Guidelines on

Hull Design & Construction including Containment System for Liquefied Natural Gas Carriers – Membrane Type Tanks

2020

IRCLASS
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Guidelines

Hull Design & Construction including Containment System for Liquefied Natural Gas Carriers – Membrane Type Tanks
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Section 1

Introduction

IRS Rules and Regulations for Construction and Classification of Steel Ships, Part 5, Chapter 4 provide requirements for compliance by Ships carrying Liquefied gas cargo in bulk. Further, Part 3 provides the prescriptive requirements to be complied with for hull structure.

These guidelines provide supplementary information on the assessments required by IRS to be performed for establishing the structural integrity of the hull and the containment systems for ships carrying Liquefied Natural Gas in bulk within Membrane Type Tanks. Membrane Type Tanks are non-self-supporting tanks which consist of a thin layer (membrane) which is liquid and gastight and supported through insulation by the adjacent hull structure. The membrane is designed in such a way that thermal and other expansion or contraction is compensated for without undue stressing of the membrane.

These guidelines focus mainly on the Ships installed with the GTT Mark III and the NO 96 Membrane Containment Systems. The GTT Mark III membrane containment system is a containment and insulation system, directly supported by the ship's hull structure. It is composed of a primary corrugated 304L stainless steel membrane of about 1.2mm thick, positioned on top of prefabricated insulation panels, and a complete secondary membrane made of composite material. This modular system employs standard prefabricated components that can accommodate various shapes and capacities of prismatic tanks. They are designed for mass production techniques and easy assembly.

The GTT NO 96 membrane containment system comprises of the primary and secondary membranes 0.7mm thick, made of Invar®, a 36% nickel-steel alloy notable for its uniquely low coefficient of thermal expansion. The primary membrane contains the LNG cargo, while the secondary membrane, identical to the primary, ensures a 100% redundancy in case of leakage. Each of the 500mm wide Invar® strakes is continuously spread along the tank walls and is evenly supported by the primary and the secondary insulation layers.

For ships equipped with variants of GTT Mark III and NO 96 systems or membrane containment systems from other manufacturers, these guidelines are to be judiciously applied bearing in mind the underlying safety principles.

Section 2

Hull Scantlings

2.1 Definitions

2.1.1 Rules: - IRS Rules and Regulations for the Construction and Classification of Steel Ships.

2.1.2 Ship – Liquefied Natural Gas Carrier with Membrane Tanks. This may also include Floating Storage Regasification Units which are ship shaped.

2.1.3 LNG – Liquefied Natural Gas (Methane (CH_4)) stored at temperatures lower than -162°C.

2.1.4 Inner Hull – The plating and the stiffeners of the hull forming the cargo tank boundaries.

2.1.5 *V* – Service speed of the ship (knots).

2.2 General

2.2.1. The hull structural members are to comply with requirements provided in Part 3 of the Rules in general except for the Inner hull structural members which should comply with requirements provided in Section 2.7 of this guideline. The corrosion margins to be utilized for this purpose are to be in accordance with Section 2.4 of this guideline. Additional requirements are to be fulfilled are specified in Section 2.8-2.10.

2.2.2 Ships exceeding 150 m in length are to also comply with the requirements in Section 2.5-2.6 of these guidelines.

2.2.3 For membrane containment systems of a novel configuration, reference is made to requirements within the IRS *Guidelines on Alternative & Risk based design evaluation*.

2.3 Thermal analysis for steel grades determination

2.3.1 A thermal analysis is to be performed to determine the temperatures at the inner hull steel. The thermal analysis is to be performed considering the ballast tanks to be empty and the cargo tanks to be completely loaded with LNG.

2.3.2 The conduction, convection and radiation modes of heat transfer are to be considered in the analysis as appropriate for the particular elements (inner and outer hull steel, air in the ballast tank void, containment system insulation) involved in the heat transfer. Hull Steel can be assumed as an excellent conductor of heat for this purpose hence the temperature gradient across the steel thickness can be assumed to be nil. Heat transfer is considered to be in the steady state phase for the analysis. In the void spaces, it is not typically necessary to consider the temperature gradient.

2.3.3 2D Thermal analyses are acceptable to IRS. A transverse section of the hull in each cargo tank is to be considered between two frames. For the cofferdam region between two cargo holds or between the engine room and cargo hold or the forward most cargo hold and the ballast tank, the cofferdam bulkheads with their heating arrangements (where provided) are to be considered in the heat balance computations.

2.3.4 The analysis is to be performed in accordance with the requirements in Part 5, Chapter 4,Cl. 4.19.1.1 of the Rules. The cargo temperature is to be taken as the actual temperature of carriage of the LNG cargo, however this is not to exceed -163°C. Additional requirements from flag Administrations may also need to be complied with as applicable.

2.3.5 Heating arrangements typically installed on the cofferdam bulkheads are to be adequate to maintain a temperature of not less than 5°C in the cofferdam. For the cofferdams sharing a boundary with the engine room and the forward ballast tanks, the temperatures of the Engine Room and forward ballast tanks to be considered will be agreed with IRS.

2.3.6 The 2D model should be discretized into regions so as to capture the thermal temperature variation. An example is shown in Figure 2.3.6. It is sufficient to model either port or starboard side.

2.3.7 Emissivity co-efficients for the steel should be taken considering the potential variation due to the coating breakdown and corrosion through the ship's service.

2.3.8 The following are to be clearly indicated in the report:

- Discretization scheme capturing the thermal temperature variation.
- Values of the conduction co-efficients of the insulation
- Values of the convection co-efficients of the external air, sea water and the air within the void space.
- Values of the fin efficiency factors for the stiffeners of the hull.
- Values of the emissivity co-efficients of the steel
- Temperatures of the inner hull steel, outer hull steel and the void spaces as obtained from the analysis.
- Required capacity of the heating coils in all the cofferdams.

2.3.9 The temperatures obtained from the analyses are to be further used to determine the steel grade. For this purpose, the stricter of the requirements between Part 3, Chapter 2, Section 2 and Part 5, Chapter 4, Section 6 are to be applied.

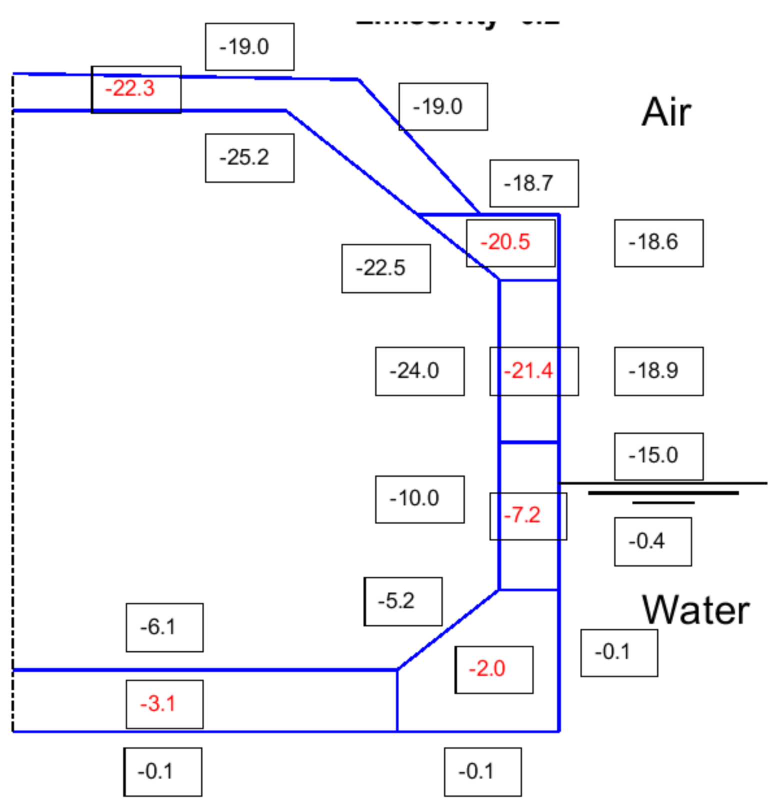

Figure 2.3.6: Typical depiction of the temperatures on the outer and inner hull and the void ballast tanks

2.4 Corrosion Allowance

2.4.1 The corrosion allowances are to be provided in accordance with the requirements in Part 3 of the Rules, other than those for cargo tanks, which are indicated in this sub-section.

2.4.2 The corrosion addition for a member is determined as shown in the formula below. The corrosion addition is to be rounded off to the next half millimeter.

$$t_c = t_{c1} + t_{c2} + 0.5$$

Where:
t_c: Corrosion addition
t_{c1}: Corrosion addition from one side
t_{c2}: Corrosion addition from the other side

In the event that the member does not share a boundary with any other space, t_{c2} is to be taken the same as t_{c1}.

2.4.3 The Corrosion additions to be considered for the Cargo Tank Region are indicated in Table 2.4.3

Table 2.4.3: Corrosion Additions

Location	Members	Corrosion addition t_{c1} or t_{c2} (as applicable) (mm)
Shell Plating	External Surfaces	0.5
Ballast & Bilge Tanks	All	1.0
Inert Spaces[1]	All	0
	Cofferdam Transverse Bulkheads	0.5
Void and Dry Spaces (not normally accessed)[2]	All	0.5

[1] The secondary insulation space is considered to be an Inert Space
[2] This includes the space between the trunk decks and the cofferdam space. The pipe duct is also considered to be a dry space

2.5 Shear capacity evaluation of Hull Girder

2.5.1 The Shear Stresses of the Hull Girder are to be evaluated for the Ships eligible for the DSA notation (see Section 3).

2.5.2 The evaluation is to be performed for the following locations:
- Longitudinal section immediately fore of the Engine Room Fore Bulkhead
- Longitudinal section at 0.4L and 0.6L
- Longitudinal section at 0.7L and 0.85L

If deemed necessary by IRS, evaluations for additional locations are to be submitted.

2.5.3 The Permissible Still Water Shear Force envelope is to be considered along with the wave shear forces provided in Part 3, Chapter 5.

2.5.4 Shear Stresses are to be calculated using a shear flow calculation as described in IRS Rules for Bulk Carriers and Oil Tankers, Vol.2, Part 1, Chapter 5.

2.5.5 The shear stresses should not exceed the permissible values as provided in IRS Rules for Bulk Carriers and Oil Tankers, Vol.2, Part 1, Chapter 5.

2.6 Ultimate Bending Moment Capacity evaluation of Hull Girder

2.6.1 An Ultimate Bending Moment Capacity evaluation of the Hull Girder is to be performed for the Ships eligible for the DSA notation (see Section 3).

2.6.2 The evaluation is to be performed for locations at mid-ships, aft bulkhead of Tank no.1 and the aft bulkhead of Tank no. 4/5. The procedure for performing the evaluation is described in IRS Rules for Bulk Carriers and Oil Tankers, Vol.2, Part 1, Chapter 5.

2.7 Scantlings for Inner Hull

2.7.1 Cargo Pressure

2.7.1.1 Cargo Pressure (p) (N/mm^2) is to be evaluated in accordance with the requirements in Part 5, Chapter 4, Section 4.28 of the Rules.

2.7.1.2 The thickness of the inner hull members is obtained using the formulae provided below:

$$t = max(t_1, t_2)$$
$$t_1 = (5 + 0.03\, min(L, 250))\sqrt{k} + t_c$$
$$t_2 = f_a \frac{s}{2}\sqrt{\frac{p}{\sigma_{perm}}} + t_c$$
$$\sigma_{perm} = min\left(\frac{220}{k} - \sigma_{hg}, \frac{160}{k}\right)$$
$$\sigma_{hg} = \left(\frac{M_{st} + M_w}{Z_{IH}}\right)$$
$$Z_{IH} = \frac{I_n}{|N.A - z|}$$

The symbols are defined as follows:

L: Rule length of the Ship (m)
fa: factor described in Part 3, Chapter 3, Section 3.2 of the Rules
s: Stiffener spacing (mm)
k: Material factor described in Part 3, Chapter 1, Section 1.2 of the Rules
M_{st}: Still Water Bending Moment (N.mm)
M_w: Vertical Wave Bending Moment as described in Part 3, Chapter 5, Section 2.2 of the Rules (N.mm)
z: Vertical Co-ordinate of the Location where the thickness is under determination measured from the Baseline (mm)
N.A: Neutral axis location of the hull cross section from the baseline (mm).
I_n: Hull Girder Moment of Inertia (mm^4)
t_c: Corrosion addition as described in section 2.4 (mm)

2.7.1.3 The section modulus of the stiffeners of the inner hull members is not to be less than that obtained from the formula below:

$$Z = \frac{spl^2}{12\sigma} + Z_c$$

l: length of the unsupported span of the stiffener (mm)
s: Stiffener spacing (mm)

p: Internal Cargo pressure as described in 2.7.1.1 (N/mm^2)
σ: Maximum permissible stress as described in 2.7.1.2.
Z_c: Section modulus considering corrosion additions (mm^3)

2.7.2 Ballast & Tank Test Pressure

2.7.2.1 The scantlings for the inner hull members constituting boundaries of ballast tanks are also to comply with the requirements in Section 2.7.1. . The design pressures to be considered are provided in Part 3, Chapter 10, Section 4, 4.2.1-2.

2.7.3 Longitudinal Stress requirements for Mark III Containment System

2.7.3.1 For Mark III Containment Systems, the following requirement is to be complied by the scantlings along the Inner Hull Boundary. It is recommended to verify this requirement using the direct strength analysis as described in Section 3.

$\sigma_{hg} + \sigma_{lo} < 185\ N/mm^2$

σ_{hg} is the combination of the longitudinal stresses due to the still and the vertical hull girder bending moments as described in Section 2.7.1

σ_{lo} is the local stress emanating due to the effect of double bottom bending

2.7.4 Longitudinal Stress requirements for NO96 Containment System

2.7.4.1 For NO 96 Containment Systems, the following requirement is to be complied by the scantlings along the Inner Hull Boundary. It is recommended to verify this requirement using the direct strength analysis as described in Section 3.

$\sigma_{hg} < 120\ N/mm^2$

σ_{hg} is the combination of the longitudinal stresses due to the still and the vertical hull girder bending moments as described in Section 2.7.1

2.8 Slamming Analysis

2.8.1 Slamming analysis is to be performed for ascertaining the integrity of the Ship in the fore region of the ship. This is required for bottom slamming and bow flare-slamming. IRS may waive off the requirements for evaluating the bow-flare slamming if this may not be significant. This will be done on a case to case basis.

2.8.2 Slamming loads should be evaluated using recognized standards, guidelines and practices. The selection of a particular standard, guideline or practice to evaluate the slamming load is to be discussed and agreed with IRS prior to performing the analysis.

2.8.3 Direct analyses may also be accepted by IRS for the evaluation of the slamming loads. It is recommended that the designer contact IRS in the early stage for finalizing the methods and the parameters to be used for the analysis.

2.8.4 Structural assessment based upon Finite element method is acceptable to IRS to ascertain the integrity of the bottom and bow-flare structure (if applicable) against the slamming loads. The structure should be idealized appropriately so that the stiffness is accurately represented. The extent of the model, the modeling strategy (use of plate elements or analysis as a grillage etc.), mesh size, boundary conditions, extent and size of patch over which the slamming load is applied is to be clearly indicated in the analysis report.

2.8.5 The stresses from the slamming analysis are to be combined suitably with the stresses due to the global loads and verified with the acceptance criteria in Section 3.2.9.

2.9 Strength analysis of the Pump Tower Base Support and the Inner Bottom Strengthening

2.9.1 The Inner Bottom is to be suitably strengthened at the location of the pump tower base support (PTBS) in order to ascertain that the pump tower thrust loads (in the transverse and longitudinal) directions are adequately transferred to the primary structure of the hull without loss of structural integrity.

2.9.2 For the purpose of ascertaining the requirement in 2.9.1, a finite element analysis is to be performed. The finite element model is to include the PTBS and its integration with the inner bottom including the underdeck stiffening. The actual extent of the model is to be agreed with IRS before performing the analysis. It is recommended that the model extent be such that it is bound by the nearest primary structural members (e.g. the transverse floors and girders) to the PTBS which would be expected to withstand the loads transferred from the PTBS. The boundaries of the model can be considered to be fixed. The transverse and longitudinal thrust loads from the pump tower are to be applied to the model and linear static analysis is to be performed.

2.9.3 The stresses obtained from the analysis are to be combined with the global stresses due to the hull girder bending moments & shear forces, local stresses due to the cargo/ballast pressures as applicable. The sum total of all stresses is to be checked with the acceptance criteria in Section 3.9.2.

2.10 Welding & Construction

2.10.1 The requirements for welding as provided in Part 3, Chapter 17 are applicable. In addition, the requirements provided in this section are also applicable

2.10.2. Fillet Welds

2.10.2.1 For connections of primary structural members welded using fillets; if the thicknesses of the abutting members differ significantly, the thickness of the primary member principally involved in the shear transfer (to the other primary member) should be considered for determination of the weld size so that the cross sectional area of the weld is not less than the cross sectional area of the member.

Section 3

Direct Strength Analysis

3.1 Application and Scope

3.1.1 The present section provides details of the requirements to be fulfilled by Ships for assignment of the DSA notation. The objective of the Direct Strength analysis is to verify the scantlings of the primary structural members of the cargo tanks for the combined effects of global and local loads against the failure modes; thereby verifying the hull structural integrity.

3.1.2 The DSA notation is mandatory for Ships with length 150 m and above.

3.1.3 The following items are assessed by the DSA class notation

- Cargo Hold Analysis – Structural integrity of the Cargo tanks considering combined effects of global and local loads for the yield and ultimate strength/buckling failure modes (assessed using a coarse mesh finite element analysis)
- Local Fine Mesh Analysis – Structural integrity of the critical locations within Cargo tank and cofferdam area (assessed using fine mesh finite element analysis)

3.1.4 The results from the Direct Strength Analysis are not to be used to reduce the scantlings obtained from the applicable prescriptive calculations specified in Part 3 or Part 5 as relevant.

3.1.5 The present section elaborates requirements for cargo tanks within 0.4L amidships. However, for verifying integrity of cargo tanks outside this region (e.g. Tank no.1, which is typically smaller in size), analysis should be performed in line with the principles outlined in this section.

3.2 Cargo Hold Analysis

3.2.1 Scope and Extent of the Model

3.2.1.1 A finite element model of the cargo tanks within 0.4L mid-ships is to be developed. This typically would be covering three cargo holds. The central cargo hold including its cofferdam boundaries is applicable to evaluation of the acceptance criteria (specified in the following sections).

3.2.1.2 All primary structural members with their associated stiffening & faceplates are to be modeled. Primary Structural members are generally listed below for the information of the user but not limited to:

- Outer-hull and Inner-Hull
- Decks, Girders & Stringers
- Longitudinal Bulkheads
- Transverse Bulkheads and Cross deck structures
- Trunk deck structures
- Web-frames
- Large brackets

3.2.1.3 For ships of with novel configurations or geometric features, the extent of the model has to be agreed with IRS.

3.2.2 Scantlings

3.2.2.1 Gross scantlings are to be considered for the finite element model.

3.2.3 Finite Element Modeling

3.2.3.1 The objective of the finite element model is to accurately capture the structural rigidity of the hull girder by modeling the structural members using the appropriate elements with the appropriate options. The present sub-section is recommendatory in nature. Any deviations from the provisions of the section are to be agreed with IRS at an early stage. The deviations are to ensure that the objective mentioned above is not compromised.

3.2.3.2 All primary structural members are to be modeled using 4 node plate/shell elements. Commercial finite element packages popularly provide these elements using reduced integration options as default. It is recommended to switch on the full integration options in the software package or ensure a mesh size adequate enough to eliminate the possibility of development of spurious deformation modes.

3.2.3.3 All stiffening members for the primary structural members including faceplates can be modeled using beam elements. The appropriate offsets should be specified while modeling such members so as to ensure the correct representation of the offset of their centroids from the main plating.

3.2.3.4 Small openings need not be modeled. The criteria for definition of a 'small opening' can be referred from the IRS Rules for Bulk Carriers and Oil Tankers, Vol.2, Chapter 7. Large openings and manholes are to be modeled.

3.2.3.5 The mass of the hull structure can be modeled by specifying the steel density (preferable) or by applying vertical forces distributed appropriately at the nodes. The masses of the containment system can be modeled by considering it to be 'smeared' on the hull structure by incorporating it in the density of the steel provided in the model. A factor of 1.1 on the density to account for un-modeled structural items as well as future design iterations is recommended. The weights of the pump towers, piping systems, cranes, manifolds, masts, cargo rooms, and other equipment are to be appropriately modeled using point mass elements distributed over the applicable nodes or vertical forces by considering the load transfer mechanisms appropriately.

3.2.3.6 The material properties of steel can be assumed to be linear elastic with an Elastic Modulus of 2.06×10^5 N/mm^2 and Poisson ratio of 0.3.

3.2.4 Mesh size

3.2.4.1 The mesh size should be such that there is one finite element between two stiffeners and atleast three elements between two frames.

3.2.4.2 The aspect ratio of the elements should be as close to 1 as practicable. It should however not exceed 2.5.

3.2.5 Modeling Report

3.2.5.1 A Report illustrating the finite element modeling is to be submitted to IRS. The report is to include the following but not limited to:

- Cargo tanks modeled
- Software package used for analysis
- Drawings/Plans used for the modeling (the revision number of the plan is to be clearly mentioned)
- Number of elements in the model and the maximum aspect ratio achieved.
- Any assumptions considered while modeling the primary structural members
- Typical mesh size used.
- Details of modeling of the mass of the hull structure and other masses as described in 3.2.3.5.
- Thickness plots to demonstrate the modeling according to the latest approved/revised drawing
- Stiffener Section details and plots to demonstrate the modeling according to the latest approved/revised drawing
- If deemed necessary, IRS may request the Finite element model to be submitted.

3.2.5.2 A typical schematic of the items to be modeled, the depiction of thickness properties etc. is shown in Figures 3.2.5.1 and 3.2.5.2

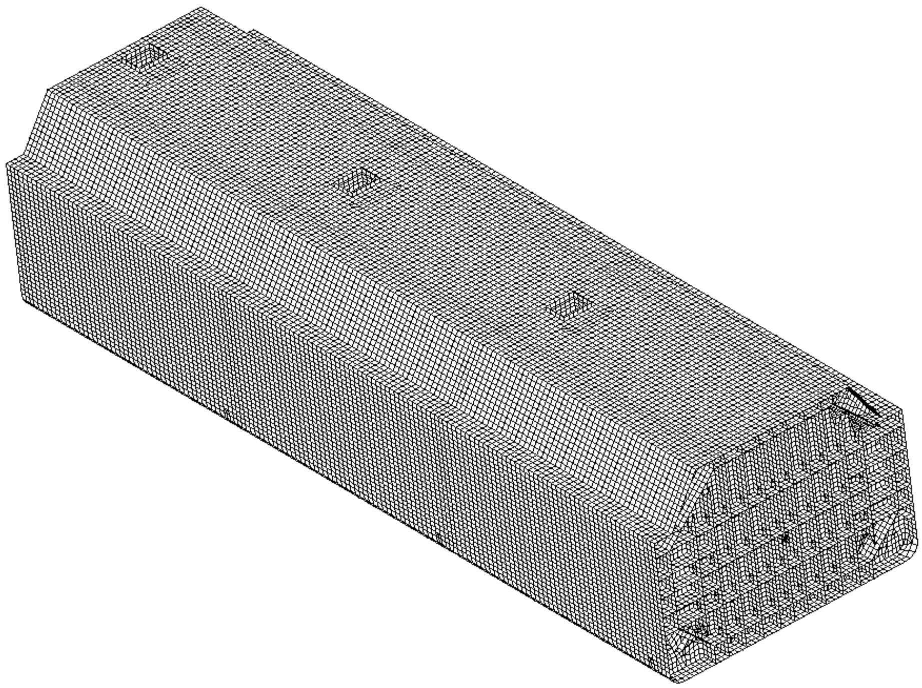

Figure 3.2.5.1 – Three Cargo Hold Model

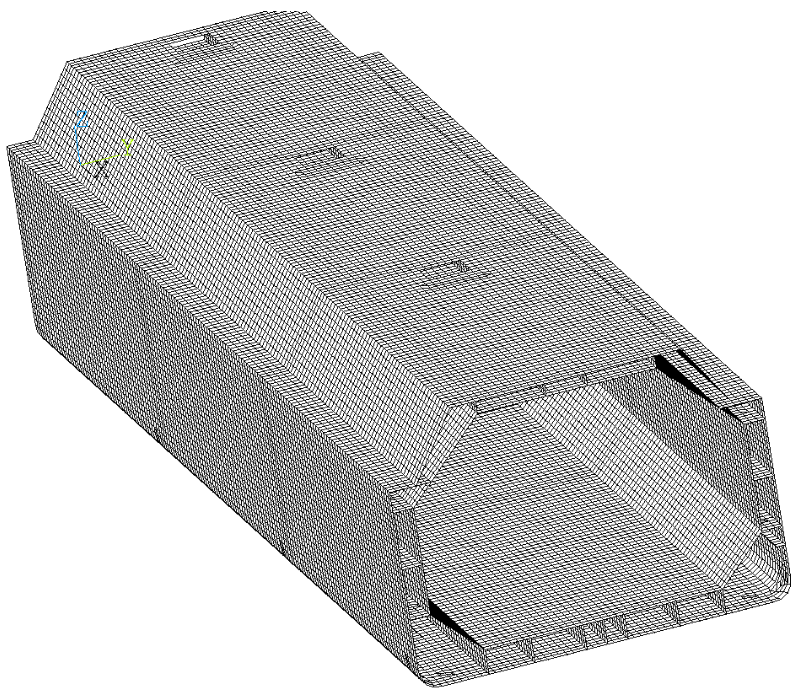

Figure 3.2.5.2 – Three Cargo Hold Model – Longitudinal Strength Members

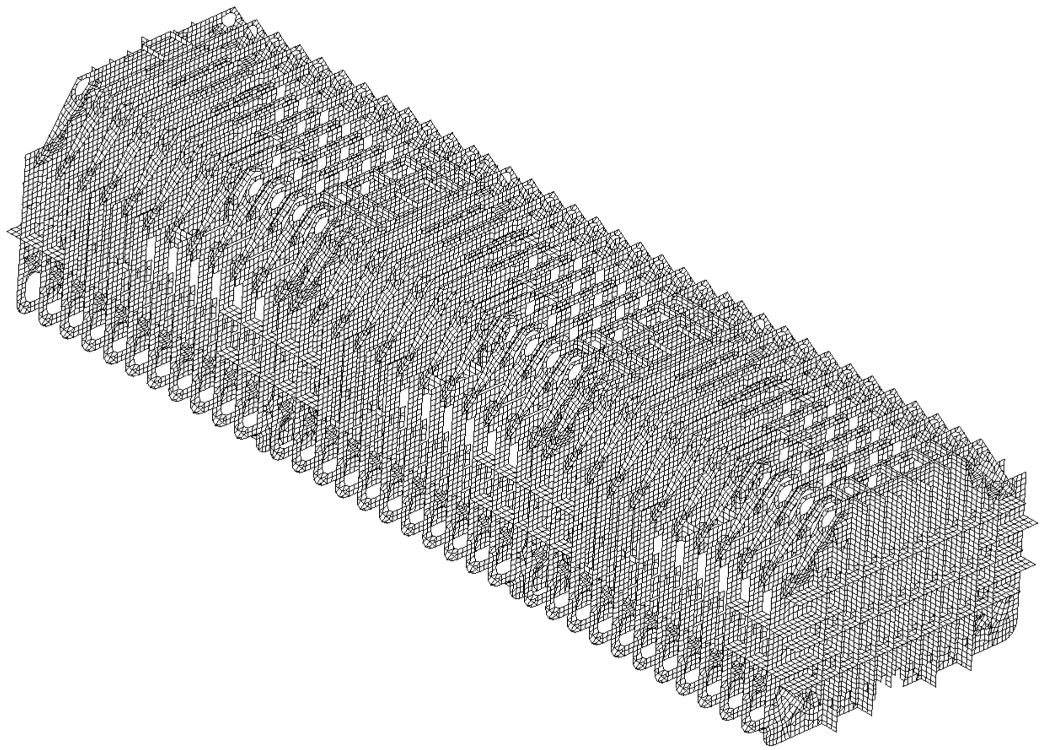

Figure 3.2.5.3 – Three Cargo Hold Model – Transverse Members

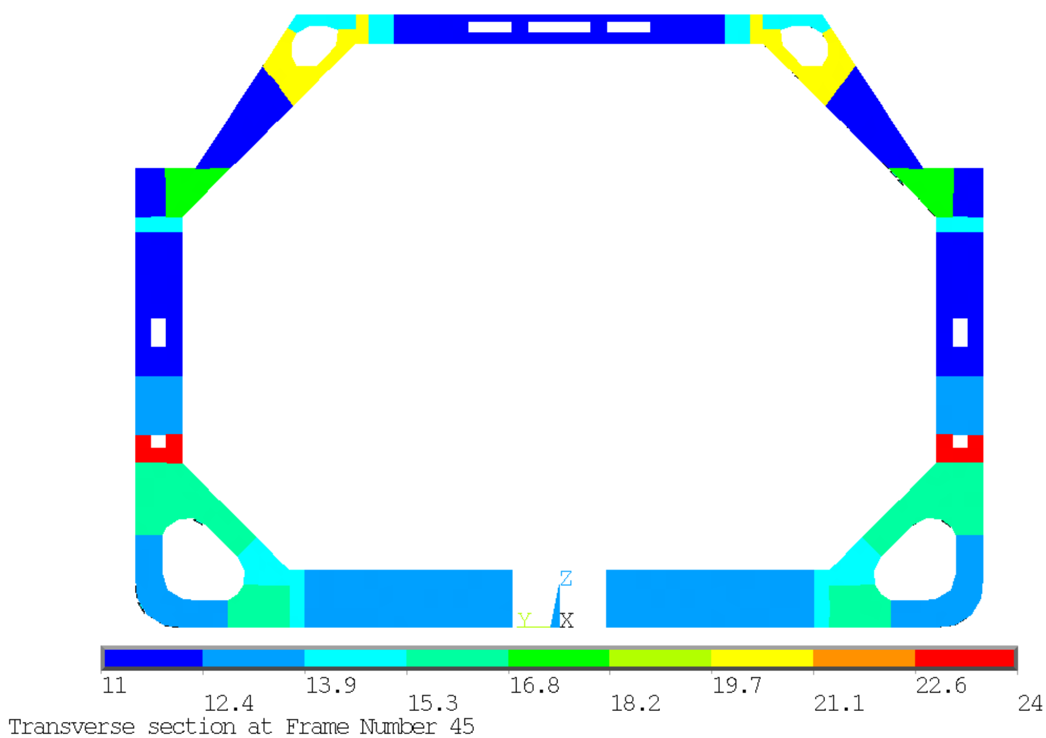

Figure 3.2.5.4 – Typical Transverse Frame – Thickness representation

3.2.6 Loads

3.2.6.1 Loading Conditions

3.2.6.1.1 The Loading Conditions to be considered for the analysis should be considered as provided in Table 3.6.2.1.1.

Table 3.6.2.1.1 – Loading Conditions to be considered

Item	LC1	LC2	LC3	LC4	LC5	LC6
Tank 1	F	E	E	F	E	F
Tank 2	F	E	F	E	E	F
Tank3[1]	F	E	E	F	F	E
Draft	Tsc	Tbal[2]	[3]			
M_{sw}	Sag	Hog	Hog	Sag	Hog	Sag
M_w	Sag	Hog	Hog	Sag	Hog	Sag
A_c	$1+a_v$	$1-a_v$	$1+a_v$	$1+a_v$	$1-a_v$	$1+a_v$
Wave	T	C	C	C	T	C

F: Full; E: Empty; T_{sc}: Scantling Draft; av: Please refer Part 3, Section 2.3; T: Trough; C: Crest

3.2.6.1.2 If the Ship will not operate in some of the loading conditions in Table 3.6.2.1.1, this will be particularly mentioned in the note to the classification certificate.

3.2.6.2 Global Loads

3.2.6.2.1 The Still water and the Wave bending moments to be used in the analysis are to be in accordance with those provided in Part 3.

3.2.6.2.2 The Still water and the Wave shear forces to be used in the analysis are to be in accordance with those provided in Part 3.

3.2.6.3 Local Loads

3.2.6.3.1 External Sea Pressure

3.2.6.3.1.1 External Sea Pressure is composed of the sum of the static and the dynamic pressures as provided in Part 3, Chapter 7 of the Rules. The external sea pressures considering crest and trough conditions are to be used as described below:

A) Wave Crest

a. Below Waterline

$$p = 0.01(T-h) + 10^{-3}\left(3.5 - \frac{1.5(T-h)}{T}\right)C_w R_s$$

b. Above Waterline

$$p = 10^{-3} R_s k_s \big(C_w - 0.8(t-h)\big)$$

B) Wave Trough

a. Below Waterline

[1] If the Tank is marked empty, then the Ballast tanks adjacent to the Cargo Tank are assumed to be completely filled. Vice-Versa applies.
[2] If unavailable, draft equal to 2/3rds Scantling draft can be assumed
[3] To be referred from the preliminary trim and Stability Booklet.

$$p = 0.01(T-h) - 10^{-3}\left(3.5 - \frac{1.5(T-h)}{T}\right)C_w R_s$$

b. Above Waterline

$$p = 0$$

Where the symbols are explained in Part 3, Chapter 7. The pressures obtained above are in the units of kN/m^2.

3.2.6.3.1.2 The Crest and Trough can be taken constant throughout the model length for the purpose of the analysis (i.e. the actual shape of the crest or trough need not be modeled).

3.2.6.3.2 Internal Cargo Pressure

3.2.6.3.2.1 Internal Cargo Pressure is to be taken in accordance with the provisions in Part 5, Chapter 4, Section 4.28. The density of LNG for this purpose is to be taken as 500 kg/m^3. The tanks are considered to be completely filled for this computation.

3.2.6.3.3 Ballast Pressure

3.2.6.3.3.1 Ballast Pressure is to be taken in accordance with the equations as below

$$p = max(\,0.024 + 0.01A_c(T_{tank} - h), 0)$$

Here, T_{tank} indicates the height of the topmost point of the tank above baseline. *h* is the height above baseline of the point where the pressure is to be evaluated. A_c is provided in Table 3.6.2.1.1.

3.2.7 Boundary Conditions

3.2.7.1 Independent Points are to be created at the aft and the fore ends of the FE model, which act as the master node of all the nodes (only those attached to the longitudinal strength members; hereafter referred to as slave nodes) at the aft and fore ends. All degrees of freedom of the aft and the fore slave nodes are to be coupled with the master node at the corresponding independent point.

3.2.7.2 At the aft independent point, U_X=U_Y=U_Z=0. At the fore independent point, U_Z=U_Y=ROT_X=0. Figure 3.2.7.2 provides an illustration of the application of boundary conditions. The co-ordinate system is also depicted in the figure 3.2.7.2 to provide the correct interpretation of the boundary conditions.

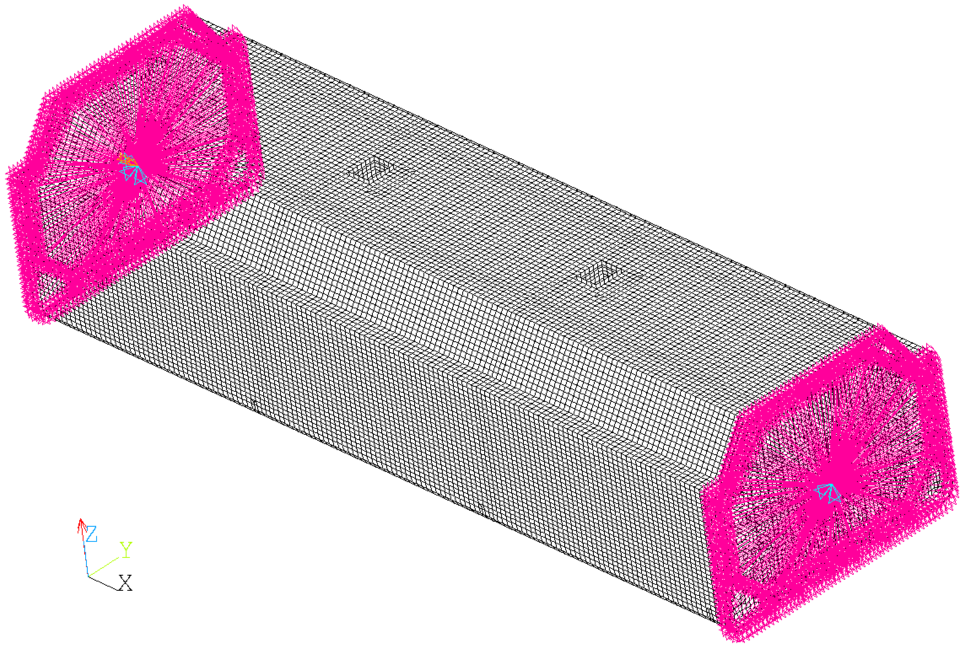

Figure 3.2.7.2 – Application of Boundary Conditions on the FE model

3.2.8 Model Balancing

3.2.8.1 The model balancing is performed to ensure the correct achievements of the Target Bending Moment in the mid-cargo hold. The target bending moment is depicted in the equation below

$$M_{target} = M_{sw} + M_w$$

3.2.8.2 The bending moment is maximized at the centre of the mid-cargo hold. This leads to the target shear force being zero at the same location. The end reaction forces (excluding the reaction force in the X direction) at the aft and the fore master nodes are to be zero (practically less than 0.1% of the net vertical force).

3.2.8.3 The balancing is achieved by applying forces and moments (F_A, M_A, F_F, M_F) at the master nodes attached to the aft and fore independent points. The procedure for balancing is described through figure 3.2.8.3 and the following equations. While developing the equations, the target shear at the considered location (X_{target}) is taken as zero, since the bending moment (M_{target}) is to be maximized at the same location. The solution of the four equations yield the four end forces. These forces are to be finally applied to the model and the model be solved to obtain the deformations and stresses which are to be assessed using the acceptance criteria.

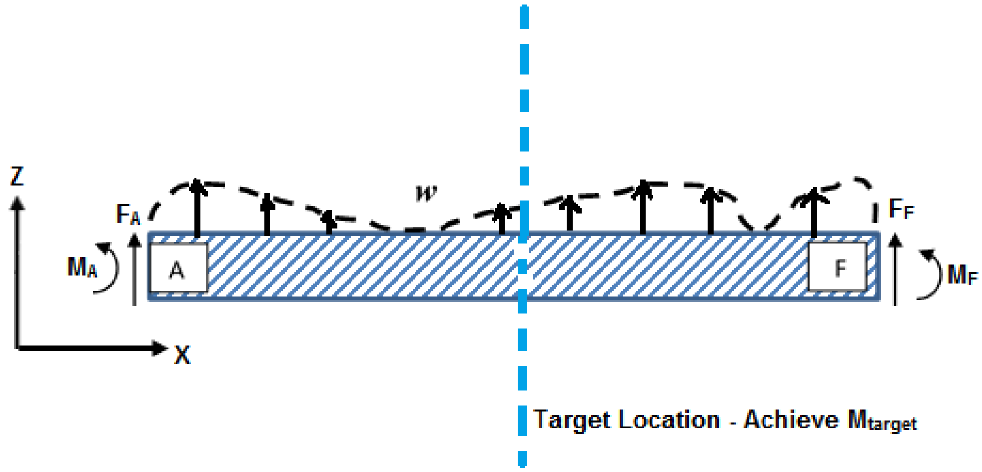

Figure 3.2.8.3 – Model Balancing scheme

$$F_A + F_F + \int_{X_A}^{X_F} w(x)dx = 0$$

$$F_A + \int_{X_A}^{X_{target}} w(x)dx = 0$$

$$M_A + M_{target} + \int_{X_A}^{X_{target}} w(x)xdx = 0$$

$$M_A + M_F + \int_{X_A}^{X_F} w(x)xdx = 0$$

3.2.9 Acceptance Criteria

3.2.9.1 Yield Failure Mode

3.2.9.1.1 Plate/Shell Elements

3.2.9.1.1.1 The stresses in the Plate element (σ_x, σ_y and τ_{xy}) are to be extracted from the model. The von-mises equivalent stress is to be computed as given below:

$$\sigma_e = \sqrt{{\sigma_x}^2 + {\sigma_y}^2 - \sigma_x\sigma_y + 3\tau^2}$$

3.2.9.1.1.2 The von-mises equivalent stress in the plate/shell elements is not to exceed 210/k. (Please also refer the acceptance criteria in 2.7.3 which should also be complied with)

3.2.9.1.2 Beam Elements

3.2.9.1.2.1 The maximum stresses in the beam elements are to be computed as the combination of axial and bending stress. Maximum shear stress is also to be obtained.

3.2.9.1.2 The maximum axial stresses in the beam elements are not to exceed 175/k. The maximum shear stresses in the beam elements are not to exceed 100/k.

3.2.9.2 Buckling/Ultimate Strength Failure Mode
3.2.9.2.1 Buckling/Ultimate Strength of Plate Panels, Stiffened Panels and Stiffeners are to be evaluated as provided in the IRS Rules for Bulk Carriers and Oil Tankers, Vol.2, Chapter 8.

3.2.9.2.2 IRS will specially consider buckling/ultimate strength evaluation using non-linear finite element techniques in lieu of the provisions on 3.2.9.2.1. For this purpose, it has to be demonstrated to the satisfaction of the IRS that the program using non-linear finite element techniques gives satisfactory results. The program is to be able to consider the effects of initial imperfections in the plating according to IACS Recommendation. 47 and residual stresses.

3.3 Local Fine Mesh Analysis

3.3.1 General

3.3.1.1 The present section provides the requirements to be fulfilled by the local structural details using a fine mesh analysis. The analysis of such details is necessary because the stresses obtained using the coarse mesh model may not be accurate due to idealization of the structural detail.

3.3.1.2 It is acceptable to IRS if the coarse mesh and the local fine mesh analysis are performed using the finite element model where the fine mesh areas are modeled in accordance with the requirements provided within the present sub-section.

3.3.2 Mandatory list of details to be evaluated

3.3.2.1 The following structural details in the cargo hold region are to be subjected to the local fine mesh analysis

- Lower and Upper knuckle connections (see figure 3.3.2.1a)
- Transverse Bulkhead stringers intersections with the Inner Hull (see figure 3.3.2.1b)
- Transverse Bulkhead intersections with the horizontal stringers & the longitudinal bulkhead (see 3.3.2.1c)
- Liquid Dome opening with the associated coamings
- Gas Dome Opening
- Other locations (which are identified as sites of stress concentration from the analysis in 3.2)

3.3.3 Structural Modeling

3.3.3.1 Plate/Shell elements are to be used for modeling.

3.3.3.2 The detail as depicted in the approved drawing is to be modeled.

3.3.3.3 The hotspot(s) are to be flanked by atleast 10 elements in each direction. The aspect ratio of the elements is not to exceed 1.2. The element size is not to exceed 50 mm in any direction. Typical mesh obtained using such specifications is depicted in figure 3.3.2.1 (a-c).

3.3.3.4 If a local model is used, the extent of the model is to be such that the boundary conditions at the model ends are distant enough to not affect the stress magnitude at the hotspot(s).

3.3.4 Loads

3.3.4.1 The loads and the loading conditions to be considered are the same as provided in Section 3.2.6.

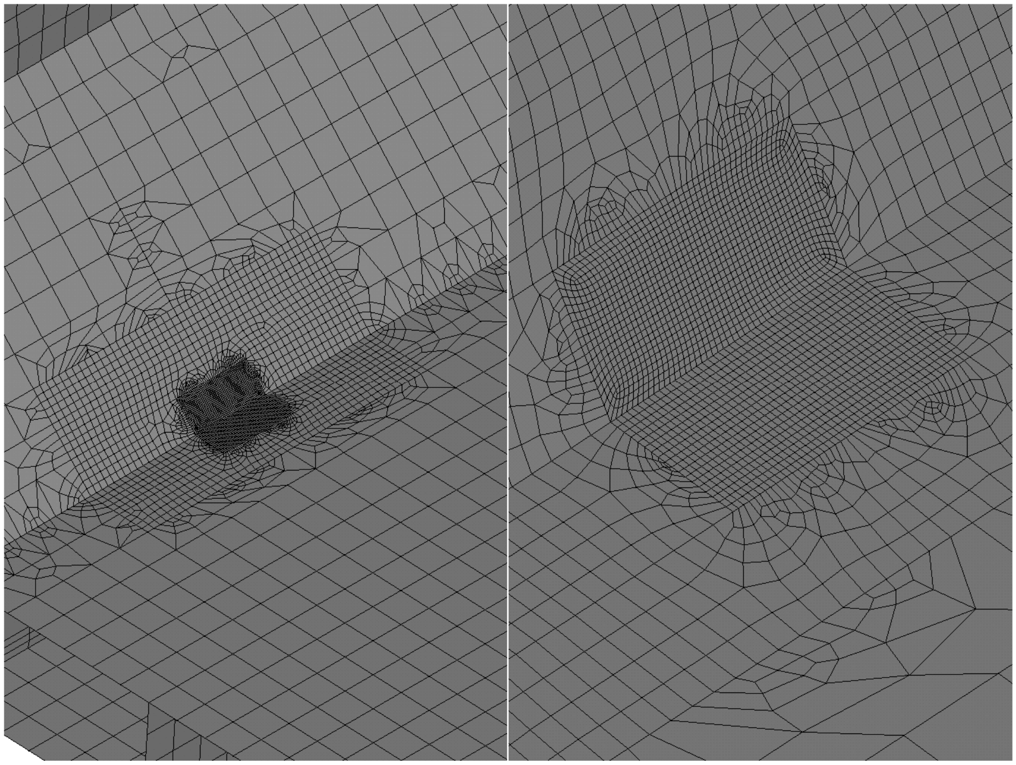

Figure 3.3.2.1.a – Mesh at the Lower Hopper Knuckle (overall mesh and the fine mesh at the hotspot)

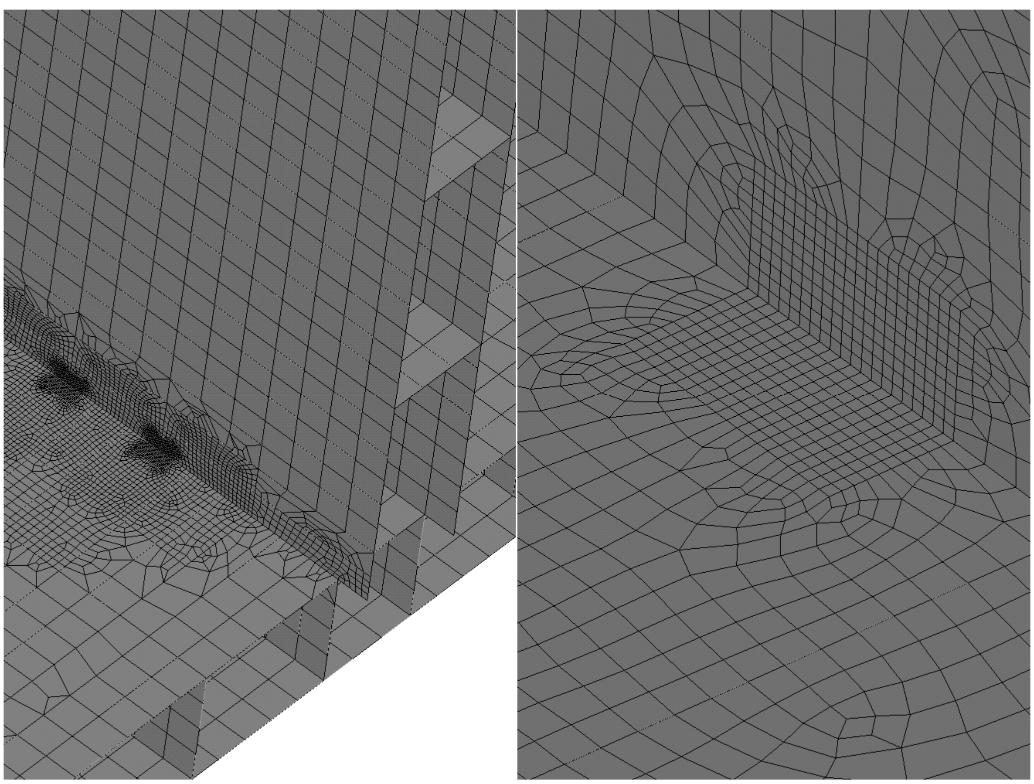

Figure 3.3.2.1.b – Mesh at the transverse bulkhead connection with the double bottom and vertical stringers (overall mesh and the fine mesh at the hotspot)

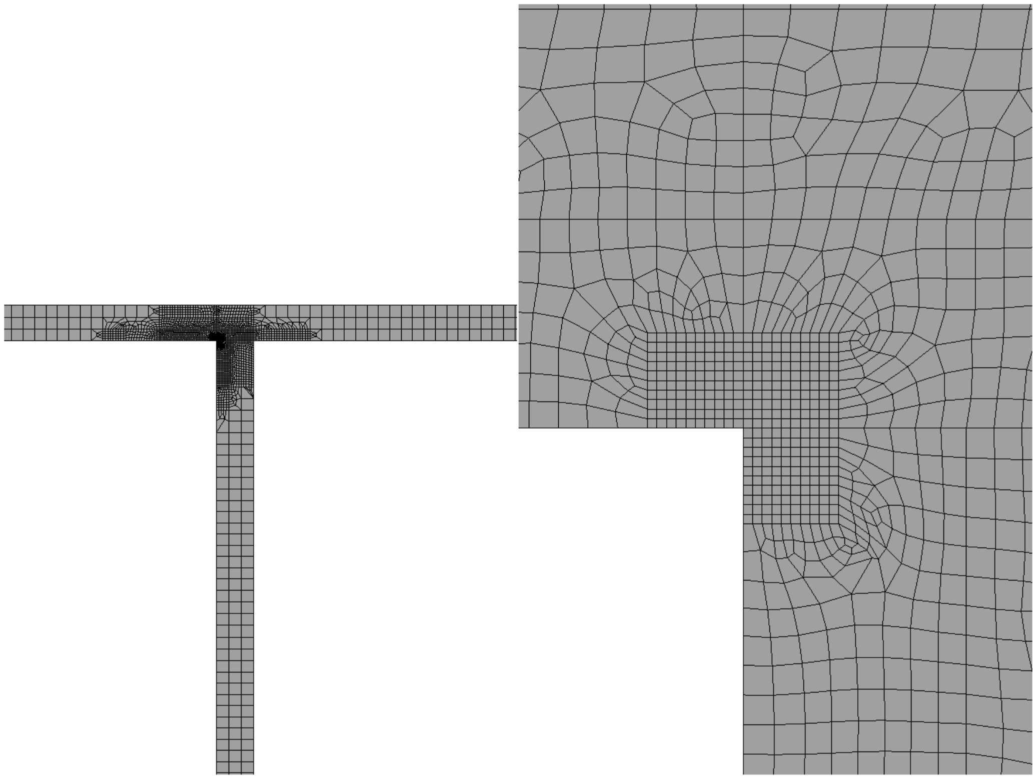

Figure 3.3.2.1.c – Mesh at the connection at the horizontal stringers (overall mesh and the fine mesh at the hotspot)

3.3.5 Boundary Conditions

3.3.5.1 If the coarse mesh cargo hold model is being used in conjunction with the local modeling og the fines mesh areas, then the boundary conditions in Section 3.2.7 are to be used.

3.3.5.2 If a local sub-model is used, then the boundary conditions have to be provided based upon the magnitudes of the displacements and the rotations at the respective nodes in the global model; which are then imposed upon the corresponding nodes in the local model.

3.3.6 Model Balancing

3.3.6.1 If the coarse mesh cargo hold model is being used in conjunction with the local modeling of the fine mesh areas, then the balancing procedure in Section 3.2.8 is to be used.

3.3.6.2 If a local sub-model is used, then the model balancing is not be performed, as the resultant boundary conditions applied at the modeled ends depict the displacement fields of the balanced model.

3.3.7 Acceptance Criteria

3.3.7.1 The utilization factor in yield failure mode is to be determined as below

$$\lambda \leq \lambda_{perm}$$
$$\lambda = \frac{\sigma_e k}{235}$$

Where:

σ_e is the maximum von-Mises equivalent stress in the elements immediately adjacent to the hotspot

λ_{perm} = 1.7 (for elements not adjacent to weld)
= 1.5 (for elements adjacent to weld)

Section 4

Fatigue Design Assessment

4.1 Application

4.1.1 Fatigue Design Assessment is necessary to ensure that the design of the hull structure is robust against the deterioration caused due to cyclic loads through the service life of the Ship. The fatigue damage of the structure is evaluated due to the global and local cyclic loads.

4.1.2 The present section is mandatory for Ships exceeding 90 m in length. Compliance with the requirements in this section is necessary for the **FDA** class notation.

4.1.3 Spectral Fatigue Analysis for the Ship is also acceptable by IRS in lieu of the requirements in the present section. The analysis is to be in accordance with the IRS Guidelines for Spectral Fatigue Analysis of Ship Structures.

4.2 Fatigue Design Assessment Principles

4.2.1 Fatigue Evaluation performed considering the Nominal Stress or the Hotspot Stress Approach is acceptable to IRS.

4.2.2 SN curve-based damage evaluation approach is recommended. SN curves considered for evaluation are to be suitable for 97.7% probability of survival.

4.2.3 The Nominal Stress approach is considered to be adequate for standard fatigue details (e.g. longitudinal stiffener – web frame connection), however Hotspot Stress evaluation is necessary for certain details especially where a multiaxial state of stress is anticipated (e.g. Hopper Knuckle Connection)

4.2.4 IRS may consider to not require assessment for those fatigue details which have been designed and detailed in accordance with well-established practices and have demonstrated a satisfactory service history (e.g. IRS Rules for Bulk Carriers and Oil Tankers, Vol.2, Part 1, Chapter 9, Section 6).

4.2.5 IRS will consider specially those fatigue details for which weld improvement techniques are utilized. Please refer 4.7.

4.2.6 The long-term stress range is determined using the Weibull distribution.

4.2.7 The loads considered for fatigue life evaluation in the present section should consider operations of the Ship solely within the North Atlantic environment. For Ships engaged on world-wide trade or specific routes, IRS will consider the load evaluation considering the actual wave data on those routes subject to submission of the necessary documentation.

4.2.8 The accumulation of Fatigue damage is evaluated using the Palmgren-Miner Rule.

4.2.9 The present section prescribes evaluation of the fatigue life considering predominantly high cycle fatigue. IRS based on its review of the documentation, may request evaluation of the fatigue life additionally considering low cycle fatigue.

4.2.10 t is recommended to follow methodology for fatigue assessment as described in [1].

4.3 Structural Details for Fatigue Design Assessment

4.3.1 The following structural details are to be mandatorily assessed:

- All Longitudinal stiffener – web frame connections within 0.4L of Midships
- Knuckle/Chamfer connection at mid of the Cargo Hold Region
- Connection of primary structural members with the transverse bulkheads of the Cargo Hold
- Connection of cross-deck structure within the cofferdam with the horizontal stringers and the girders in the Cargo Hold Region
- Opening of the Liquid dome on the trunk deck
- Scarphings and Locations of termination of the primary structural members
- Structural details identified for fine mesh analysis in Section 3.

4.4 Loads for Fatigue Design Assessment

4.4.1 The Stress ranges for each structural detail in 4.3 should be evaluated. These should consider the global loads (bending moments, shear forces), applicable local loads (cargo pressure, ballast pressures etc.) and any other fluctuating loads. In absence of any service or site restrictions, the North Atlantic wave environment is to be considered for the evaluation of fatigue loads. It is recommended that the stress ranges be evaluated considering a probability of exceedance which may range from 10^{-3} – 10^{-5} [14]. Consideration of alternate probability of exceedance would need to be suitably justified.

4.4.2 The mean stress effect should be taken into account while evaluating the stress range.

4.4.3 The evaluated stress range should be representative of the stress fluctuations expected over the service life of the ship or 20 years, whichever is higher. The stress cycles considered for the fatigue assessment are not to be less than 1×10^8.

4.4.4 Local stress concentrations as well as the correlation between the global stress range and the local stress ranges should also be considered (e.g. the maxima of the global stresses and the local stresses may not necessarily occur at the same time).

4.4.6 Finite element methods can also be used to evaluate the stresses for which stress concentration factors are not readily available.

4.5 SN Curves

4.5.1 SN Curves (adapted from the data contained within UK HSE report [15]) as shown in Table 4.5.1 should be used for the fatigue evaluation. It may be noted that these curves are two standard deviations below the median (i.e. 97.7% probability of survival, indicated by the equation $NS^m = K_2$, where N corresponds to the number of fatigue load cycles to failure at stress range S (N/mm^2), K_2 is indicated in the table 4.5.1 for each fatigue class). The SN curves have a change of slope from m to m+2 at $N=10^7$ cycles, which corresponds to the stress range S_q (N/mm^2). These SN curves are valid for details in air environment or details exposed to sea-water but sufficiently protected from corrosion. For unprotected joints exposed to sea-water, the fatigue life obtained from these curves is to be reduced by a factor of 2. For details which have their life distributed between protective and non-protective environment, this should be considered during the fatigue life evaluation.

Table 4.5.1 – SN Curves								
Class	K_1			m	Standard Deviation		K_2	S_q
		Log_{10}	Log_e		Log_{10}	Log_e		
B	2.34E+15	15.3697	35.39	4	0.1821	0.4194	1.01E+15	100.2
C	1.08E+14	14.0342	32.3153	3.5	0.2041	0.47	4.23E+13	78.2
D	3.99E+12	12.6007	29.0144	3	0.2095	0.4824	1.52E+12	53.4
E	3.29E+12	12.5169	28.8216	3	0.2509	0.5777	1.04E+12	47
F	1.73E+12	12.237	28.177	3	0.2183	0.5027	6.30E+11	39.8
F2	1.23E+12	12.09	27.8387	3	0.2279	0.5248	4.30E+11	35
G	5.66E+11	11.7525	27.0614	3	0.1793	0.4129	2.50E+11	29.2
W	3.68E+11	11.5662	26.6324	3	0.1846	0.4251	1.60E+11	25.2

4.5.2 Based upon the class of the detail and type of stress utilized (whether nominal or hotspot), appropriate SN curve should be selected. The SN curves are applicable for plate thicknesses which do not exceed the reference thickness of 22 mm. For plate thickness exceeding 22 mm, the stress range is to be multiplied by a factor $(t/22)^{0.25}$, where t is the thickness of the member whose fatigue life is being evaluated.

4.6 Fatigue Life Evaluation

4.6.1 Fatigue life evaluation is based upon the Palmgren-Miner damage summation. The damage index D=1 is to be considered to be the limit state for fatigue failure.

4.6.2 The Fatigue Life of all the mandatory details should not be less than the service life of the ship or 20 years, whichever is higher.

4.7 Fatigue Life Improvement

4.7.1 The use of weld improvement techniques such as burr grinding, hammer peening etc. may be considered for enhancing the fatigue life of the structural details. These should be clearly indicated on the drawings for those structural details where they are to be used along with other accompanying information as may be necessary.

4.7.2 The fatigue life improvement using the techniques in 4.7.1 is to be documented in the report with suitable justification for the expected increase in fatigue life using the above techniques.

Section 5

Construction Monitoring

5.1 Application & Scope

5.1.1 The present section provides requirements for the new construction of Ships to be assigned the (Construction Monitoring) **CM** notation and built under the supervision of IRS.

5.1.2 The aim of the CM notation is to ensure an acceptable quality of construction at the critical locations thereby ensuring the structural integrity of the hull.

5.1.3 Critical Locations are defined as those locations which are identified to be important for the structural integrity of the hull (identified from Direct Strength Analysis, Fatigue Assessment), those locations where the fabrication is difficult in practice due to the complexity of the details or the finesse of the tolerances to be achieved. Those locations which have been previously reported on Ships within IRS or the global fleet as being particularly susceptible to failure or cracking are also to be included within the list of critical locations.

5.2 Requirements

5.2.1 A construction monitoring plan is to be submitted to IRS for approval. The builder's shipbuilding quality standard and the details of the builder and sub-contractors' (if any) facilities are to be also submitted for IRS review. These standards are not to be less stringent than IACS Recommendation 47. If deemed necessary by IRS, IRS may visit the builder's facilities including those of the sub-contractors (if any) to ascertain the capability of the builder to fabricate and construct the critical locations.

5.2.2 The construction monitoring plan is to identify and consider all the critical locations (see section 5.1) as applicable.

5.2.3 The construction monitoring plan is to provide details of the following for each critical location:

- Construction tolerances to be achieved. These may be in terms of dimensional tolerances, maximum values for gaps, misalignments etc.
- Fabrication procedures/Construction procedures including sequences of welding
- Non-destructive testing plan and acceptance criteria in accordance with recognized standards
- Defect rectification plan.

5.2.4 All critical locations will be inspected by IRS surveyor to ascertain and record the actual construction tolerances achieved.

5.2.5 Records of the Non-destructive testing for the critical locations are to be made available to the IRS surveyor.

Section 6

Sloshing Load Assessment

6.1 Application & Scope

6.1.1 The section describes the assessment of the sloshing impact loads for the containment system and the pump tower.

6.1.2 Alternative assessments in lieu of the requirements within this section will be accepted by IRS provided that the designer is able to demonstrate a level of safety equivalent to that in the present section.

6.2 Determination of Barred Filling Ranges

6.2.1 An assessment is to be performed to determine the limits (fill heights or fill volumes) beyond which all the LNG Membrane tanks are not to be filled. This evaluation will consider the possible time periods of sloshing of LNG within the tank at different filling height levels and the expected zone of operation so that the wave periods do not overlap with the sloshing periods. For the sloshing periods, both longitudinal and transverse directions of the tank are to be considered.

6.2.2 For sister ships, or, for ships which have geometry & configuration of cargo tanks and the ship particulars not significantly different (i.e. within ±2% in dimensions) from ships in service for whom such assessment has been already performed, IRS may consider waiving the requirement for performing the assessment in 6.2.1 subject to submission of all relevant calculations and documentation of the ship for whom the said assessment has already been performed.

6.2.3 The evaluated barred filling ranges will be endorsed by IRS and is to be clearly indicated within the Cargo Operating Manual and the Loading Manual.

6.3 Sloshing Impact Load Assessment

6.3.1 Application & Scope

6.3.1.1 The sloshing impact load assessment is to be performed for

- For novel design concepts of the membrane containment system
- For novel designs of the tank geometry
- For unrestricted filling of the tank(s)

6.3.1.2 The methodology for assessment of the sloshing impact loads is described in 6.4. The methodology is recommendatory in nature and it should be used in its entirety to the extent practicable. The designer is advised to communicate any deviations or any alternative method to IRS at the early stages of design appraisal.

6.3.2 Model Test Requirements for Sloshing Impact Load Assessment

6.3.2.1 Sloshing loads on the containment system are to be evaluated by performing model tests (see 6.4.7 for detailed requirements). IRS may consider other standards or procedures of the containment system manufacturer subject to the submission of such documentation and its evaluation by IRS to its satisfaction.

6.3.2.2 Tests are to consider the wave environment encountered by the Ship in accordance with the IACS Recommendation 34 [3]. If the ship is envisaged to operate on designated fixed routes, the data of these intended routes should be considered and these routes should be clearly mentioned in the Certificate of Class. Further reference is made to 6.3.3 for determination of parameters for developing the test programme.

6.3.2.3 Sloshing model test details as given below (but not limited to) are to be submitted to IRS for approval:

- Details of the test facility (e.g. capacity to simulate the ship motions, details of the staff and their competency etc., make & calibration certificates for the equipment)
- Model geometry & scaling (atleast 1/40 scale model to be used)
- Materials used for the model and method of fabrication.
- Test programme (ship motions for different speeds and headings, wave heights and periods to be considered, test durations (atleast 5 hours), number of tests for each wave scenario (i.e. generation of random seeds for irregular seas), schedule of the tests etc.)
- Locations of pressure sensors within the model and method of attachment of the sensors to the model.
- Capability to measure the area on which the pressure pulse acts (i.e. cluster of sensors)
- Type, make and capacities of pressure sensors (minimum and maximum pressures)
- Sampling frequency of pressures (should be atleast 20 kHz),
- Details of fluid and gas used in the test.
- Capture and storage facilities & methods for the data
- Criteria for acceptance/rejection of a test result
- Any other relevant information

6.3.2.4 IRS reserves the right to inspect the test facility and witness some or all of the tests.

6.4 Methodology for prediction of design sloshing impact pressures

6.4.1 General

6.4.1 This sub-section provides guidelines for the methodology for prediction of design sloshing impact pressures. It is recommended that this step be performed keeping IRS involved through the various stages. This methodology is recommendatory in nature and alternatives will be accepted by IRS subject to proper technical justification supported by experimental data. Typical methods to evaluate the sloshing impact pressures can be referred in [4], [5] and [8] for more details.

6.4.2 Environment Data

6.4.2.1 For the design of LNGC with worldwide operations, the wave scatter data of North Atlantic for fully developed sea can be considered. The Standard Wave Data of IACS [3] provides the wave scatter table of the North Atlantic trade route. The 3 h short-term sea can be modelled according to the spectral density definition using Pierson-Moskowitz (PM) spectrum. Other route-specific or site-specific wave scatter data along with definition of 3 hour wave spectrum may also be considered in consultation with IRS. Appropriate justification is required to be provided for the selected environment conditions. The selected wave situations for sloshing analysis are required to be provided to IRS, prior to the model tests.

6.4.2.2 A long-term based approach is recommended where several wave situations representative of the wave scatter diagram are considered along with their probabilities of occurrence [12,13]. In case of long-term analysis appropriate probability of occurrence of individual short-term sea conditions at various heading situations should be considered.

6.4.3 Sea-keeping analysis

6.4.3.1 Sea-keeping analysis should be performed to determine the motions and accelerations of the ship. The purpose of this step is to obtain tank excitation motions for a specific short-term sea condition which are required for model tests. The ship motion time histories are generally determined based on short-term spectral analysis based on predetermined transfer functions.

6.4.3.2 Forward speed seakeeping tools based on frequency-domain or time-domain based on 3D boundary element method such as Rankine Panel Method, Green Function Method based codes may be employed to compute linear transfer functions/response amplitude operator (RAO) and quadratic transfer function (QTF).

6.4.3.3 The seakeeping tools are to model the sway and surge motions adequately and be capable of capturing the sway-roll coupling effect accurately.

6.4.3.4 The seakeeping tool is to be approved and validated prior to the sloshing analysis.

6.4.3.5 Froude scaling is to be used to scale the motions for model tests.

6.4.3.6 Individual 3 hour short-term response over several selected design scenarios are required to be evaluated for measuring slosh induced pressures. Time history of motion responses in short-term sea can be computed using inverse fast Fourier transforms (IFFT) technique based on precomputed transfer functions and phases through Monte Carlo approach. The generated time series may be verified through comparison of FFT of the time signal with input response spectrum.

6.4.3.7 Harmonic excitation amplitudes are to be taken at 1/10th level from the short-term response spectrum of the extreme design sea scenario. The period characterizing the harmonic excitations can be taken as the zero-crossing period and phases (relative to each DOF) are obtained from RAO analysis. The harmonic excitations are required for determining loads on pump tower. Besides critical sloshing wave cases are required to be considered in case of extreme-value approach, with encounter wave periods ranging within 30% of slosh natural frequency in first mode.

6.4.3.8 Speed and heading combinations are recommended to be considered. It is recommended to consider no speed loss for sea states with significant wave height (Hs) within 5 m, a speed reduction of V/2 may be considered for significant wave height over 9 m in case of head and following seas. A minimum speed of 5 knots is required to be considered in beam waves at sea states with significant wave height greater than 9 m. The consideration of speeds is described in the table below.

Table 6.4.3.8: Consideration of speeds for the seakeeping analysis

Wave Height [m]	Heading (°)				
	Following	Stern Quartering	Beam	Bow Quartering	Head
	0 – 45	45 – 60	60 - 120	120 - 135	135 – 180
Hs < 5	V				
5 < Hs < 9	linearly interpolate				
Hs > 9	V/2	5 knots			V/2

6.4.3.9 Sloshing is caused by the external ship motions, and the sloshing forces acting on the tank, influence global ship motions (typically sway and roll). It is recommended to consider the slosh coupling effects in determining the sloshing induced design loads [10,11]. The coupling algorithm is sensitive to phasing between the internal slosh induced forces/moments and external wave induced forces/moments. Validation of the slosh-coupled ship motion solver is necessary to be established against experiments.

6.4.4 Loading Conditions

6.4.4.1 Loading conditions resulting in most severe motions are to be considered for sloshing load analysis. Slosh loads are expected to be high for loading conditions where the ship motions are severe and where the slosh natural frequencies are in range of the ship motion (typically roll) natural frequency.

6.4.4.2 It is recommended to perform sloshing analysis for the tanks which are expected to be more sensitive to sloshing loads. The forward most tanks are generally more vulnerable to sloshing impact pressure loads due to severe relative motions, hence No.1 and No. 2 tanks are generally recommended to be considered for analysis.

6.4.4.3 LNG carriers are generally not permitted for filling within the barred ranges. The barred filling range is generally defined as 10%H to 70%H (Where H is the height of the tank). For such ships, slosh analysis can be performed considering the loading conditions of tanks with lower and upper filling limits. The lower and upper filling limits can be defined as 10%H and 70%H respectively, in absence of actual data. At lower filling limits, the sloshing phenomenon is generally characterized by hydraulic bores and progressive waves, along with flow separation and gas entrapped impacts. At higher fillings, the sloshing phenomenon is generally characterized with standing wave with one or two nodes and often breaking near the tank corners. Gas entrapped impacts are also likely at high fill conditions such as > 90%H.

6.4.4.4 For ships, which are intended to encounter partial filling or for the ships with unrestricted fill heights, the filling conditions within the barred filling range are to be considered for sloshing analysis in addition. A minimum interval of 10%H is recommended to be considered, i.e., 20%H, 30%H, 40%, 50%H, 60%H. Other filling conditions close to the above defined range may also be considered in lieu, which correspond to specific loading conditions. Tanks with partial filling are expected to experience higher slosh loads. And generally partial fillings ranging 20%H – 50%H result in higher slosh-induced pressures. Consideration of additional cases of fill levels other than the ones specified above may be recommended by the class. The designer is recommended to contact IRS in the early stage on the selection of filling condition is prior to commencing model tests.

6.4.5 Load Scenarios

6.4.5.1 Performing sloshing analysis over all possible load scenarios is generally not feasible, hence representative load scenarios should be employed. The wave parameters for the representative load scenarios are to be discretized with an interval not exceeding 30º for relative wave heading and 2 s interval of zero crossing period over the scatter table. Consideration of coarse intervals of the wave parameters may bias the statistical interpretation of loads. Justification of the considered representative load scenarios and their corresponding probabilities is to be provided to IRS. If the heading probability information is not provided, an equi-probable assumption may be used for heading condition of LNGC. Discretization of the load scenarios is to be considered in consultation with IRS.

6.4.5.2 Screening of load scenarios assists to reduce the total number of cases for expensive model tests. The primary screening criteria is based on the event rate and magnitude of pressure above the set threshold limit. At the initial stage sloshing analysis, model tests may be performed for a short duration (30 min). Based on the event rate and severity of sloshing impact pressures obtained from post processed data, the load scenario can be eliminated or continued for the complete duration. Contribution plots should be provided representing the severity of load scenarios on derived design loads.

6.4.6 **Additional considerations for FSRUs and Floating LNG Terminals**

6.4.6.1 In case of floating LNG systems, such as FLNG terminals, FPSOs and FSRUs, the following are necessary to be considered:

Site specific environment description

- Directional wave scatter data,
- wave spectrum definition and spreading
- Wind and current direction and magnitude
- Water depth

Wave heading analysis to establish heading probability, considering

- Mooring effects
- DP (dynamic positioning) system

A filling probability should be established based on operational procedures. The fill probability governs the minimum required number of fill levels to be considered for sloshing analysis

6.4.7 Model Tests

6.4.7.1 Recommended procedures and guidelines of ITTC on Sloshing Model Tests [2] can be referred for sloshing model tests. The capability of the motion generation platform is needed to be established prior to model tests. Model tests which fail to meet the desired accuracy limits of motion generation are not to be further considered.

6.4.7.2 Ullage gas heavier to air is required for water as sloshing fluid in model tests to maintain consistent gas-liquid density ratio. In other words, the ratio of densities between gas and liquid of model test fluids at ambient temperature is to be equal to the density ratio of methane and LNG. Alternate fluid mixture such as Sulphur hexafluoride (SF_6) and nitrogen (N_2) as recommended by ITTC can be used. The choice of the fluid mixture is to be approved by IRS prior to commencement of model tests.

6.4.7.3 Model Tests should be performed subjecting the model in the test rig to the irregular time histories of the ship motions obtained in 6.4.2(scaled to model size). It is recommended that the time-step of the motion history be atleast 0.01 seconds. It is important to record the motions being actually imparted to the model in the test rig so as to check the correctness and accuracy of the test. Based upon the results and convergence obtained, it may sometimes be necessary to repeat the tests with multiple time-histories for a given filling limit, sea-state and heading.

6.4.7.4 The pressure impulses should be recorded using appropriate sensors which are clustered to as to capture the temporal and spatial variations. Hence, it is important that the test rig employs a cluster of sensors over the subject areas where sloshing impacts pressure are anticipated.

6.4.7.5 In order to estimate statistically converged 3 hours extreme pressure from model test, a sufficiently long test duration of 5 hours is recommended.

6.4.8 Post processing of the sloshing impact pressures

6.4.8.1 From the acquired and recorded data of sloshing impact pressures for each test, suitable post-processing should be performed so as to provide the following outputs for a given test case:

- Sloshing Event Rate (Number of Sloshing impacts measured during the test divided by the test duration. For this purpose, a threshold pressure is usually defined above which all events with pressures exceeding threshold pressures will be counted as Sloshing Impact)
- Pressure history (temporal and spatial) on various location areas of interest

6.4.8.2 For the post-processing as described in 6.4.8.1, the pressure peaks should be extracted. Only the peaks which actually represent the impact loads in the entire duration are to be considered. A peak over threshold method in combination with moving window technique may be adopted to identify the pressure peaks [9,11,12]. The set threshold value is to be consistent for all load scenarios. The pressure data should to be filtered to remove the low frequency hydrostatic effects and high frequency noise. The choice of the low pass and high pass filter is not to affect the quality and accuracy of the measured impact pressure data.

6.4.8.2 For data from each short-term duration test as described in 6.4.8.1, a Weibull three parameter distribution is recommended to be applied to obtain the exceedance probability distribution of the sloshing impact pressures. The equation below describes the Weibull distribution.

$$F(p) = e^{-\left(\frac{p-\mu}{\lambda}\right)^{\xi}}$$

Here, λ is the shape parameter, ξ is the scale parameter and μ is the location parameter. To ensure a credible fit, a sufficient number of events/impacts should be available.

The choice of the scale, shape and location parameters should be to simulate an appropriate fit of the distribution through appropriate parameter estimation techniques. Any other theoretical distribution (such as Generalized Pareto distribution) which best fits the pressure data may also be used [9]. Determination of best fit distribution is to be decided based on goodness of fit tests such as Anderson-Darling or Cramer-Von Mises test [12]. The basis of choice of selected distribution is to be agreed with IRS.

6.4.8.3 The sloshing impact pressures should then be extrapolated to long term values using the equation below:

$$F_L(p) = \sum_{i=1}^{A} P(E_i) \sum_{j=1}^{B} P(E_j) \sum_{k=1}^{C} F_{ijk}(p) P(E_{ijk}) \mathrm{P}(E_k)$$

$$S_{ijk} = N_{ijk} T_{ijk}$$

$$P(E_{ijk}) = \frac{S_{ijk}}{\sum_{i=1}^{A} \sum_{j=1}^{B} \sum_{k=1}^{C} S_{ijk}}$$

The index k represents the headings, index j represents the sea-state and index i represents the filling levels. F_{ijk} is the distribution obtained corresponding to a given heading, sea-state and filling level as shown in 6.4.8.2. N_{ijk} represents the number of sloshing impacts for the given condition (heading, seastate and filling level). T_{ijk} represents the duration of time for which the condition ijk will be observed.

$P(E_k)$: Probability of occurrence of the heading in that sea-state

$P(E_j)$: Probability of occurrence of the sea-state

$P(E_i)$: Probability of the Ship being in that filling condition

6.4.8.4 From the long-term extrapolation in 6.4.8.3, the sloshing impact pressure obtained is further scaled to the full-scale model by applying a suitable factor. This factor typically is determined based on experience and observed full scale measurements. Annual probability of exceedance is determined from the equation below. The design sloshing impact pressure is then evaluated at a suitable annual probability of exceedance (not to be taken more than 10^{-4}, unless the designer can satisfactorily justify a higher exceedance level))

$$F_{annual}(p) = 1 - (1 - F_L(p))^{N-annual}$$

$N_{-annual}$ is the average number of sloshing impacts occurring in one year.

6.4.9 Idealization of the Sloshing Impact Pressures

6.4.9.1 For determining the integrity of the containment system, detailed calculations using numerical methods or experiments are typically performed (see Section 7). It is necessary to idealize the sloshing impact pressure in terms of a time-history curve for the analysis. This can be done by idealizing the sloshing impact pressure time-history as a triangular pulse [6]. Where the rise time and decay time required for characterizing the impact can be determined by establishing statistical inference on the rise and decay time [4,9]. Owing to the fact of uncertainty in scaling, it is recommended to characterize the impulse considering conservative dynamic amplification factor (DAF) of the structure. The choice of the rise and the decay times for the pulse should be documented and justified in the analysis report to be submitted to IRS.

6.5 Report of the Sloshing Impact Pressures

6.5,1 Based on the results of the model tests, a report is to be submitted to IRS with the following details:

- Details of the sea-states screened out/not considered for the tests
- Liquid Motion natural frequencies in the tank variation with the filling height
- Details of the model and techniques used for sea-keeping along with the verification of appropriateness and accuracy of the modeling
- RAOs obtained from sea-keeping
- Details of test results and convergence
- Scaling scheme to convert the model scale pressure to ship scale
- Long term exceedance probability plots of the design sloshing impact pressure for the critical locations (i.e. tank corners, knuckles typically) considering the area on which the pulse is applied.
- Design pressure impulse including the magnitude and the rise & fall time (if idealized as a triangular impulse). Quasi static pressure values may be provided in lieu if static analysis for the strength determination of the containment system is envisaged.
- Any other relevant observations

6.6 Computation of Sloshing Loads on the Pump Tower

6.6.1 General

6.6.1 The loads on the pump tower can be estimated either by Model tests or numerical CFD Simulations. If model tests are utilized, then the details of the tests including the model, scale, positioning of sensors etc. are to be submitted to IRS prior to performing the test.

6.6.2 CFD Simulations

6.6.2.1 IRS recommends the use of CFD Simulations to estimate the loads on the pump tower.

6.6.2.2 CFD tools based on RANS or LES implemented using FVM (Finite Volume Method) or FDM (Finite Difference Method) and other methods such as SPH (Smoothed Particle Hydrodynamics) or MPS (Moving Particle Semi-implicit) can be employed for sloshing analysis. The CFD tool is to be validated against experimental data. FVM based CFD tools are often used by industry, which are based on volume-of-fluid (VOF) technique. VOF is prone to dispersion of free surface and improved variants such as VOF with interface compression or combined level-set and volume-of-fluid (CLSVOF) models are recommended. A description of the solution scheme and validation of the computational tool are to be provided to IRS.

6.6.2.3 The forces on pump tower members can be computed based on Froude-Krylov approximation, where the pump-tower structure is not required to be modelled and the forces on the members are computed based on Morrison equation. The load scenarios and loading conditions as described in 6.4 should be considered for evaluating the loads on the pump tower members. Since the analysis of the pump tower is performed using linear static analysis, it is recommended to evaluate the velocities at the time instant which maximizes the longitudinal or lateral load on the pump tower. These velocities should be used further to compute the force as per the Morrison equation.

$$F_i = \left(0.5C_{di}\rho D_i u_i|u_i| + \frac{\pi}{4}C_{mi}\rho {D_i}^2\dot{u}_i\right)L_i$$

Here F_i is the vector of the force on the i^{th} element . *Ui* is the velocity of LNG inside the tank for the i^{th} element. D_i is the diameter of the element. Cd is the drag co-efficient Cm is the inertia co-efficient. L_i is the length of the element.

6.6.2.4 The values of drag and inertia coefficient are to be taken carefully considering the dependent parameters such as Reynolds number, Keulegan-Carpenter number. Dependence of other physical behavior of local flow such as wave impact zone, shielding effect may also be carefully considered in choosing the drag and inertia co-efficients for relevant members.

6.6.2.5 The design loads on pump tower are to be determined through statistical analysis of the short-term loads in a similar way as described for sloshing impact pressures. Where the design extreme value of load is characterized by the total load on pump tower structure, while suitable combination of loading profiles obtained from short-term sea conditions are required to be applied [12,13].

6.7 Comparative Assessment for Scantlings of the Inner Hull Considering Sloshing Impact Loads

6.7.1 Application

6.7.1 For sloshing impact loads, the Comparative Assessment method is used for determination of scantlings of the applicable inner hull locations, using comparison with designs which have been proven to be adequate as demonstrated from their satisfactory service history.

6.7.2 IRS will decide upon the application of the Comparative Assessment method based upon a review of the documentation as below submitted. Otherwise, the procedure in Section 7 is to be followed.

- Ship Principal Particulars

- Intended Zone of Operation
- Tank Geometry & Arrangement
- Intended Filling Ranges
- Details of the Containment System
- Availability of a reference design

6.7.2 Reference Design

6.7.2.1 For the application of comparative assessment, an LNG ship with membrane type tanks is to be selected which has demonstrated satisfactory service history and further fulfils the requirements in 6.4.3. This is termed as the reference design. Using the reference design, assessment of the scantlings of the present design is made using similarity principles.

6.7.2.2 It is presumed here that simple scaling laws apply. i.e, the variable parameter is the sloshing impact pressure of the present design. Once this parameter is determined through model tests, then the various scantlings can be appropriately scaled from the reference design, to obtain the scantlings.

6.7.3 Criteria for selecting a reference design

6.5.3.1 The reference design is selected, based upon similarity on the following factors:

- Principal particulars
- Arrangement of Cargo Region
- Size and Shape of Cargo tanks
- Containment system
- Filling Limits

6.7.3.2 IRS will decide whether a particular design should be used as a reference design based upon review of the above factors and the service record of the ship.

6.7.4 Procedure for performing Comparative Assessment

6.7.4.1 The pressures for the reference and the present designs are obtained through model test experiments are described in 6.3 above. Computational/Numerical analysis based calculations can also be used for evaluation of Sloshing Loads. However, the results for the model tests of the reference tests will be required to scale the pressure obtained from the numerical estimations of the design with the reference design to the actual full scale values.

6.7.4.2 The plate scantlings of an inner hull location are obtained as below:

$$t = t_{ref} \frac{s}{s_{ref}} \sqrt{\frac{p}{p_{ref}} \frac{\sigma_{ref}}{\sigma}}$$

6.5.4.3 The Stiffener scantlings of an inner hull location are obtained as below:

$$Z = Z_{ref} \frac{s}{s_{ref}} \frac{p}{p_{ref}} \frac{\sigma_{ref}}{\sigma} \left(\frac{l}{l_{ref}}\right)^2$$

Section 7

Strength Assessment of the Containment System

7.1 General

7.1.1 The strength assessment of the containment system is required for determination of selection of appropriate scantlings for the various load bearing components.

7.1.2 The strength assessment is to be performed considering the maximum internal pressure load envisaged at the location in accordance with Part 5, Chapter 4 Section 4.28 of the Rules. However, at the limits of the barred filling ranges or for ship tanks which are to be designed for unrestricted fill heights, sloshing pressures would be the governing factor to determine the scantlings.

7.2 Application & Scope

7.2.1 The present section provides guidelines for checking the strength of the GTT Mark III and NO 96 containment systems. These guidelines are generic in nature. The requirements for analysis should be discussed by the manufacturer and agreed with IRS before their application.

7.2.2 For ships of configuration which are very similar to ships with satisfactory service history and both the ships' operational profile is similar (same barred filling limit ranges), the strength of the containment system need not be re-assessed if the same scantlings are installed as on the vessel with the demonstrated satisfactory service history.

7.2.3 The present guidelines prescribe two levels for 3D FEM based strength analysis

- Level 1: Assessment of adequacy of the Cargo Containment System to withstand the Operating Loads (Internal Pressure Loads due from the Cargo (Part 5, Chapter 4, Section 4.28), Hull Deformations, Thermal Loads and Self-weight). Static analysis of the containment system is considered satisfactory to check this requirement.

- Level 2: Assessment of the Cargo Containment System Capacity to withstand the Sloshing Impact Design Loads evaluated from Section 6. This will require a Transient analysis of the containment system considering non-linearities (geometric and material). Effect of Strain-rates would also need consideration. IRS may consider experimental test results in lieu of the transient analysis.

7.3 Level 1 Strength Analysis

7.3.1 Mark III Containment System

7.3.1.1 Panels for Analysis

7.3.1.1 The following containment system panels are to be considered for evaluation:

- Flat Panels located at the upper and lower chamfers
- Transverse Bulkhead and Deck Connections Corner Panels (90^0)
- Hopper Tank and Deck Connections Corner Panels (135^0)
- Other panels (necessary if partial filling levels are permitted)

7.3.1.2 The designer is recommended to contact IRS early during the design phase to identify the panels for analysis, finalize the acceptance criteria with the permissible values.

7.3.1.2 Finite Element Modeling

7.3.1.2.1 A flat panel can be modeled considering a minimum extent of 1080 mm x 1080.

7.3.1.2.2 A corner panel is to be modeled in its entirety.

7.3.1.2.3 The Primary and the Secondary Membranes need not be modeled. If the Primary membrane is modeled, then the corrugations need to be modeled precisely in both the directions and shell elements are recommended to be used.

7.3.1.2.4 The top and bottom plywood can be modeled using shell elements with midside nodes. Alternatively 3D brick elements can be used with midside nodes, however these will lead to increase in the computational time.

7.3.1.2.5 Polyurethane Foam (primary and secondary insulation) is to be modeled using 3D brick elements with midside nodes. At least five elements across the depth of the foam are to be ensured. The element edge length in the surface direction is to be such that at least five elements are present between locations of any two mastic ropes.

7.3.1.2.6 The mastic ropes can be modeled using shell elements.

7.3.1.2.7 The slots in the plywood and the polyurethane foam insulation below the corrugations are to be modeled.

7.3.1.2.8 A typical finite element model for a Mark III containment system flat panel is shown in Figure 7.3.1.2.8.

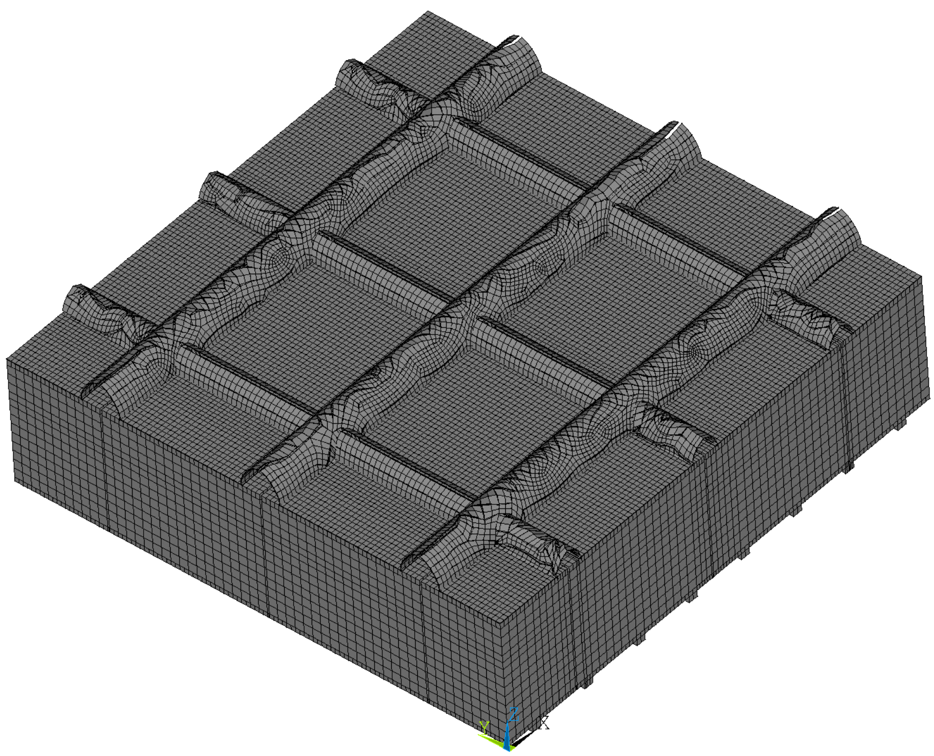

Figure 7.3.1.2.8 – FE Model of a Flat Panel

7.3.1.3 Loads

7.3.1.3.1 The cargo pressure load is to be applied over the panel (as obtained from Part 5, Chapter 4, Section 4.28).

7.3.1.3.2 The self-weight of the panel is also to be applied. This is achieved by providing the density of each layer and switching on gravity effects.

7.3.1.3.3 Thermal loads should be applied by applying the respective temperatures on each layer, considering LNG at the primary barrier at -163^{o}C.

7.3.1.3.4 The effect of hull deformations due to the deformation of the double bottom (either due to cargo pressures or ballast pressures) should be incorporated in the analysis.

7.3.1.4 Boundary Conditions

7.3.1.4.1 The Uz degree of freedom is to be appropriately specified at the mastic ropes to simulate the effect of the hull deformations (see 7.3.1.3.4).

7.3.1.4.2 Symmetry conditions can be applied on the vertical faces of the panel.

7.3.1.5 Acceptance Criteria

7.3.1.5.1 Static analysis should be performed with the applied loads and boundary conditions. The resultant stresses and displacements should be checked as given below:

Top & Bottom Plywood

7.3.1.5.2 The tensile and compressive stresses along and perpendicular to the plywood laminate fibers are not to exceed the corresponding ultimate tensile and compressive strengths. For the bottom plywood, the bending stress (between two mastic ropes) and the shear (at the mastic ropes) obtained is not to exceed the ultimate bending strength and the ultimate shear strength of the bottom plywood. Factor of Safety (*FS*) to be considered in the acceptance criteria is described as below. The testing is to be performed considering the appropriate steady state temperature within the foam and a suitable number of samples. IRS may accept data from previous tests conducted, provided the characteristics of the plywood are not changed significantly.

$$\sigma_{1t} < FS * \sigma_{1tu}$$
$$\sigma_{2t} < FS * \sigma_{2tu}$$
$$\sigma_{1c} < FS * \sigma_{1cu}$$
$$\sigma_{2c} < FS * \sigma_{2cu}$$
$$\sigma_b < FS * \sigma_{bu}$$
$$\tau_b < FS * \tau_{bu}$$

Where:
σ_{1t}, Tensile Stress along the plywood laminate fiber direction
σ_{1c} Compressive Stress along the plywood laminate fiber direction
σ_{2t}, Tensile Stress perpendicular to the plywood laminate fiber direction
σ_{2c} Compressive Stress perpendicular to the plywood laminate fiber direction
σ_{1tu}, Ultimate Tensile Strength along the plywood laminate fiber direction
σ_{1cu} Ultimate Compressive Strength along the plywood laminate fiber direction
σ_{2tu}, Ultimate Tensile Strength perpendicular to the plywood laminate fiber direction
σ_{2cu} Ultimate Compressive Strength perpendicular to the plywood laminate fiber direction
σ_b Bending Stress between two mastic ropes
τ_b Bending Shear Stress at the location of the mastic ropes
σ_b Ultimate Bending Strength between two mastic ropes
τ_b Ultimate Shear Strength at the location of the mastic ropes
FS: Factor of Safety which should not exceed 0.5.

Polyurethane Foam

7.3.1.5.3 The compressive stress σ_p within the polyurethane foam is not to exceed the crushing strength of the foam σ_c. The Factor of Safety (*FS*) is to be taken in accordance with 7.3.1.5.2. The crushing strength of the foam is obtained from the tests. The testing is to be performed considering the appropriate steady state temperature within the foam and a suitable number of samples. IRS may accept data from previous tests conducted, provided the characteristics of the foam are not changed significantly.

$$\sigma_p < FS * \sigma_c$$

Mastic

7.3.1.5.4 The maximum reaction load on the mastic ropes is to be obtained (P_m)and this load should not be less than the crushing load of the mastic ropes. The crushing strength (P_{mcu})of the mastic is obtained from the tests. The Factor of Safety (*FS*) is to be taken in accordance with 7.3.1.5.2. The testing is to be performed considering the appropriate steady state temperature within the foam and a suitable number of samples. IRS may accept data from previous tests conducted, provided the characteristics of the foam are not changed significantly.

$$P_m < FS * P_{mcu}$$

7.3.15.5 IRS may accept alternative criteria in lieu of the above checks if these criteria are accompanied by satisfactory technical justification.

7.3.2 NO 96 Containment System

7.3.2.1 Panels for Analysis

7.3.2.1 The following containment system panels are to be considered for evaluation:

- Flat Panels located at the upper and lower chamfers
- Transverse Bulkhead and Deck Connections Corner Panels (90^0)
- Hopper Tank and Deck Connections Corner Panels (135^0)

7.3.2.2 The designer is recommended to contact IRS early during the design phase to identify the panels for analysis, finalize the acceptance criteria with the permissible values.

7.3.2.2 Finite Element Modeling

7.3.1.2.1 A flat panel can be modeled considering an assembly unit of a primary and a secondary box.

7.3.1.2.2 A corner panel is to be modeled in its entirety.

7.3.1.2.3 The Primary and the Secondary Membranes need not be modeled.

7.3.1.2.4 The Plywood boxes (primary & secondary) should be modeled using plate/shell elements. The plywood cover plates for the boxes should also be modeled. The staple elements connecting the plywood cover plate and the plywood stiffening are to be correctly modeled while also considering the presence of the invar tongue element. This can be specified using appropriate constraint equations between the relevant degrees of freedom.

7.3.1.2.6 The mastic ropes can be modeled using shell elements.

7.3.2.3 Loads

Please refer 7.3.1.3.

7.3.2.4 Boundary Conditions

Please refer 7.3.1.4.

7.3.2.5 Acceptance Criteria

Please refer 7.3.1.5 for the acceptance criteria regarding the plywood elements and the mastic ropes. In addition, the instability failure of the plywood members is also to be checked.

7.4 Level 2 Strength Analysis

7.4.1 Level 2 strength analysis requires advanced simulations which consider the following:

- Non-linear behavior of the materials which includes material inelastic nature and instabilities
- Strain rate effects
- Exact or idealized nature of the sloshing impact pressure pulses (both in spatial and temporal dimensions)
- Modeling of the supporting hull structure and its structural interaction with the containment system.

7.4.2 The analysis program details, assumptions/limitations, modeling criteria (extent, structural idealization, material properties), boundary conditions, load application, analysis settings (i.e. transient dynamic analysis considering strain-rate effects, inelasticity, large deformations, time-steps, convergence criteria and acceptance criteria) are to be submitted to IRS for its approval. Reference is made to [5-7] for additional guidance to perform such analysis.

7.4.4 The designer is encouraged to contact IRS during the early design stages to ensure agreement on the above parameters.

7.5 Structural Assessment of the Pump Tower

7.5.1 General

7.5.1.1 The purpose of structural analysis of the Pump Tower is to ascertain its structural integrity against the following failure modes

- Ultimate Limit State
- Fatigue Limit State
- Vibration

7.5.1.2 The analysis in the present section is not required for Pump Towers whose design (dimensions, ship arrangements & size etc.) is not significantly changed from previous pump tower designs which have demonstrated a satisfactory service history or comply with the requirements in the present guidelines.

7.5.2 Modeling

7.5.2.1 The pump tower including the liquid dome and the pump tower base is to be modeled

7.5.2.2 The pump tower structural members can be modeled using beam/pipe elements. The liquid dome plate and the pump tower base can be modeled using Shell/Plate elements. It is recommended that each tubular member be discretized with atleast five beam/pipe elements. For the liquid dome and the base support, each boundary should have atleast 10 elements.

7.5.2.3 Linear elastic material model can be used for the pump tower, liquid dome and pump tower base.

7.5.3 Loads

7.5.3.1 The weights of the structural members of the pump tower, liquid dome and pump tower base are to be modeled. The outfitting weights can be modeled by assuming them to be smeared over the pump tower structural members.

7.5.3.2 The weights of the pumps and equipment at the pump tower base should be modeled as point mass elements with the translational degrees of freedom.

7.5.3.3 The sloshing loads due to the motion of LNG within the tanks should be applied on the pump tower structural members as described in Section 6.6.

7.5.3.4 Thermal Loads should be applied on the model. It is recommended that for the portion of the pump tower submerged in LNG, temperature of -163^{o}C should be applied. For the zone of pump tower surrounded by vapour space, temperature of -30^{o}C can be considered. The co-efficient of thermal expansion can be taken as 1.1×10^{-5} m/m/^{o}C.

7.5.4 Loading Conditions

7.5.4.1 The following loading conditions are recommended to be considered when evaluating the strength:

- Empty tank for inspection (only self-weight of the pump tower is active)
- Empty tank (only self-weight and thermal loads are active – Cooling down condition before LNG loading)
- Tank at 10% and 70% filling height (or at the barred filling limits) (self-weight, thermal loads and velocities of LNG due to Ship motion are active)
- Other conditions for partial filling (if applicable) of the tank. (self-weight, thermal loads and velocities of LNG due to Ship motion are active)

7.5.4.2 For the loading conditions for fatigue evaluation, it can be assumed that the ship's lifetime operations are represented by the full load condition and the ballast conditions equally (i.e. each has an equal weightage of 50%). Evaluation of the fatigue loads at 95% and 5% of the filling height for the natural period of roll of the ship is recommended in absence of any other data. For ships which are permitted to load cargo within the barred filling limits (e.g. FSRUs), additional loading conditions would have to be taken into consideration.

7.5.5 Boundary Conditions

7.5.5.1 The nodes at the boundaries of the liquid dome are considered to be fixed.

7.5.5.2 The nodes at the pump tower base should be suitably constrained to simulate the restraint in the longitudinal and transverse directions of the ship.

7.5.5.3 The nodes of the pump tower tubular members (beam/pipe elements) are to be coupled to those of the liquid dome and the pump tower base. In commercial FE software, this is accomplished by using the master-slave concept.

An analysis model with the applied boundary conditions is shown in figure 7.5.5.4.

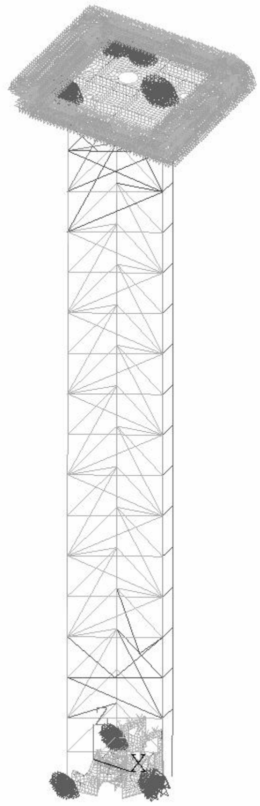

Figure 7.5.5.4a – Global Model of the Pump Tower structure with the liquid dome and the pump tower base

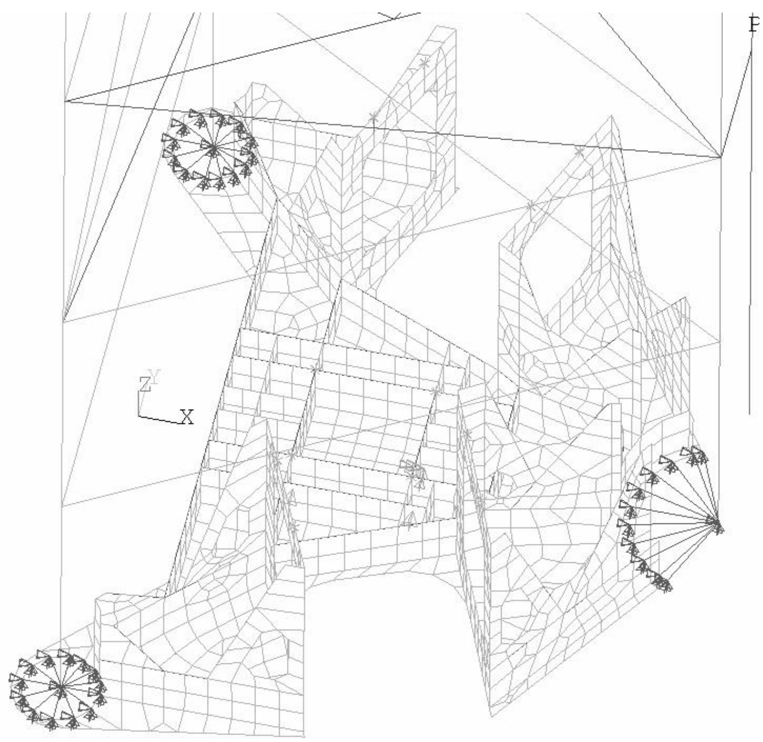

Figure 7.5.5.4b – Closer view of the Pump Tower base with the Master-Slave Coupling and the boundary conditions

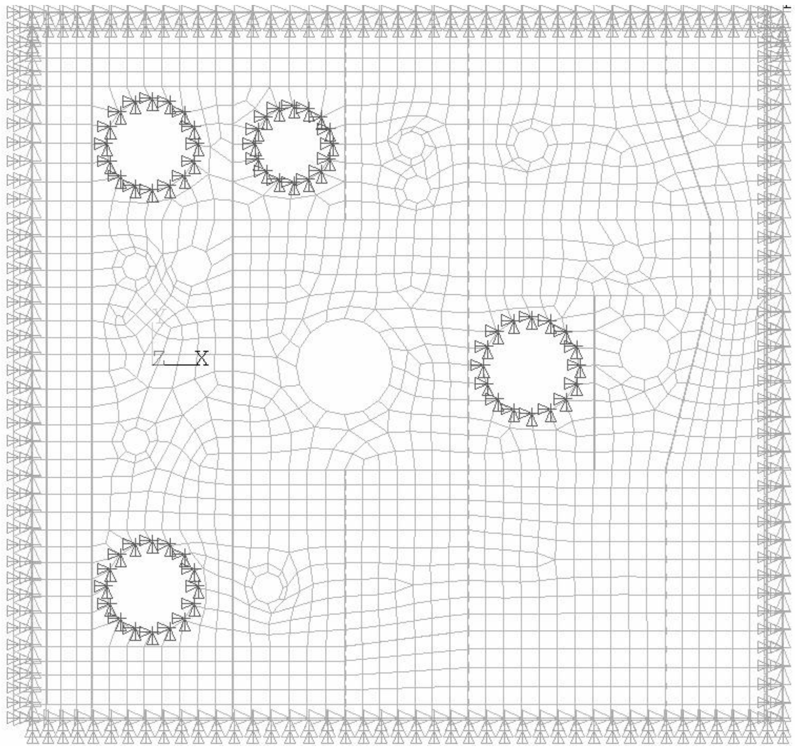

Figure 7.5.6.4c – Closer view of the Liquid Dome with the Master-Slave Coupling and the boundary conditions

7.5.6 Analysis

7.5.6.1 Strength Analysis

7.5.6.1.1 A linear elastic static analysis is deemed sufficient to establish the stresses within the pump tower members.

7.5.6.2 Fatigue Analysis

7.5.6.2.1 A linear elastic analysis is performed to determine the axial and bending stresses in each tubular member. The loading conditions are described in 7.5.4.2. The locations of fatigue analysis are typically the intersection of the main tubular chord members with the braces. The saddle and the crown positions are recommended to be evaluated.

7.5.6.2.2 The stress ranges are to be enhanced with appropriate stress concentration factors to correctly evaluate the stress range at the weld toe and the weld root.

7.5.6.2.4 The long-term distribution of stress ranges can be assumed to be a Weibull distribution.

7.5.6.2.5 The number of fatigue stress cycles to be encountered by the ship considering a design life of 20 years or the design life of the containment system which-ever is higher are to be evaluated. The fatigue damage is to be computed considering this number of stress cycles. Appropriate SN curve representing fatigue resistance of the pump tower material of construction in LNG is to be chosen. At fatigue failure, the damage index is considered as 1.

7.5.6.3 Fatigue Analysis

7.5.6.3.1 It is recommended to perform a free vibration analysis of the pump tower to obtain the vibration modes which may be excited by various sources as listed below (but not limited to)

- Sloshing of the LNG within the tank

- Propeller & Main Engine Excitation frequencies.

Added mass of the LNG should also be considered to determine these 'wet' frequencies.

7.5.7 Acceptance Criteria.

7.5.7.1 Ultimate Limit Strength Check

7.5.7.1.1 The following failure modes (as applicable) for the tubular members (beam elements) should be checked in accordance with recognized rules & standards (e.g. API RP 2A, AISC) and the utilization factors each pump tower member are to be determined:

- Combined Bending Moment & Tension
- Combined Bending Moment & Compression
- Global buckling
- Local buckling

7.5.7.1.2 The plate members in the liquid dome and the pump tower base are checked using the acceptance criteria in Section 4. For this purpose, the combined stresses (hull girder stresses + stresses from the pump tower strength analysis) should be considered for the liquid dome.

7.5.8.2 Fatigue Limit Strength Check

7.5.7.2.1 The fatigue life of welded connections should not be less than 20 years or the design life of the containment system whichever is higher.

7.5.7.3 Vibration Limit Strength Check

7.5.7.3.1 The free vibration frequencies of the pump tower are not to coincide in a ±10% band with the excitation frequencies of all sources.

References

1. Espen Cramer, Robert Loseth, Kjell Olaison (1995). Fatigue Assessment of Ship Structures. Journal of Marine Structures. Vol.8, pp. 359-383.
2. ITTC. Guidelines for Sloshing Model Tests (7.5-02—07-02.7)
3. International Association of Classification Societies. Recommendation no. 34: Standard Wave Data
4. Kuo, J., Campbell, R., Ding, Z., Hoie, S., Rinehart, A., Sandstrom, R., Yung, T., Greer, M., Danaczko, M. (2009). LNG Tank Sloshing Assessment Methodology – The New Generation. Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan June 21-26.
5. Gervaise, E., de Seze, P., Maillard, S.(2009). Reliability-based Methodology for Sloshing Assessment of Membrane LNG Vessels. Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan June 21-26.
6. Pillon, B., Marhem, M., Leclere, G., Canler, G.(2009). Numerical Approach For Structural Assessment of LNG Containment Systems. Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan June 21-26.
7. Issa. J., Garza Rios, L., Taylor, R., Lele, S., Rinehart, A., Bray, W., Tredennick, O., Canler, G., Chapot, K. (2009). Structural Capacities of LNG Membrane Containment Systems. Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan June 21-26.
8. Rognebakke, O., Orpedal, J., Ostvold, T. (2009). Sloshing Impact Design Load Assessment. Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan June 21-26.
9. Fillon, B., Diebold, L., Henry, J., Derbanne, Q., Baudin, E. and Parmentier, G. (2011). Statistical Post-Processing of Long-Duration Sloshing Test. Proceedings of the Twenty-first International Offshore and Polar Engineering Conference, Hawaii, USA, June 19-24.
10. Saripilli, J. R. and Sen, D. (2018). Numerical studies on effects of slosh coupling on ship motions and derived slosh loads. Applied Ocean Research, 76, 71-87.
11. Saripilli, J. R. and Sen, D. (2018). Sloshing-coupled ship motion algorithm for estimation of slosh-induced pressures. Journal of Marine Science and Application, 76, 71-87.
12. Saripilli, J. R., Dhavalikar, S. and Sen, D. (2019). Estimation of design slosh-induced loads using numerical simulations, Proceedings of Fourteenth International Symposium on Practical Design of Ships and Other Floating Structures, Yokohama, Japan, September 22-26.
13. Saripilli, J. R., Dhavalikar, S. and Sen, D. (2019). Seakeeping and sloshing assessment methodology for floating LNG terminals, Proceedings of Sixth International Conference on Ship and Offshore Technology, Kharagpur, India, November 7-8.