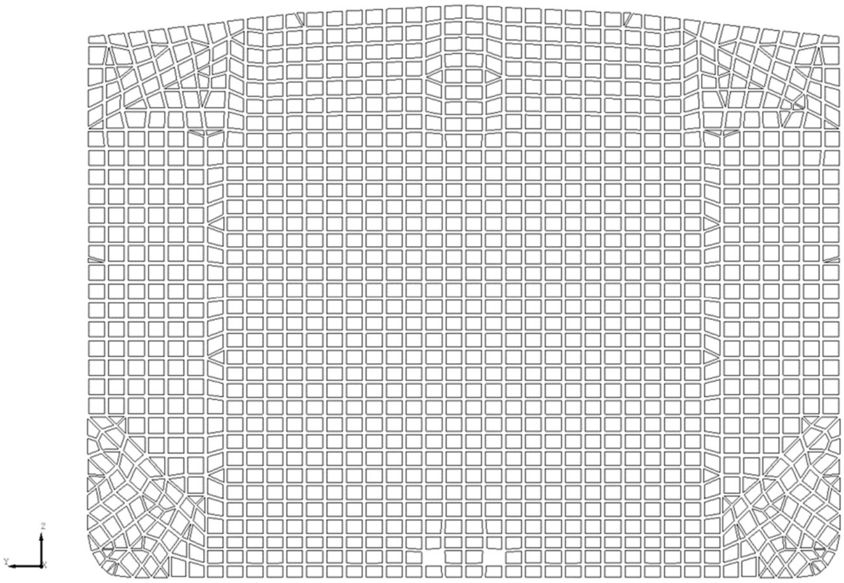


Figure 19 Typical finite element mesh on transverse bulkhead

2.4. Structural modelling

2.4.1. Supporting structure idealization

a) It is very important to get the force distribution on each support by independent tank. Therefore, all tank supports are to be idealized by shell elements according to the arrangement of tank supports. The spacer between upper and lower seat of the hull and tank supports should be considered using solid elements, gap elements or 1D element such as spring or rod element.

b) If solid elements are used, contact elements should be defined for interface surface. In case of gap elements implementation, the upper and lower surface of tank support seat is to be rigidly linked respectively with 6 DOF constraints. If the gap elements or contact elements are used, analysis results should be obtained using a nonlinear analysis. Figure 20 shows the typical implementation of gap elements with 6 DOF constraints.

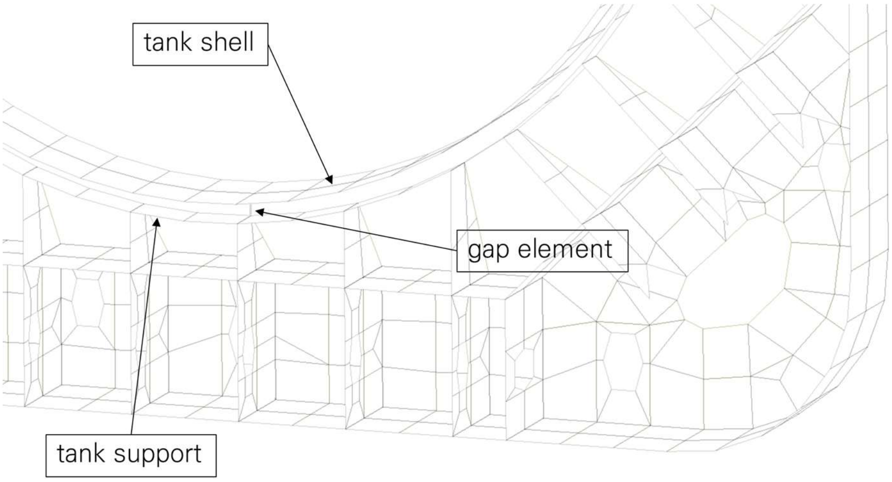


Figure 20 Tank support (Implementation of 1D Gap element with 6 DOF constraints)

c) For the usage of linear 1D element, the spring or axial stiffness is to be calculated based on the actual elastic modulus of the spacer materials. And an iterative procedure is required to eliminate any spring or rod element sustaining tensile stress. Spring or rod element may require two or three elements to correctly represent the behaviors of the support.

d) The coefficient of friction between the spacer between upper and lower seat of the tank supports is used according to Table 9 unless specifically defined in design stage by designer. In case of accidental loading conditions, i.e. collision and flooded, friction is not considered with a conservative viewpoint.

Table 9 Friction coefficient between wooden spacer and steel plate

kinetic friction coefficient	0.15
static friction coefficient	0.3

2.4.2.

Structural modelling refers to **Part 15 of the Rules**.

2.5. Boundary conditions

2.5.1. General

All boundary conditions described in this section are in accordance with the global coordinate system defined in **Pt 15, Ch 4, Sec 1 of Rules for the Classification of Steel Ships**. The boundary conditions given [2.5.2] are applicable to cargo hold finite element model analyses in cargo hold region.

2.5.2. Boundary Conditions

The rigid links connect the nodes on the longitudinal members at the model ends to an independent point at the neutral axis in the centerline. The boundary conditions to be applied at the ends of the mid-hold cargo hold FE model are given in Table 10. For the case of TC 5 as given in Table 12, additional boundary condition as given in Table 11 is to be applied at the aftward and forward bulkheads of middle hold in the model.

Table 10 Boundary constraints at model ends for mid-hold

Location	Translation			Rotation		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Aft End						
Independent point	–	Fix	Fix	M_{T-end}	–	–
Cross Section	–	Rigid link	Rigid link	Rigid link	–	–
Fore End						
Independent point	–	Fix	Fix	Fix	–	–
Intersection of centerline and inner bottom	Fix	–	–	–	–	–
Cross Section	–	Rigid link	Rigid link	Rigid link	–	–
Note 1: [–] means no constraint applied (free). Note 2: See Figure 21.						

Table 11 Additional boundary constraints at bulkhead sections for cargo hold model

Location	Translation			Rotation		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Aft bulkhead in the middle hold						
Line D, Line B	–	Fix	–	–	–	–
fore bulkhead in the middle hold						
Line D, Line B	–	Fix	–	–	–	–
Note 1: [–] means no constraint applied (free). Note 2: See Figure 22.						

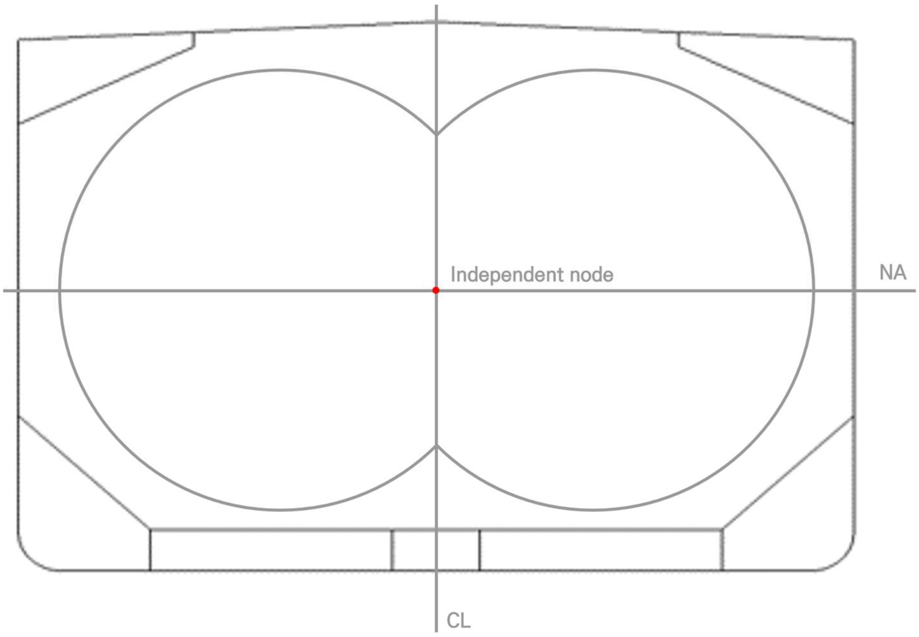


Figure 21 Boundary conditions applied at the model end sections of mid model

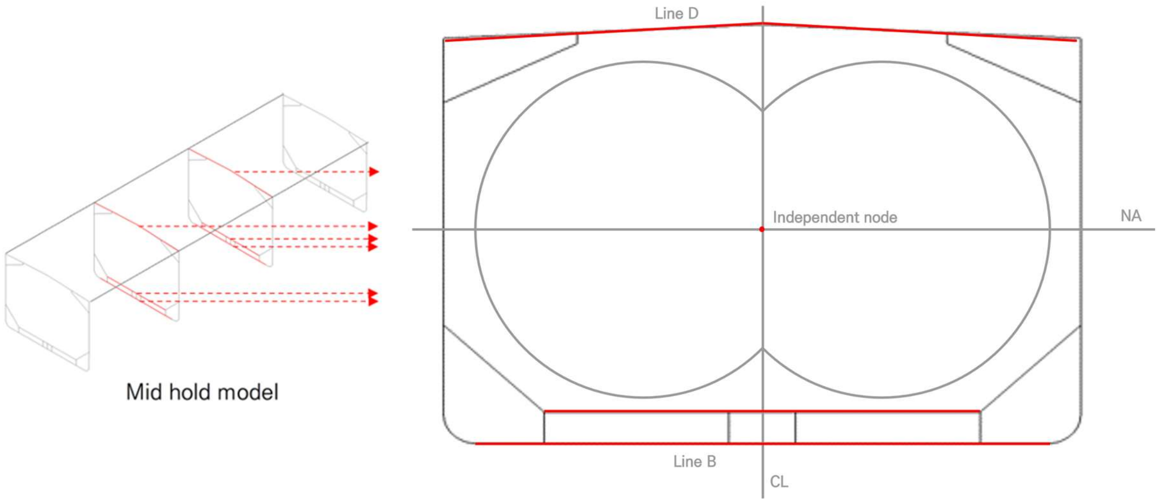


Figure 22 Additional boundary conditions applied at the model

3. FE load combinations

3.1. Design load combinations

3.1.1. FE load combination definition

A FE load combination is defined as a loading pattern, a draught, a value of still water bending and shear force, associated with a given dynamic load case.

3.1.2. Loading conditions

Loading conditions to be considered for a strength assessment generally are as follow:

a) Standard loading conditions for yielding and buckling strength assessment are given in [3.1.3].

b) For fatigue assessment, standard designs are given in **Pt 15, Ch 9, Sec 1 of Rules for the Classification of Steel Ships.**

3.1.3. Load combinations

For cargo hold structural strength analysis for midship holds, the design load combinations specified in Table are to be used as a minimum.

Each design load combination given in Table 12 consists of a loading pattern and dynamic load cases as given in **Pt 15, Ch 4, Sec 2 of Rules for the Classification of Steel Ships**. Each load combination requires the application of the structural weight, internal and external loads and hull girder loads. For seagoing condition, both static and dynamic load components (S+D) are applied.

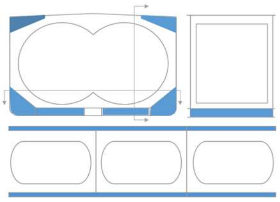
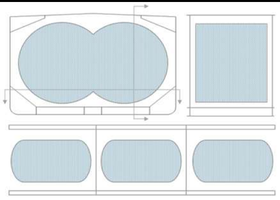
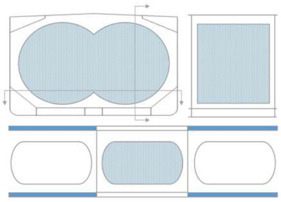
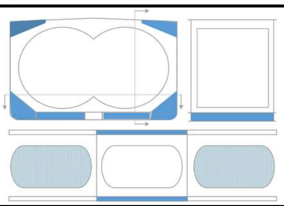
The "maximum shear force load combinations" are marked as "Max SFLC"in the load combination tables of Table . The "other shear force load combinations" are those which are not the maximum shear force load combinations. They are not marked in the load combination tables of Table .

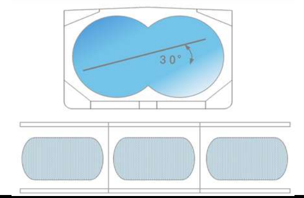
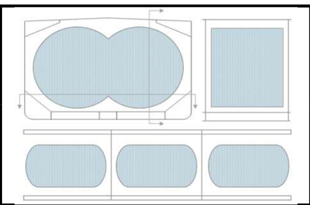
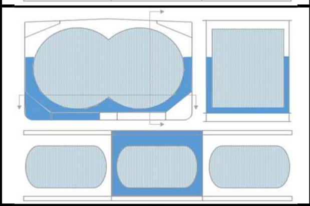
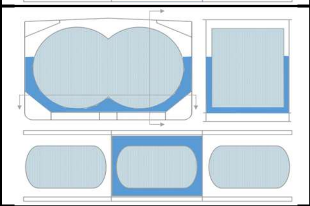
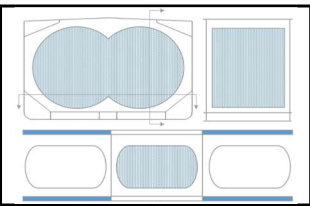
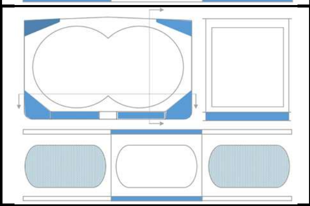
Excessive asymmetric loading shall be avoided, if asymmetric loading is specifically required in the loading manual, these loading conditions are to be documented and be assessed for compliance.

3.1.4. Additional loading conditions

Where the loading conditions specified by the designer are not covered by the load combinations given in [3.1.3], these additional loading conditions are to be examined according to the procedure in [4].

Table 12 Standard loading conditions applicable to cargo hold region

No	Loading Pattern	Draught	% of perm. SWBM	% of perm. SWSF	Dynamic load cases	Pressure by IGC (Pt 7, Ch 5, 428)
Seagoing condition						
TC1		T_{BAL}	0% Sagging	≤ 100%	HSM1	
			100% Hogging	≤ 100%	HSM2, BSR-2P	
TC2		T_{SC}	100% Sagging	≤ 100%	HSM1, BSR-1P, BSP-1P	
			0% Hogging	≤ 100%	HSM2, BSP-1P, BSR-1P	
TC3		$0.75T_{SC}$	100% Sagging	100% Max SFLC	HSM1	
			75% Hogging	≤ 100%	HSM2	
TC4		$0.9T_{SC}$	0% Sagging	≤ 100%	HSM1, BSP-1P	
			100% Hogging	100% Max SFLC	HSM2	

TC5		T_{SC}	≤ 100%	≤ 100%	N/A	
Accidental condition						
TC6		T_{SC}	≤ 100%	≤ 100%	N/A	0.5g 0.25g
TC7		T_{DAM}	≤ 100%	≤ 100%	N/A	
TC8		T_{SC}	≤ 100%	≤ 100%	N/A	
Harbour condition						
TC9		$0.75T_{SC}$	100% Sagging		N/A	
TC10		$0.9T_{SC}$	100% Hogging		N/A	

4. Load application

4.1.

The load application refers to **Part 15 of Rules for the Classification of Steel Ships**.

4.2. Reference coordinate system

The ship's geometry, motions, accelerations and loads are defined with respect to the following right-hand coordinate system, see **Figure 23**:

Origin : At the intersection among the longitudinal plane of symmetry of ship, the aft end of L and the baseline.

X_{axis} : Longitudinal axis, positive forwards.

Y_{axis} : Transverse axis, positive towards portside.

Z_{axis} : Vertical axis, positive upwards.

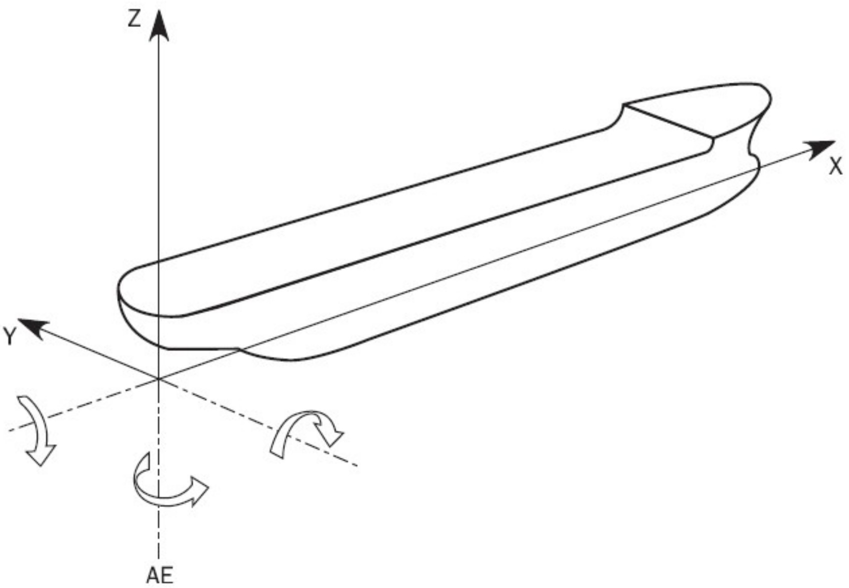


Figure 23 Reference coordinate system

5. Analysis criteria

5.1. General

5.1.1. Evaluation areas

Verification of results against the acceptance criteria is to be carried out within the longitudinal extent of the mid-hold, as shown in Figure 24. The longitudinal extent is from the aft bulkhead of mid-hold to the forward bulkhead of mid-hold.

In cases of TC5 of Table 12 with additional boundary condition as defined in Table 4, the hull envelope including outer bulkheads, is to be excluded.

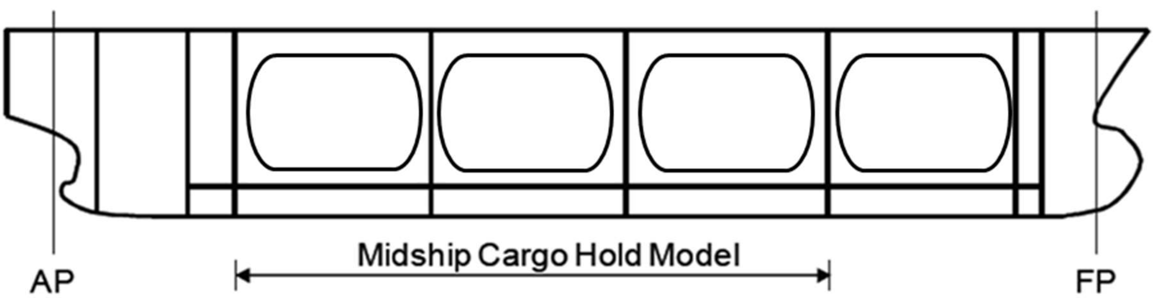


Figure 24 Longitudinal extent of evaluation area

5.1.2. Structural members

The following structural elements within the evaluation area are to be verified with the criteria given in [5.2] and [5.3]:

• All hull girder longitudinal structural members within Mid-hold including adjacent cofferdams and one web frame spacing more in forward and aftward direction from the cofferdams.

• All primary supporting structural members and bulkheads within the mid-hold.

• All structural members being part of the transverse bulkheads.

5.2. Yield strength assessment

5.2.1. Von mises stress

For all plates of the structural members defined in [5.1.2], the von Mises stress, σ_{vm}, in N/mm^2, is to be calculated based on the membrane normal and shear stresses of the shell element. The stresses are to be evaluated at the element centroid of the mid-plane (layer), as follows:

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

where:

σ_x, σ_y : Element normal membrane stresses, in N/mm^2.

τ_{xy} : Element shear stress, in N/mm^2.

5.2.2. Axial stress in beams and rod elements

For beams and rod elements, the axial stress, σ_{axial}, in N/mm^2, is to be calculated based on axial force alone. The axial stress is to be evaluated at the middle of element length.

5.2.3. Coarse mesh permissible yield utilization factors

The coarse mesh permissible yield utilization factors, λ_{yperm}, given in Table 13, are based on the mesh sizes and element types described in [2.3] to [2.4].

The yield utilization factor resulting from element stresses of each structural component are not to exceed the permissible values as given in Table 13.

Table 13 Coarse mesh permissible yield utilization factor

Structural component	Coarse mesh permissible yield utilization factor, λ_{yperm}
Plating of all longitudinal hull girder structural members, primary supporting structural members and bulkheads. Face plate of primary supporting members modelled using shell or rod elements.	1.0 (load combination S+D)
	0.8 (load combination S)
	1.0 (load combination A)

5.2.4. Yield criteria

a) Hull

The structural elements given in [5.1.2] are to comply with the following criteria:

$$\lambda_y \leq \lambda_{yperm}$$

Where:

λ_y : Yield utilization factor.

$\lambda_y = \frac{\sigma_{vm}}{R_y}$ for shell element in general.

$\lambda_y = \frac{\sigma_{vm}}{R_{eH}}$ for accidental condition or the loading condition with AC-A.

$\lambda_y = \frac{|\sigma_{axial}|}{R_y}$ for rod or beam elements in general.

$\lambda_y = \frac{|\sigma_{axial}|}{R_{eH}}$ for accidental condition or the loading condition with AC-A.

σ_{vm} : Von Mises stress, in N/mm^2.

σ_{axial} : Axial stress in rod or beam element, in N/mm^2.

λ_{yperm} : Coarse mesh permissible yield utilization factors defined in Table 13.

The yield check criteria are to be based on axial stress for the flange of primary supporting members.

Where the von Mises stress of the elements in the cargo hold FE model in way of the area under investigation by fine mesh exceeds the yield criteria, average von Mises stress, obtained from the fine mesh analysis, calculated over an area equivalent to the mesh size of the cargo hold finite element model is to satisfy the yield criteria above.

In way of cut-outs, yield utilization factor is to be obtained with shear stress correction, as given in [5.2.6].

Table 14 C, D Factors

	AC-S	AC-SD	AC-A
C	2.4	2.4	2.0
D	1.2	1.2	1.0

5.2.5. Shear stress correction for cut-out

Except as indicated in [5.2.6], the element shear stress in way of cut-outs in webs is to be corrected for loss in shear area in accordance with the following formula. The corrected element shear stress is to be used to calculate the von Mises stress of the element for verification against the yield criteria.

$$\tau_{cor} = \frac{h\, t_{mod}}{A_{shr}} \tau_{elem}$$

where:

τ_{cor} : Corrected element shear stress, in N/mm^2.

h : Height of web of girder, in mm, in way of opening. Where the geometry of the opening is modelled, h is to be taken as the height of web of the girder deducting the height of the modelled opening.

t_{mod} : Modelled web thickness, in mm, in way of opening.

A_{shr} : Effective shear area of web, in mm^2, taken as the web area deducting the area loss of all openings, including slots for stiffeners, calculated in accordance with Pt 15, Ch 3, Sec 7, [1.4.8] **of Rules for the Classification of Steel Ships**.

τ_{elem} : Element shear stress, in N/mm^2, before correction.

5.2.6. Exceptions for shear stress correction for openings

Correction of element shear stress due to presence of cut-outs is not required for cases given in Table 15 provided λ_y / C_r complies with the criteria given in [5.2.4].

5.3. Buckling strength assessment

5.3.1. Allowable buckling utilization factor

The allowable buckling utilization factor is defined in Table 16.

Table 15 Exceptions for shear stress correction

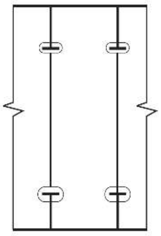
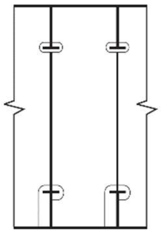
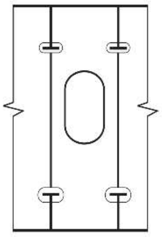
Identification	Figure	Difference between modelled shear area and the effective shear area in % of the modelled shear area $\frac{A_{FEM-n50} - A_{shr-n5}}{A_{FEM-n50}} \cdot 100\%$	Reduction factor for yield criteria, C_r
Upper and lower slots for local support stiffeners fitted with lugs or collar plates		〈 15%	0.85
Upper or lower slots for local support stiffeners fitted with lugs or collar plates		〈 20%	0.80
In way of opening; upper and lower slots for local support stiffeners fitted with collar plates		〈 40%	0.60
$A_{shr-n50}$: Effective net shear area of web, in mm^2, taken as the web area deducting the area lost of all openings, including slots for stiffeners, calculated in accordance with Pt 15, Ch 3, Sec 7, [1.4.8].			

Table 16 Allowable buckling utilization factor

Structural component	η_{all}, Allowable buckling utilization factor
Plates and stiffener Stiffened and unstiffened panels Web plate in ways of openings	1.00 for load combination: S+D 0.80 for load combination: S 1.00 for load combination: A, T
Pillars	0.75 for load combination: S+D 0.65 for load combination: S 0.75 for load combination: A, T

Section 3 – Local Structural Strength Analysis

1. General

1.1.

The local strength analysis of structural details is to be in accordance with the requirements given in this section.

1.2. Fine mesh analysis procedure

The details to be assessed by fine mesh analysis are to be modelled according to the requirements given in [2], under the FE load combinations defined in [3] and to comply with the criteria given in [4].

1.3. Modelling of standard structural details

The fine mesh analysis may be carried out the area of high stress concentration identified during coarse mesh analysis.

2. Structural model

2.1. General

Evaluation of detailed stresses requires the use of refined finite element mesh in way of areas of high stress. This fine mesh analysis can be carried out by fine mesh zones incorporated into the FE model. Alternatively, separate local FE models with fine mesh zones in conjunction with the boundary conditions obtained from the global model may be used.

2.2. Extent of model

If a separate local fine mesh model is used, its extent is to be such that the calculated stresses at the areas of interest are not significantly affected by the imposed boundary conditions. The boundary of the fine mesh model is to coincide with primary supporting members in the global model, such as web frame, girders, stringers and floors.

2.3. Mesh size

The mesh size in the fine mesh zones is not to be greater than 50 × 50 mm. The extent of the fine mesh zone is not to be less than 10 elements in all directions from the area under investigation. A smooth transition of mesh density from fine mesh zone to the boundary of the fine mesh model is to be maintained.

2.4. Elements

2.4.1.

All plating within the fine mesh zone is to be represented by shell elements. The aspect ratio of elements within the fine mesh zone is to be kept as close to 1 as possible. Variation of mesh density within the fine mesh zone and the use of triangular elements are to be avoided. In all cases, the elements within the fine mesh model are to have an aspect ratio not exceeding 3. Distorted elements, with element corner angles of less than 45° or greater than 135°, are to be avoided. Stiffeners inside the fine mesh zone are to be modelled using shell elements. Stiffeners outside the fine mesh zones may be modelled using beam elements.

2.4.2.

Where fine mesh analysis is required for main bracket end connections and hatch opening, the fine mesh zone is to be extended at least 10 elements in all directions from the area subject to assessment, see **Figure 26.**

Where fine mesh analysis is required for an opening, the first two layers of elements around the opening are to be modelled with mesh size not greater than 50 × 50mm. A smooth transition from the fine mesh to the coarser mesh is to be maintained. Edge stiffeners which are welded directly to the edge of an opening are modelled with shell elements. Web stiffeners close to an opening may be modelled using rod or beam elements located at a distance of at least 50mm from the edge of the opening. An example of fine mesh zone around an opening is shown in **Figure 27.**

2.4.3.

Face plates of openings, primary supporting members and associated brackets are modelled with at least two elements across their width on either side.

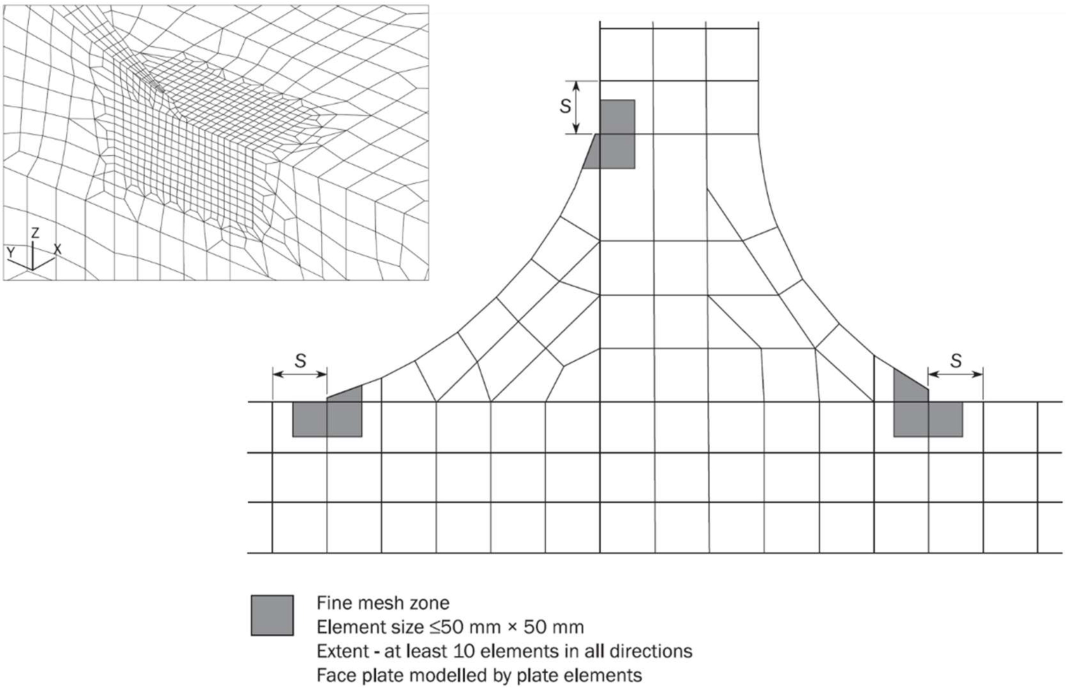


Figure 25 Fine mesh zone around bracket toes

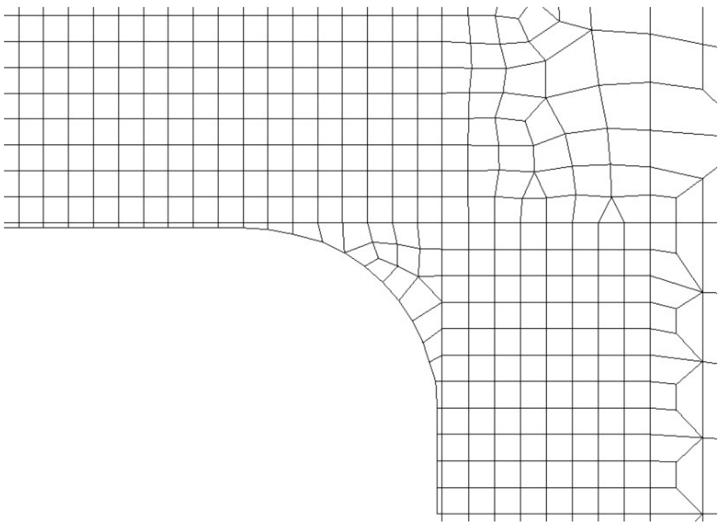


Figure 26 Fine mesh zone around hatch opening structures

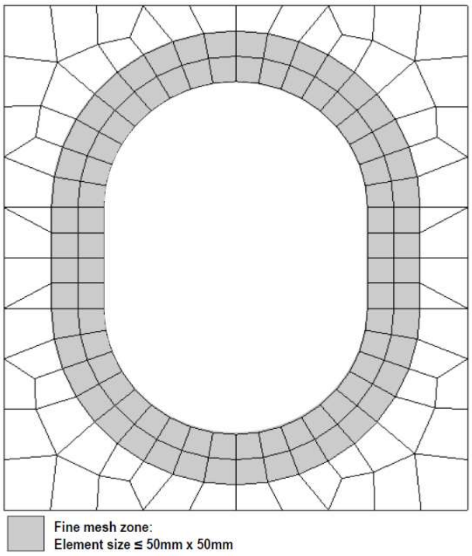


Figure 27 Fine mesh zone around an opening

3. FE load combinations

3.1. General

The fine mesh detailed stress analysis is to be carried out for all FE load combinations applied to the corresponding global analysis.

3.2. Application of loads and boundary conditions

Where a separate local model is used for the fine mesh detailed stress analysis, the nodal displacements from the global model are to be applied to the corresponding boundary nodes on the local model as prescribed displacements. Alternatively, equivalent nodal forces from the global model may be applied to the boundary nodes. Where there are nodes on the local model boundaries which are not coincident with the nodal points on the global model, it is acceptable to impose prescribed displacements on these nodes using multi-point constraints. The use of linear multi-point constraint equations connecting two neighboring coincidence nodes is considered sufficient. All local loads, including any loads applied for hull girder bending moment and/or shear force adjustments, in way of the structure represented by the separate local finite element model are to be applied to the model.

4. Analysis criteria

4.1. Stress assessment

4.1.1. General

Stress assessment of the fine mesh analysis is to be carried out for the FE load combinations.

4.1.2. Reference stress

Reference stress is von Mises stress, σ_{vm}, which is to be calculated based on the normal membrane and shear stresses of the shell element evaluated at the element centroid. The stresses are to be evaluated at the mid plane of the element.

4.1.3. Permissible stress

The maximum permissible stress is based on the mesh size of 50 x 50mm as specified in **[2.1]** to **[2.4]**. Where a smaller mesh size is used, an area weighted von Mises stress calculated over an area equal to the specified mesh size may be used to compare with the permissible stresses. The averaging is to be based only on elements with their entire boundary located within the desired area. The average stress is to be calculated based on stresses at element centroid; stress values obtained by interpolation and/or extrapolation are not to be used. Stress averaging is not to be carried across structural discontinuities and abutting structure.

4.2. Acceptance criteria

4.2.1.

Verification of stress results against the acceptance criteria is to be carried out in accordance with [4.1]. The structural assessment is to demonstrate that stress complies with the following criteria:

$$\lambda_f \leq \lambda_{fperm}$$

where:

λ_f : Fine mesh yield utilization factor.

$\lambda_f = \frac{\sigma_{vm}}{R_Y}$ for shell elements in general

$\lambda_f = \frac{|\sigma_{axial}|}{R_Y}$ for rod or beam elements in general

σ_{vm} : Von Mises stress, in N/mm^2.

σ_{axial} : Axial stress in rod element, in N/mm^2.

λ_{fperm} : Permissible fine mesh utilization factor, taken as:

- Element not adjacent to weld:
- $\lambda_{fperm} = 1.70\ f_f$ for S+D
- $\lambda_{fperm} = 1.36\ f_f$ for S
- Element adjacent to weld:
- $\lambda_{fperm} = 1.50\ f_f$ for S+D
- $\lambda_{fperm} = 1.20\ f_f$ for S

f_f : Fatigue factor, taken as:

- f_f=1.0 in general, including the free edge of base material,
- f_f=1.2 for details assessed by very fine mesh analysis complying with the fatigue assessment criteria given in Pt 15, Ch 9, Sec 2 of Rules for the Classification of Steel Ships.

Note 1: The maximum permissible stresses are based on the mesh size of 50 × 50 mm. Where a smaller mesh size is used, an average von Mises stress calculated in accordance with [4.1] over an area equal to the specified mesh size may be used to compare with the permissible stresses.

Note 2: Average von Mises stress is to be calculated based on weighted average against element areas:

$$\sigma_{vm-a} = \frac{\sum_1^n A_i \sigma_{vm-i}}{\sum_1^n A_i}$$

where:

σ_{vm-av} is the average von Mises stress.

Note 3: Stress averaging is not to be carried across structural discontinuities and abutting structure.

Chapter 4

Buckling for Cargo Holds

Section 1 – General Considerations

Section 1 – General Considerations

1. Assumption

1.1.

This section contains buckling requirements for direct strength analysis. The plate panel of hull structure is to be modelled as stiffened of unstiffened panel. Method A and Method B which are defined as shown in Figure 28, Figure 29 and Figure 30 are to be applied while referring to that of single hull bulk carrier prescribed in Pt 13, Ch 8, Sec 4 of Rules for the Classification of Steel Ships. Buckling assessments are to comply with the principles and requirements of Part 15 of Rules for the Classification of Steel Ships except for the requirements specified in this Guideline.

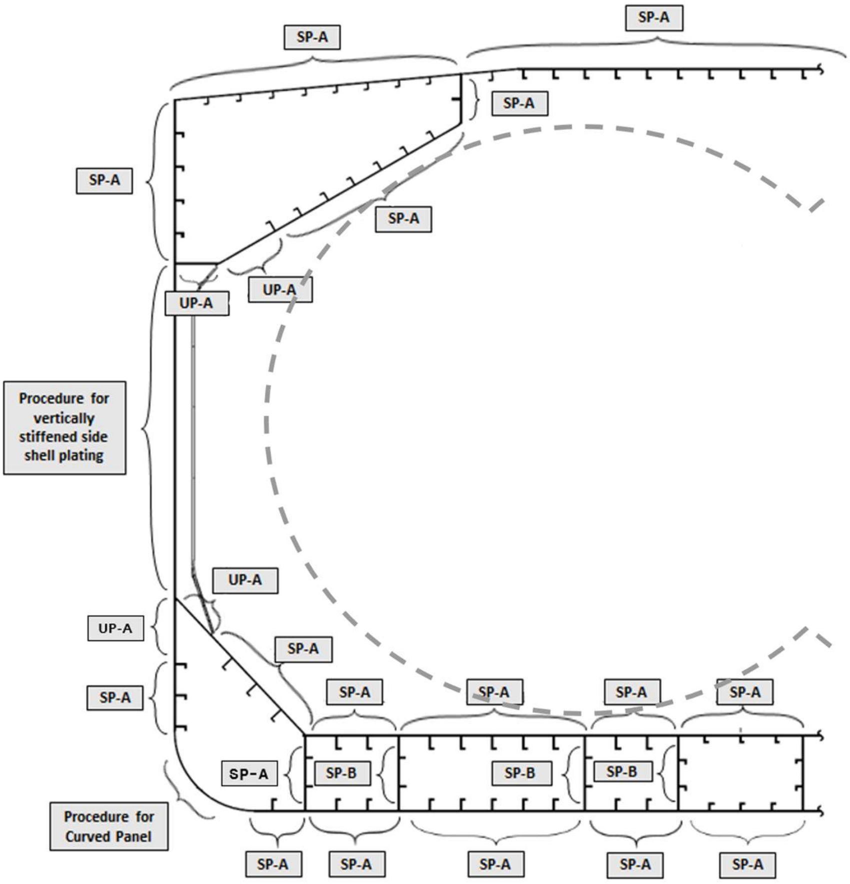


Figure 28 Longitudinal plates in Type C gas carrier

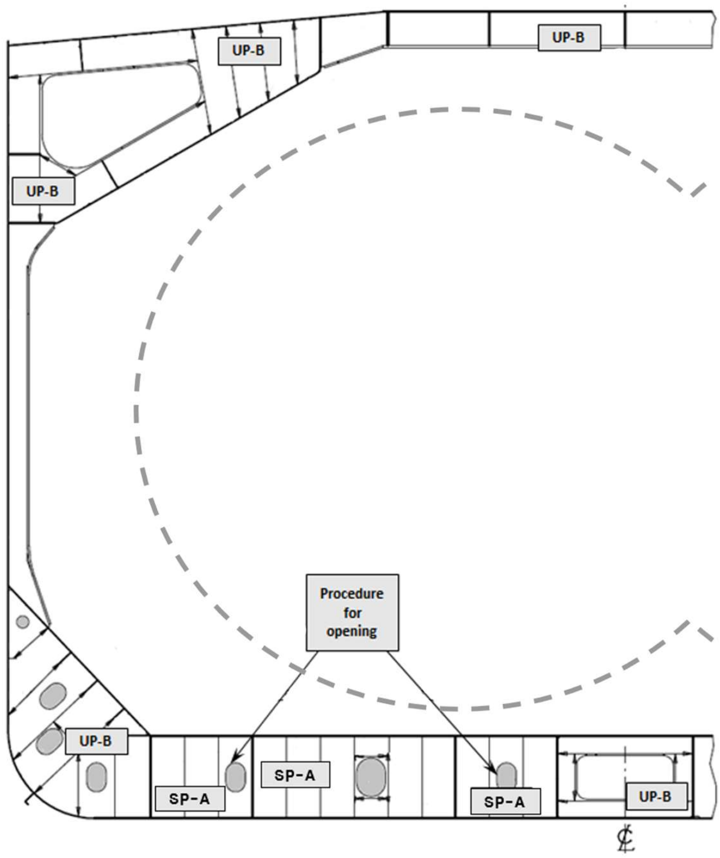


Figure 29 Transverse web frame in Type C gas carrier

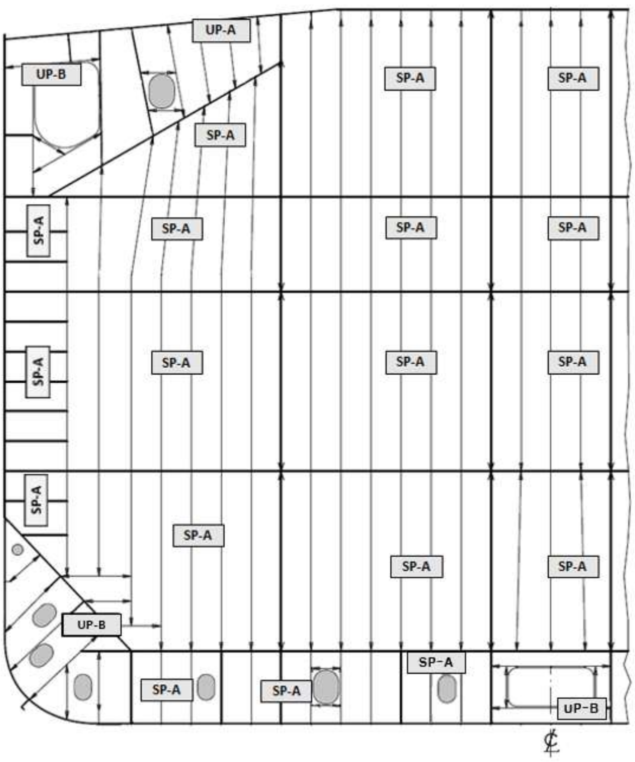


Figure 30 Transverse bulkhead in Type C gas carrier

Chapter 5

Fatigue for Cargo Holds

Section 1 – General Considerations

Section 1 – General Considerations

1. Assumption

1.1.

This section contains fatigue requirements to evaluate fatigue strength of the ship's structural details considering an operation time in worldwide environment for unrestricted navigation. A more severe trading route may be specified e.g. North Atlantic. Fatigue assessments are to comply with the principles and requirements of Pt.15, Ch.9 of Rules for the Classification of Steel Ships.
And when fatigue assessment by finite element stress analysis is performed at the request of the designer, the support structure and independent tank shall be maintained linearly by contact without a slip.

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