2022

# Guidance for Strength Assessment of Membrane-Type LNG Tanks under Sloshing Loads

GC-17-E

KR

# GUIDANCE FOR
# STRENGTH ASSESSMENT MEMBRANE-TYPE LNG TANKS
# UNDER SLOSHING LOADS

## *Foreword*

1. Unless expressly specified otherwise, the requirements in the Guidance apply to ships for which are contracted for construction are signed on or after 1 July 2022.

### Summary of changes

| | (Amendment Type / No.) | Rule Version Date | Effective Date |
|---|---|---|---|
| 1 | Full Revision | 01 Jan 2022 | 01 July 2022 |

1. Title of the Guidance is changed from “Guidance for Assessment of Sloshing Load and Structural Strength of Cargo Containment System” to “Guidance for Strength Assessment of Membrane-Type LNG Tanks under Sloshing Loads”.
2. Main revision for sloshing loads estimation by model test is made based on “Integrated Sloshing Load Analysis Procedure for Korean Research Institutes” and “ITTC Recommended Procedures and Guidelines-Sloshing Model Test”.
3. For the strength assessment, DAF (Dynamic Amplification Factor) concept is newly adopted in “Level 1 evaluation” scheme which has 3 assessment methods - comparative, reinforced comparative and absolute method. In “Level 2 evaluation” scheme, only one method is applicable; absolute method.
4. This revision include too many changes, the comparison table for Old/New is not provided separately.

# CONTENTS

# CHAPTER 1 GENERAL

## Section 1 Application

### 101. Application

1. This guidance deals with the sloshing load induced by the liquid cargo in tank due to ship motion in LNG carriers. This guidance applies to the assessment procedure and the acceptance criteria of cargo containment system under the sloshing load for the membrane type LNG carrier.

   In addition, this guidance applicable to the calculation procedure of the sloshing impact load for the ship with liquid cargo tank beyond Rules for the Classification of Steel ships (hereinafter referred to as "the Rules" in this guidance), **Pt 13, Sub 1, Ch 4, Sec 6**, [6].
2. This guidance applies the evaluation procedure for the sloshing load and the structural strength of cargo containment system for offshore LNG storage and regasification structures using the membrane tank technology.
3. Requirements of this guidance shall apply in addition to the other requirements of the relevant Rules.

### 102. Overview

1. Sloshing means movement of liquid inside the enclosed space. In the case of ships, the place where sloshing occurs most frequently is the liquid cargo hold, and is affected by the motion period of the cargo tank, the geometry, the density of the fluid cargo or the viscosity and the filling ratio, etc. The ship motion generates the motion of cargo tank and causes the sloshing phenomenon.
2. Sloshing in a tank is related to the complex physical phenomena such as the wave breaking, the phase change between liquid and gas in the tank, the cushioning effect made by the gas and the primary barrier.
3. Sloshing results in the high impact load on the inner structure and the support of cargo containment system. Particularly the prismatic membrane type tank with the flat and the edge zone generates the high pressure by the sloshing impact. Structural safety issue of the LNG CCS due to the sloshing pressure has become the important design factor.
4. Due to the strong nonlinearity and irregularity of the sloshing phenomenon, the sloshing load is generally estimated using the model test or numerical simulations. Until now, the analysis method through model experiment is considered to be the most reliable.
5. Overall flowchart of sloshing assessment of LNG tank is shown in **Figure 1**. During the model test, small-scaled model tank with partially filled with water is excited by irregular motion in seaway which representing design/operation conditions. During the test, dynamic pressures are measured at the inner-side of tank wall.
6. The measured pressures are used for structural strength evaluation through appropriate post-processing. In the post-processing stage, time history of pressure is converted into the time history of loads for various loaded area, and is used to extract sloshing load events through statistical analysis. The extracted sloshing load is used for strength evaluation.
7. Structural strength evaluation can be categorized into two levels: “Level 1 evaluation” and “Level 2 evaluation”. Level 1 evaluation is dynamic structural analysis to evaluate the safety of the CCS by converting the sloshing load into the static load.
8. The methods of assessment can be divided into three types.

   (1) Comparative Method

      (a) If there is a reference case, which is the almost same as the target ship and has same CCS, comparative method can be applied by comparing the design sloshing load of the target ship and the reference ship.

(2) Reinforced Comparative Method

(a) If there is a reference case, but different CCS shape or specification, strength evaluation is performed by comparing the ratio of CCS capacity and design load in the reference ship to the ratio of CCS capacity and design load in the target ship.

(3) Absolute Method

(a) If there is no reference case, the capacity of CCS should be compared with the design load to evaluate whether there is a margin of more than UF. Here UF means utilization factor which will be given in detail in later chapter.

9. Level 1 evaluation can relatively reduce the cost of evaluation, but gives conservative results, so if the structural safety is not satisfied at Level 1 evaluation, the Level 2 evaluation should be performed.

10. Level 2 evaluation is to perform more advanced structural analysis compared to Level 1 evaluation. Unlike Level 1 evaluation that utilizes the static load, Level 2 evaluation uses the dynamic sloshing load obtained in the experiment to perform structural analysis. Dynamic structural analysis to determine whether the result meets the acceptance criteria by applying the design sloshing load.

11. If a cargo hold strength assessments are to be performed based on methods other than those described above, this should be fully discussed with the Society in advance.

## 103. Equivalence

1. In the case that the application of this guidance is not appropriate or that the Society allow that the special method and the procedure not specified in this guidance is at least equivalent to those in effect for the provision of this guidance, it is assumed to be appropriate for the provision of this guidance.

2. If the other evaluation method of sloshing load is equivalent to the evaluation method of this guidance, the Society can approve the method as an alternative. In this case in order to verify that the evaluation of sloshing load is at least equivalent to the standard of this guidance, the related informations should be submitted to the Society and the evaluation method is to be consulted with the Society. From the initial design phase, the purpose to use the different method should be sufficiently discussed.

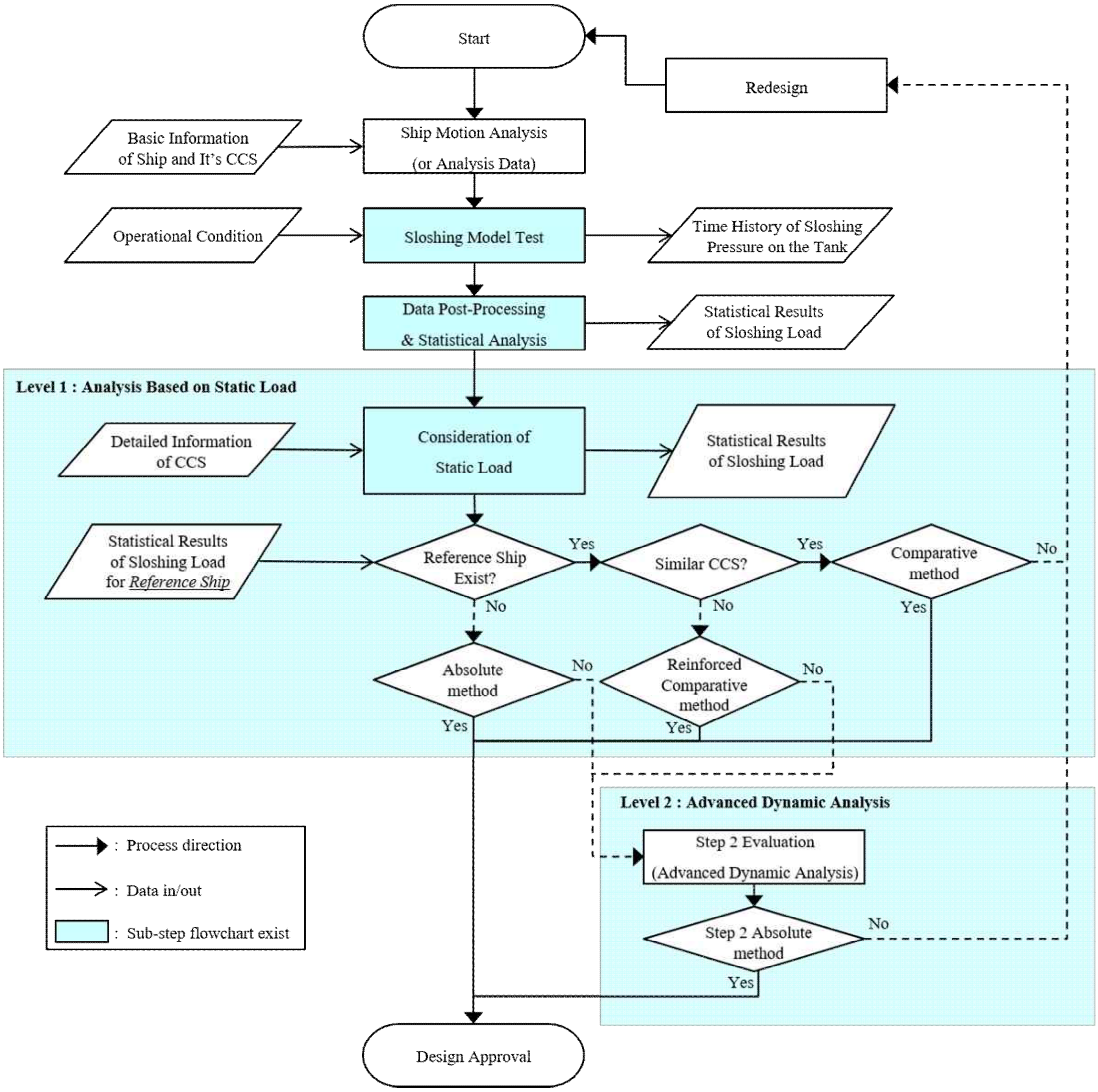



Figure 1 Flowchart of assessment of sloshing load and strength of cargo containment system

# Section 2 Symbols and definitions

## 201. Primary symbols and units

Unless otherwise specified, the general symbols and their units used in these Rules are those defined in **Table 1.**

Table 1 Primary symbols

| Symbols | Meaning | Units |
|---|---|---|
| $S$ | Wave energy density | $m^2\sec$ |
| $H_s$ | Significant wave height | $m$ |
| $w$ | Angular wave frequency | $rad/\sec$ |
| $T_z$ | Average zero up-crossing wave period | $\sec$ |
| $\theta_0$ | Main wave heading | $\deg$ |
| $\theta$ | Relative spreading around the main wave heading | $\deg$ |
| $r_{xx}$ | Roll radius of gyration | $m$ |
| $r_{yy}$ | Pitch radius of gyration | $m$ |
| $r_{zz}$ | Yaw radius of gyration | $m$ |
| $B$ | Breadth of ship | $m$ |
| $L_{pp}$ | Length between perpendiculars | $m$ |
| $x_G, y_G, z_G$ | Ship center of gravity under consideration | $m$ |
| $x_{CT}, y_{CT}, z_{CT}$ | Center of gravity of tank under consideration | $m$ |
| $g$ | Gravitational acceleration | $m/s^2$ |
| $X_1$ | Surge at the ship center of gravity | $m$ |
| $\ddot{X}_1$ | Longitudinal acceleration at the ship center of gravity | $m/s^2$ |
| $X_2$ | Sway at the ship center of gravity | $m$ |
| $\ddot{X}_2$ | Transverse acceleration at the ship center of gravity | $m/s^2$ |
| $X_3$ | Heave at the ship center of gravity | $m$ |
| $\ddot{X}_3$ | Vertical acceleration at the ship center of gravity | $m/s^2$ |
| $X_4$ | Roll | $rad$ |
| $\ddot{X}_4$ | Roll acceleration | $rad/s^2$ |
| $X_5$ | Pitch | $rad$ |
| $\ddot{X}_5$ | Pitch acceleration | $rad/s^2$ |
| $X_6$ | Yaw | $rad$ |
| $\ddot{X}_6$ | Yaw acceleration | $rad/s^2$ |
| $T_{rise}$ | Rise time of sloshing impact | $msec$ |
| $T_{decay}$ | Decay time of sloshing impact | $msec$ |

| Symbols | Meaning | Units |
|---|---|---|
| $P_{peak}$ | Peak pressure of sloshing impact | $N/mm^2$ |
| $P_{is}$ | Interacted pressure of sloshing impact with $P_{peak}$, $T_{rise}$, and $T_{decay}$ | $N/mm^2$ |
| $P_{3hrs}$ | Most probable maximum pressure for 3hour simulation (test) | $N/mm^2$ |
| $NF$ | Number of considered filling conditions | - |
| $NH$ | Number of considered heading conditions | - |
| $NS$ | Number of considered sea states | - |
| $p_{ijk}$ | Occurrence probability of filling $i$, heading $j$, sea state $k$ condition | - |
| $R_{ijk}$ | Event rate of $ijk$ condition | - |
| $R$ | Average event rate | - |
| $Q_{ijk}(P)$ | Exceedance probability of sloshing load $ijk$ condition | - |
| $H$ | Height of cargo tank considered | $m$ |
| $P_{unit}$ | Unit pressure | $N/mm^2$ |
| $C$ | Structural capacity of cargo containment system | - |
| $\sigma_{unit}$ | Maximum stress which is obtained by the static analysis while applying the unit load | $N/mm^2$ |
| $\sigma_y$ | Allowable stress | $N/mm^2$ |
| $K$ | Buckling coefficient | - |

## 202. Definitions of terms

Table 2 Definition of terms

| Terms | Definition |
|---|---|
| Sloshing | The motion of the free fluid surface in LNG tank. |
| Potential flow | The flow of idealized fluid without the viscosity effect. |
| Critical wave domain | The wave range which generates the lifetime maximum sloshing loads. |
| Panel pressure | The averaged pressure over each measured pressure signal of the sensor stack. |
| Critical sea state | The sea state that generate the lifetime maximum sloshing loads. |
| Wave spectrum | The graph showing the distribution of the wave energy over wave frequency. |
| Diffraction-Radiation Method | The method to analyze the fluid motion phenomenon with the theory of diffraction-radiation. |
| Roll damping model | The model including the hull viscous roll damping. |
| Triangular impulse pressure | The sloshing loads which are idealized to have pressure shape over time in triangle shape. |
| Rise time | The time during when triangular impact pressure increases from the lowest to the highest. |
| Decay time | The time during when triangular impact pressure decreases from the highest to the lowest. |
| Skewness | The ratio obtained by dividing the decay time with the rise time of triangular impulse pressure. |
| CFD | The numerical analysis for fluid motion using computer program. |
| Sloshing model test | The experiments to measure (estimate) the sloshing load by the small scaled cargo tank with enforced motion excitation. |
| Pressure sensor | The sensor attached to the tank model and used to measure the sloshing pressure. |
| Design sloshing load | The design load used for the structural analysis of cargo containment system and obtained from the model test. |
| Dynamic amplification factor (DAF) | The ratio of the dynamic response to the static response for unit load with particular rise time. |
| Interacted load | The sloshing load obtained by multiplying $P_{peak}$ and $DAF_{is}$. |
| Comparative method | One of the evaluation method for cargo containment system. By selecting the membrane LNG ship with a proven service history as the reference ship, the similar LNG cargo containment system is to be evaluated. |
| Reinforced comparative method | One method of comparative method and to consider the strength of cargo containment system. |
| Absolute method | One method of strength assessment for LNG cargo containment system. It derives the design sloshing load and evaluate the structure strength of cargo containment system by performing the direct structural analysis. |
| Membrane | The film form substance used in the LNG cargo containment system. |
| Cargo containment system | The facility for storing cargo. If the primary barrier, the secondary barrier, the insulation are installed, cargo containment system means every thing and may include adjacent hull structure required to support these. |

| Terms | Definition |
|---|---|
| Primary barrier | The inner structure element (liquid-tight container) in contact with the cargo and designed to store the cargo when the cargo containment system is composed of two barriers. |
| Secondary barrier | The ability to store the liquid leakage temporarily, if any liquid cargo leaks from the primary barrier. It is the outer components of the cargo containment system (liquid-tight) designed to prevent the temperature drop of the hull structure to the dangerous condition such as the supercooled state. |
| MarkⅢ | The layered foam type cargo containment system with membrane developed by GTT which use STS 304L as the primary barrier. |
| KC-1 | The cargo containment system developed by KC LNG TECH which is the layered foam type. |
| Polyurethane foam | The filling material for the purpose of heat insulation at layered foam type cargo containment system. |
| Mastic | The material in contact with the hull directly in cargo containment system. |
| Top plywood | The plywood below the primary barrier and in contact with polyurethane foam at the layered foam type cargo containment system. |
| Back plywood | The plywood between insulation polyurethane foam and mastic at the layered foam cargo containment system. |
| NO96 | The cargo containment system developed by GTT which is the box type membrane cargo containment system. |
| Primary insulation box | The box between the primary and secondary barriers at the box type cargo containment system (NO96). |
| Secondary insulation box | The box in contact with hull through the mastic at the box type cargo containment system (NO96). |
| Acceptance criteria | The maximum stress, the maximum strain, the buckling and the service limit that cargo containment system can withstand without failure. |
| Strength of cargo containment system | The maximum strength that cargo containment system withstand without failure. |

# Section 3 Documentation

## 301. Resource for approval

1. Commonly required data for the approval

   (1) The motion analysis data of the target ship

   (a) The input data of motion analysis (loading conditions, the draft, the metacenter height and the gravity center of ship, etc)

   (b) The model data of motion analysis

   (c) The detail result of motion analysis

   (d) The analysis data of critical sea states and wave conditions for the model test

   (2) The model test data of the target ship

   (a) The model tank and the sensor specification

   (b) The specification of the motion generator and the data measuring system

   (c) The monitoring data of motion generator

   (d) The measured data

   (e) The analysis data of the design sloshing load

   (f) The post-processing method of the model test

   (3) Depending on the assessment method of the CCS, the following materials should be submitted to the Society and to be approved by the Society. In addition, if deemed necessary, the Society may require the submission of data other than those specified below.

2. The approval data for the comparative method

   (1) Commonly required data which mentioned at **Ch 1, Sec 3, 301, 1**.

3. The approval data for the reinforced comparative method

   (1) Commonly required data which mentioned at **Ch 1, Sec 3, 301, 1**.

   (2) The approval data of CCS of the reference ship

   (a) The navigation information including the date, the filling ratio, the ship speed and the wave angle of incidence

   (b) The comparison data and analysis data between the sailing sloshing load and the design sloshing load

   (c) The design sloshing load of the reference ship

   (3) The structural strength assessment data of CCS of the target ship

   (a) Material properties and their basis

   (b) The acceptance criteria and its basis

   (c) The structural analysis result

   (d) The comparison evaluation data for the CCS of the reference ship and that of the target ship

   (4) The drawing and the related support data of CCS

   (a) The data for type of CCS

   (b) The detail drawing of representative basic model

4. The approval data for the absolute method

   (1) Commonly required data which mentioned at **Ch 1, Sec 3, 301, 1**.

   (2) The structural strength assessment data of CCS of the target ship

(a) Material properties and their basis

(b) The acceptance criteria and its basis

(c) The structural analysis result

(3) The drawing and the related support data of CCS

(a) The data for type of CCS

(b) The detail drawing of representative basic model

### 302. The reference data

(1) Principal dimensions of the ship

(2) Restrictions on cargo operations, such as limiting the height of the cargo loading, cooling down speed

(3) Layout of CCS in each cargo hold

(4) General arrangement of ship with the CCS installed

(5) Design constraints of the CCS

# CHAPTER 2 ASSESSMENT OF DESIGN SLOSHING LOAD

## Section 1 Sloshing analysis condition

### 101. Target tank selection

1. The analysis should be performed on the cargo tanks that are expected to have the largest sloshing among tanks on the ship.
2. The severity of sloshing is closely related to the size, shape, and excitation motion of the tank. In a general manner, it is recommended to determine target tank as the large tank which is far from the ship motion center.
3. Generally, the most severe sloshing phenomenon is expected to occur in No. 2 cargo tank. **Figure 1** shows the typical membrane type LNG cargo hold and No. 2 Cargo hold.

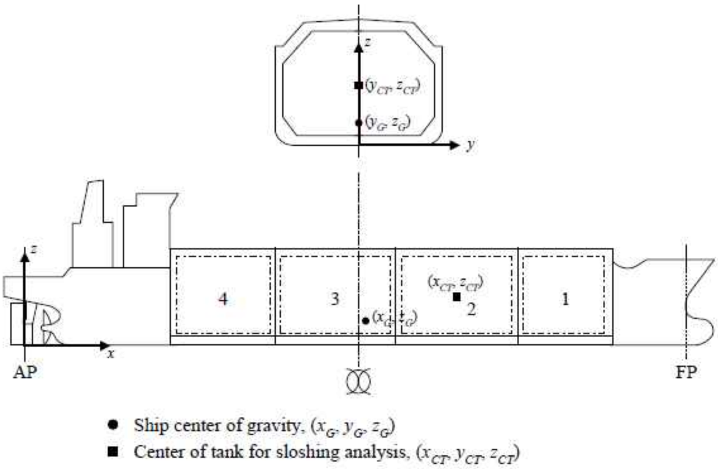



**Figure 1 LNG cargo hold and No. 2 cargo hold location**

### 102. Loading condition

1. Tank filling ratios

   (1) Tank filling ratio for the sloshing analysis should be determined based on the loading manual presented by the designer. Otherwise, in addition to the standard filling ratio, the analysis should be performed for the partial filling ratio.

   (2) The filling ratio should be indicated by the ratio of the filling height to the cargo tank height, H.

      (a) The standard filling ratio means that more than 70% and that lower than 10% of tank height. The analysis should be performed for the filling ratio of 10%, 70%, 80%, and 95% of the tank height (0.10H, 0.70H, 0.80H, and 0.95H). One of the 70% and 80% of the cargo hold height might be excluded according to the operational conditions. This exclusion needs to be discussed with the Society in advance.

      (b) If the vessel has no limit to the filling ratio, the sloshing analysis should be performed for 0.10H, 0.20H, 0.30H, 0.50H, 0.70H, 0.80H, and 0.95H filling conditions.

2. Loading conditions for the seakeeping analysis

   (1) Main factors of motion analysis such as the draft, the metacenter height and the ship's center of gravity vary depending on the tank filling ratio. In general, the motion analysis for each filling ratio is carried out by the loading condition given in the loading manual. For the standard filling ratio, loading conditions of more than 70% filling ratio can be used as the full load condition at arrival and loading conditions of less than 10% filling ratio can be used as the ballast condition at arrival.

### 103. Short-term/long-term approach

1. Design sloshing load should be evaluated based on the design life time of the target vessel. In general, 25 year is considered for LNG carrier.
2. There are two methods for deriving the sloshing design load, short-term approach and long-term approach.
3. The short-term approach estimates the design sloshing load considering very extreme environmental conditions which the vessel could experience during her design life time. In that manner 1 year and 40 years return period is considered for beam and head waves respectively. The short-term approach does not require the sloshing load information at mild sea states and consider 3-hour most probable maximum load of critical wave condition as design load.
4. The long-term approach examines all the environmental conditions the vessel might experience. It additionally considers probabilities of sloshing events as well as probabilities of the sea states based on the wave scatter diagram. Therefore, probability level of design sloshing should be based on the design life, not 3hour maximum.

### 104. Wave environmental condition

1. General

(1) LNG carriers are assumed to operate in the North Atlantic without restriction. The design should be conducted by the sea condition of the North Atlantic. The wave data of the North Atlantic is using the wave diagram of 「IACS Recommendation No.34 (Nov. 2001)」 and is shown in **Table 1**.

(2) The wave scatter diagram is used to calculate the extreme sea load with the return period of design life time.

(3) In ships with restricted in service area, specific wave environment condition is considered on a case-by-case basis.

**Table 1 IACS North-Atlantic Wave Diagram**

| $H_S / T_Z^*$ | 1.5 | 2.5 | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 | SUM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.0 | 0.0 | 1.3 | 133.7 | 865.6 | 1186.0 | 634.2 | 186.3 | 36.9 | 5.6 | 0.7 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3050 |
| 1.5 | 0.0 | 0.0 | 0.0 | 29.3 | 986.0 | 4976.0 | 7738.0 | 5569.7 | 2375.7 | 703.5 | 160.7 | 30.5 | 5.1 | 0.8 | 0.1 | 0.0 | 0.0 | 0.0 | 22575 |
| 2.5 | 0.0 | 0.0 | 0.0 | 2.2 | 197.5 | 2158.8 | 6230.0 | 7449.5 | 4860.4 | 2066.0 | 644.5 | 160.2 | 33.7 | 6.3 | 1.1 | 0.2 | 0.0 | 0.0 | 23810 |
| 3.5 | 0.0 | 0.0 | 0.0 | 0.2 | 34.9 | 695.5 | 3226.5 | 5675.0 | 5099.1 | 2838.0 | 1114.1 | 337.7 | 84.3 | 18.2 | 3.5 | 0.6 | 0.1 | 0.0 | 19128 |
| 4.5 | 0.0 | 0.0 | 0.0 | 0.0 | 6.0 | 196.1 | 1354.3 | 3288.5 | 3857.5 | 2685.5 | 1275.2 | 455.1 | 130.9 | 31.9 | 6.9 | 1.3 | 0.2 | 0.0 | 13289 |
| 5.5 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 51.0 | 498.4 | 1602.9 | 2372.7 | 2008.3 | 1126.0 | 463.6 | 150.9 | 41.0 | 9.7 | 2.1 | 0.4 | 0.1 | 8328 |
| 6.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 12.6 | 167.0 | 690.3 | 1257.9 | 1268.6 | 825.9 | 386.8 | 140.8 | 42.2 | 10.9 | 2.5 | 0.5 | 0.1 | 4806 |
| 7.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.0 | 52.1 | 270.1 | 594.4 | 703.2 | 524.9 | 276.7 | 111.7 | 36.7 | 10.2 | 2.5 | 0.6 | 0.1 | 2586 |
| 8.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 15.4 | 97.9 | 255.9 | 350.6 | 296.9 | 174.6 | 77.6 | 27.7 | 8.4 | 2.2 | 0.5 | 0.1 | 1309 |
| 9.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 4.3 | 33.2 | 101.9 | 159.9 | 152.2 | 99.2 | 48.3 | 18.7 | 6.1 | 1.7 | 0.4 | 0.1 | 626 |
| 10.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 10.7 | 37.9 | 67.5 | 71.7 | 51.5 | 27.3 | 11.4 | 4.0 | 1.2 | 0.3 | 0.1 | 285 |
| 11.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 3.3 | 13.3 | 26.6 | 31.4 | 24.7 | 14.2 | 6.4 | 2.4 | 0.7 | 0.2 | 0.1 | 124 |
| 12.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 1.0 | 4.4 | 9.9 | 12.8 | 11.0 | 6.8 | 3.3 | 1.3 | 0.4 | 0.1 | 0.0 | 51 |
| 13.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 1.4 | 3.5 | 5.0 | 4.6 | 3.1 | 1.6 | 0.7 | 0.2 | 0.1 | 0.0 | 21 |
| 14.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 1.2 | 1.8 | 1.8 | 1.3 | 0.7 | 0.3 | 0.1 | 0.0 | 0.0 | 8 |
| 15.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 | 3 |
| 16.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 1 |
| SUM | 0 | 0 | 1 | 165 | 2091 | 9280 | 19922 | 24879 | 20870 | 12898 | 6245 | 2479 | 837 | 247 | 66 | 16 | 3 | 1 | 100000 |

2. Wave spectrum

(1) The wave spectrum is represented by the Bretschneider or two parameter Pierson-Moskowitz spectrum, described by the following expression :

$$S(w) = \frac{H_s^2}{4\pi}(\frac{2\pi}{T_z})^4 w^{-5} \exp\left[-\frac{1}{\pi}(\frac{2\pi}{T_z})^4 w^{-4}\right]$$

where,

$S$ : Wave energy density ($m^2 \sec$).

$H_s$ : Significant wave height ($m$).

$w$ : Angular wave frequency ($rad/\sec$).

$T_z$ : Average Zero up-crossing wave period ($\sec$).

(2) Long-crested wave can be used from a conservative perspective. For more realistic analysis, short-crested wave with $\cos^n(\theta)$function can be used if necessary. Spreading function usually defined as $f_s(\theta) = k\cos^2(\theta)$ where $k$ is selected such that:

$$\sum_{\theta_0 - 90^\circ}^{\theta_0 + 90^\circ} f_s(\theta) = 1$$

where,

$\theta_0$ : Main wave heading ($\deg$).

$\theta$ : Relative spreading around the main wave heading ($\deg$).

3. Determination of wave environment in short-term approach

(1) The model test should be performed by selected extreme sea state. The severity of the sea state should be determined based on the sea state occurrence possibility, the response of tank motion, the proximity of the tank resonance period to the encountering wave period.

(2) The design sloshing load should be defined on the basis of the long-term probability over $10^{-8}$. Unlike the ship motions, the spectral-based long-term statistical analysis can not be used for the estimation of sloshing load due to the high nonlinearity. Alternatively, an equivalent short-term approach can be used to predict the long-term extreme value. The procedure is as follows.

(a) The design sea state showing the most severe storm which the ship can meet during the life need to be defined. Various sea state in heading sea and beam sea should be considered. **Table 2** is example of extreme wave conditions of North Atlantic Sea for 5hour simulation with return periods of 40 years and 1 year. These are based on the occurrence probability shown in wave scatter diagram in **Table 1** and Inverse First Order Reliability Method (iFORM) was applied. The sea state of 40 years is used for heading wave (150°~180°), that of 1 year for beam sea (90°~120°). For quartering seas, an interpolated wave height may be used.

(b) Wave period should be considered within the range of 30% from the natural sloshing periods of the cargo tank with 1 second increment.

(c) The short-term extremes of sloshing loads for each sea state are assessed. The duration for each sea state is assumed to be 3 hours.

(d) The sea state to produce the maximum sloshing loads is to be found.

(e) If necessary, the model test and statistical analysis of sloshing loads for the additional sea state and the heading should be carried out.

4. Determination of wave environment in long-term approach

(1) The long-term approach examines all the environmental conditions the vessel might experience. In principle, zero-crossing period conditions should be considered within the range of 30% from the natural sloshing periods of the tank with 1 second increment and significant wave heights should cover the lowest to the highest with 3 $m$ increment. This requires a considerable number of model tests, so if there is a realistic burden to perform the tests, appropriate grouping and screening can be performed in consultation with the Society.

Table 2 Extreme wave condition of North Atlantic sea corresponding to 40-year and 1-year return periods

| $T_z$(sec) | $H_s(m)$ | |
|---|---|---|
| | 40-year wave | 1-year wave |
| 4.5 | 2.4 | 2.0 |
| 5.5 | 5.3 | 3.2 |
| 6.5 | 8.3 | 5.8 |
| 7.5 | 10.9 | 8.1 |
| 8.5 | 12.9 | 9.9 |
| 9.5 | 14.4 | 11.2 |
| 10.5 | 15.3 | 12.0 |
| 11.5 | 15.9 | 12.4 |
| 12.5 | 16.1 | 12.3 |
| 13.5 | 15.9 | 11.7 |
| 14.5 | 15.3 | 10.4 |
| 15.5 | 14.4 | 7.4 |

## 105. Vessel speed

1. Speed of the vessel is varied with regards to the wave heading angle and the wave height as presented in **Table 3**.

Table 3 Vessel speed assumption

| Heading angle / Wave height | $0^\circ \le \theta < 45^\circ$ | $45^\circ \le \theta < 135^\circ$ | Heading angle / Wave height | $135^\circ \le \theta < 180^\circ$ |
|---|---|---|---|---|
| $H_S \le 5$m | $V_{\max}$ | $V_{\max}$ | $H_S \le 4$m | $V_{\max}$ |
| $H_S > 5$m | $V_{\max}$ | 2/3 $V_{\max}$ | 4m$< H_S \le 7$m | 2/3 $V_{\max}$ |
| - | | | $H_S > 7$m | 1/2 $V_{\max}$ |

## 106. Wave heading angle

1. Short-term approach
   (1) The wave heading angle should be chosen based on the tank shape, the tank motion and the encountering frequency range for each filling ratio.
   (2) As general, four relative wave heading angles can be considered from the beam sea condition to the head sea condition with a 30° increment (90°, 120°, 150°, 180°).
2. Long-term approach
   (1) Consideration of wave heading angle and their occurrence probability should be based on operational condition of target ship.
   (2) As a default, four relative wave heading angles can be considered from the beam sea condition to the head sea condition with a 30° increment (90°, 120°, 150°, 180°) as even probability.

### 107. Test phase

1. General

(1) Sloshing model test procedure can be classified into two phases, i)screening phase and ii)design phase (**Figure 2**). During the screening phase, examine the sloshing load in a wide range of environmental conditions. After analyzing the test results performed in the screening phase, critical conditions for deriving the design sloshing load can be identified. Then, in the design phase, longer duration test be conducted for critical condition.

2. Short-term approach

(1) During the screening phase, extreme environmental and operational conditions of **Ch 2, Sec 1, 104, 3** should be tested for five hours in real scale. By comparing extreme sloshing load, several severe test conditions are to be selected as critical condition.

(2) In the design phase, additional long-duration test should be performed for critical conditions determined in screening phase. Critical conditions requires 30 hours test data in real scale. Which means that five additional 5-hour test be conducted for critical condition. By conducting the long-duration model test, reliability of estimated design sloshing load would be improved. After that, most probable maximum pressure for 3 hours ($P_{3hrs}$) at critical condition will be considered as design sloshing load.

3. Long-term approach

(1) During the screening phase, extreme environmental and operational conditions of **Ch 2, Sec 1, 104, 4** should be tested for five hours in real scale. By comparing contribution to the long-term probability of sloshing load, several conditions which shows large long-term contribution are to be selected as critical condition.

(2) In the design phase, additional long-duration test should be performed for critical conditions determined in screening phase. Critical conditions requires 10 hours test data in real scale.

(3) Contribution to the long-term probability of each single condition can be obtained in short form as follows:

$$Long-term\,contribution = P_{3hrs} \times Occurrence\,probability$$

Here, Occurrence probability means the proportion occupied by a specific sea state in the entire wave scatter diagram, and the sum of the occurrence probabilities of all conditions considered for the analysis should be 1.

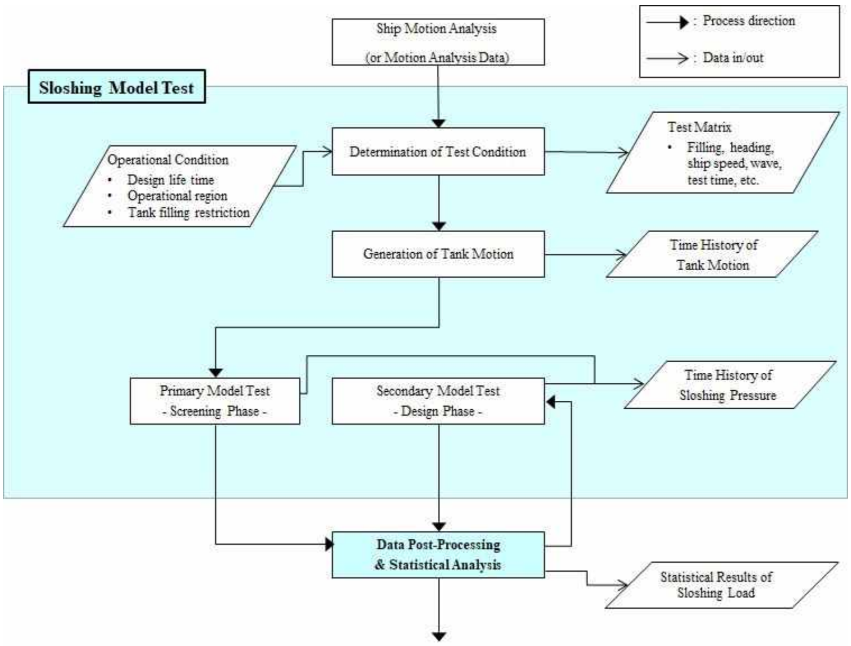



**Figure 2 Flowchart of sloshing model test**

## 108. Seakeeping analysis

1. General

(1) Seakeeping analysis should be performed by a spectrum-based approach based on the response amplitude operator (RAO). The response amplitude operator of the tank motion is used to generate the time histories of irregular tank motion for the model test.

(2) Using the program approved by the Society, the analysis of ship motion and wave load should be performed.

2. Diffraction-radiation method

(1) The calculation of wave induced motion should be performed by applying the seakeeping analysis software using the diffraction-radiation method based on the potential flow. Well-known software are HydroStar, KR3D, WAMIT, WADAM as a frequency domain software, and WASIM and WISH as a time domain software. Since considering the sloshing effect could reduce roll motion response, it is not essential to consider the sloshing coupling effect in seakeeping analysis.

(2) If the different analysis program as suggested by the Society is used, the motion analysis results for the standard LNG carrier presented by the Society should be submitted. In the case that the application of this guidance is not appropriate or that the Society allow that the special method and the procedure not specified in this guidance is at least equivalent to those in effect for the provision of this guidance, it is assumed to be appropriate for the provision of this guidance.

3. Consideration of hydrodynamic model

(1) The hull shape of LNG carrier should be accurately modeled using the data provided by the designer. The center of gravity for each loading condition and the filling ratio, the mass and the inertia radius should refer to the loading manual provided by the designer.

(2) The analysis model of ship motion should be able to reflect the geometry and hydrodynamic characteristics of the ship wetted surface. The panel should be segmentalized in order to analyze the input wave and the diffracted wave.

(3) 2D strip model

At least 25~30 strips should be applied, including at least 10~14 offsets points on half side. A good representation in areas with large transitions in shape (bow and fore part, bilge) should be ensured using higher density of strips and offsets points. Even areas with constant shape should be divided into several segments to consider the gradient of the hydrodynamic pressure distribution.

(4) 3D panel model

The element size should be sufficiently small to avoid numerical errors. At least 30~40 stations, including 15~20 panels at each half station should be applied. This means 500~800 elements on half side. A good representation in areas with large transitions in shape (bow and fore part, bilge) should be ensured using higher density of panels. Areas with constant shape should be divided into several panels to consider the hydrodynamic pressure distributions.

(5) When the radius of gyration of LNG carrier is not provided in the loading manual at the initial design state, the following values can be used.

$r_{xx} = 0.35B$ : Full load condition

$0.45B$ : Ballast condition

$r_{yy} = r_{zz} = 0.25L_{pp}$

where,

$r_{xx}$ : Roll radius of gyration ($m$).

$r_{yy}$ : Pitch radius of gyration ($m$).

$r_{zz}$ : Yaw radius of gyration ($m$).

$B$ : Breadth of ship ($m$).

$L_{pp}$ : Length between perpendiculars ($m$).

4. The response amplitude operator of ship motion and tank acceleration.

(1) All response amplitude operators for the ship motion and the acceleration of tank center with six degrees of freedom should be obtained. The transverse and longitudinal acceleration of the tank center is defined in the same coordinate system fixed to the tank and should include the effect of tilt and gravity.

(a) The longitudinal acceleration at the tank center

$$A_x = \ddot{X}_1 + (z_{CT} - z_G)\ddot{X}_5 - (y_{CT} - y_G)\ddot{X}_6 + gX_5$$

(b) The transverse acceleration at the tank center

$$A_y = \ddot{X}_2 - (z_{CT} - z_G)\ddot{X}_4 + (x_{CT} - x_G)\ddot{X}_6 - gX_4$$

(c) The vertical acceleration at the tank center

$$A_z = \ddot{X}_3 + (y_{CT} - y_G)\ddot{X}_4 - (x_{CT} - x_G)\ddot{X}_5$$

where,

$x_G, y_G, z_G$ : Ship center of gravity under consideration ($m$).

$x_{CT}, y_{CT}, z_{CT}$ : Center of tank under consideration ($m$).

$g$ : Gravitational constant ($m/s^2$).

$X_1$, $\ddot{X}_1$ : Surge and longitudinal acceleration at the ship center of gravity ($m$, $m/s^2$).

$X_2$, $\ddot{X}_2$ : Sway and transverse acceleration at the ship center of gravity ($m$, $m/s^2$).

$X_3$, $\ddot{X}_3$ : Heave and vertical acceleration at the ship center of gravity ($m$, $m/s^2$).

$X_4$, $\ddot{X}_4$ : Roll and roll acceleration ($rad$, $rad/s^2$).

$X_5$, $\ddot{X}_5$ : Pitch and pitch acceleration ($rad$, $rad/s^2$).

$X_6$, $\ddot{X}_6$ : Yaw and yaw acceleration ($rad$, $rad/s^2$).

(2) The hydrodynamic load analysis should consider all heading angles from 0° to 360°, with the heading angle spacing less than 30°.

(3) The frequency of the sufficiently wide range should be taken into consideration. The recommended frequency range is from 0.2$rad/s$ to 1.2$rad/s$ in increment of 0.05$rad/s$.

5. Roll damping model

(1) The roll motion of the ship in oblique waves is greatly affected by the hull viscous roll damping especially near the roll resonance. In the motion analysis based on the potential flow theory, the roll damping model with proper viscosity should be introduced in the panel method.

(2) The experimental data or the test method for roll damping model can be used in determining the hull viscous roll damping under the consultation with the Society. Roll damping effect of rudders and bilge keels should be considered in the motion analysis.

6. Extreme values for ship motion

(1) In order to determine the lifetime maximum of each ship motion and acceleration, the extreme value analysis should be performed. The tank motion and acceleration and sea state for sloshing simulations is selected as the lifetime maximum value.

## 109. Generation of time history of tank motion

1. Generation of irregular tank motion

(1) The response spectrum of tank motion should be generated by combining the response amplitude operator of the hull motion with the wave spectrum.

(2) In order to avoid repeating the motion sequence, it is recommended to use more than 200 wave frequency components with non-uniform discretization.

(3) The generated motion data should be checked based on the frequency domain whether the applied sea condition and the motion performance of the target ship are well reflected.

2. Capacity of motion generator

(1) The motion generator should be able to generate 6 degree of freedom. Otherwise, it should be verified that the omission of motion element does not affect the sloshing impact pressure significantly.

(2) The capacity of motion generator (power and torque) should be determined by performing the appropriate numerical analysis.

### 110. Verification of tank motion

1. Verification of global motion

(1) During the model test, the motion of model tank and the force and torque of motion generator should be continuously monitored. If the tank motion deviate from the prescribed motion more than 3% or the power and torque of motion generator is outside the maximum capacity allowed, the measured data should be discarded.

2. Verification of impact motion

(1) In the case that the weight of the support is not sufficient, the impact motion of tank can be induced by sloshing impact load and impact pressure and its duration can be affected. Acceleration of tank motion should be monitored and compared to the input. If the acceleration of model tank has a significant deviation at the moment of sloshing impact, the result should be reported.

# Section 2 Sloshing analysis - Model test

## 201. General

1. The model test should be carried out in all cases except for the case of performing the comparison method with the sloshing simulation.
2. The model test should be performed for the critical sea condition and the wave condition selected through the analysis of hull motion in accordance with **Ch 2, Sec 1**.

## 202. Motion platform

1. The motion platform should be able to simulate 6-dof ship (tank) motion in seaway. The accuracy of the motion platform must be calibrated through an independent measurement system. In terms of the accuracy of the motion platform, the difference between the input motion and the output motion should be less than 3%.
2. If the deviation is larger than 3%, the effect of input and output motion deviations on sloshing pressure should be verified and discussed with the Society. A few studies have been conducted for the effect of input and output difference of sloshing motion time signals on the sloshing impact pressure.

## 203. Cargo hold model

1. Tank model
   (1) Experimental tanks should be made by accurately reflecting the shape of the actual cargo hold. Tank surface can be made as flat which means that flow interference due to bumpy surface (eg. corrugation) can be ignored.
   (2) When an internal structure is implemented, its modelling should be properly simplified and discussed with the Society.
   (3) Making the model with a transparent material is recommended to observe flow inside. **Figure 3** shows an example of the model tank with the pressure sensor and the measuring cable installed.
   (4) The tank model and the support has to be designed to have the sufficient strength to minimize the vibration and the motion caused by the sloshing pressure during the model test. The area vulnerable to impact should have the additional reinforcement.
   (5) The local vibration resonance period of the tank wall should be measured and compared to the duration of sloshing impact. Vibration tests shall proceed by installing a pressure hole and a pressure transducer. During the vibration test, the fluid in the tank should be loaded with a sufficient height.

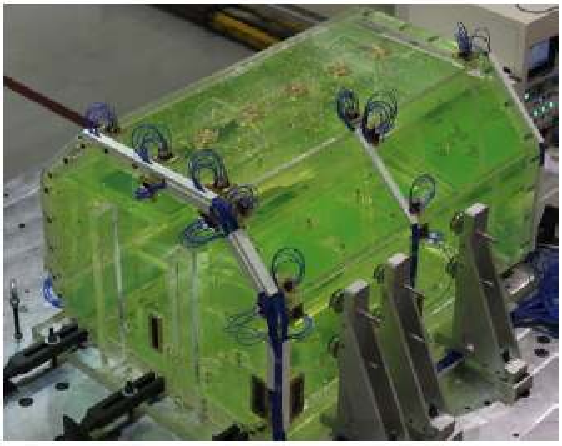


Figure 3 Model tank and sensor installation

### 204. Liquid and ullage gas

1. Ullage and scaling law of density effect

   (1) In principle, the similarity of ullage pressure and density ratio should be satisfied. But ambient air and water can be used in conservative and practical manner.

   (2) If it needs to improve the similarity of the density ratio between two fluids, ambient air could be replaced by heavier gas such as a mixture of nitrogen and Sulphur hexafluoride.

2. Requirement of model tank

   (1) When other ullage pressure different from the air pressure is required during the model test, the vacuum test for the model tank should be performed. A pressure sensor should be installed with the same conditions as the actual experimental model test in vacuum.

### 205. Pressure sensor

1. The pressure sensor must be suitable for measuring the sloshing load. The recommended features are as follows.

   (1) The pressure sensor should be usable in wet condition and not sensitive to temperature changes.

   (2) The pressure sensor should be flush mounted on the inner wall of the tank so that it does not interfere with the flow inside the tank.

   (3) In order to measure localized sloshing impact, the measurement area of the sensor should be small, and multiple pressure sensors should be installed in a cluster.

   (4) The pressure sensor should have a high impact resistance and the measured pressure should not be interfered by the structure of the tank with movement of the tank, sloshing impact and other possible noise sources.

   (5) The measured capacity of the pressure sensor should be sufficiently higher than the expected sloshing pressure.

   (6) The response of the pressure sensor should be high enough to capture the sloshing shock (which is closely related to the natural frequency of the sensor).

2. The sensor specification including the effective measurement area, the pressure range, the response time and the other features should be reviewed by the provider of model test and the Society.

3. Arrangement of pressure sensor should be determined based on the objectives of the test. The arrangement needs to be discussed with the Society. If the location of the sensors is not specified through the discussion, following typical hotspots of the sloshing impact are recommended as shown in **Figure 4**. The hotspots are corners and edges at tank roof and upper-chamfers at high filling condition. In low filling condition, the hotspots are tank side walls near the filling height and intersections between upper-chamfers and side walls. The sensors need to be positioned as close to the edges. Performance and accuracy of the sensors should be checked at least once a year.

4. Since the sloshing impact load has strong locality, the pressure sensors should be installed in the form of a cluster in the sloshing hotspot. In order to capture the spatial distribution of sloshing impact, at least 3x3 sensors should be installed in the 1.5$m$x1.5$m$ of real scale area.

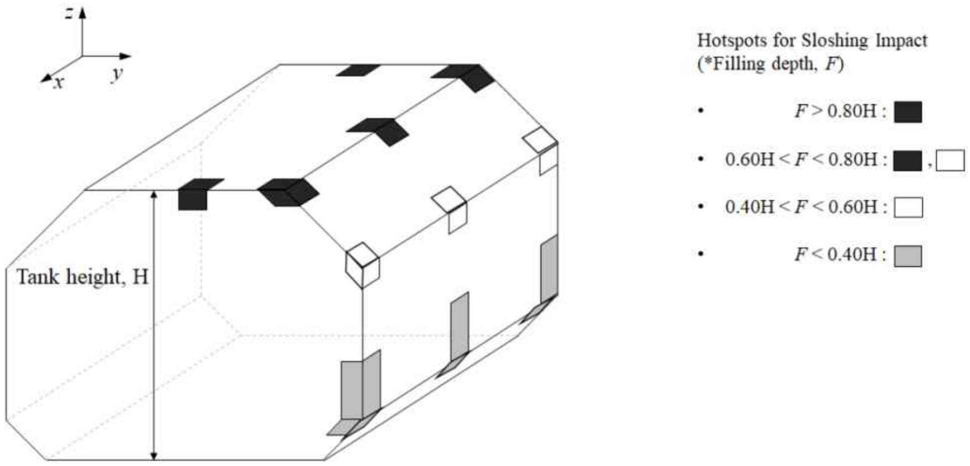



Figure 4 Typical sloshing hotspots of membrane-type tank (ITTC)

### 206. Video recording

1. At least one earth-fixed video should be recorded to capture global motion of flow and model tank during the test. If it is necessary, platform fixed video camera would be installed to capture the flow, excluding the motion of the tank.
2. To capture the details of local motion of the flow, high-speed cameras with using Particle Image Velocimetry (PIV) technique could be used.

### 207. Fluids in the tank

1. Ambient air and water are practically the most easily available fluids for sloshing model test. However, density ratio of air and water is different from that of Boil-Off Gas (BOG) and LNG, so the sloshing load tends to be excessively predicted.
2. The density ratio of the ambient air and water is about 0.0012, and the density ratio BOG and LNG in the actual LNG cargo hold is about 0.004. One of the most practical ways to match the density ratio of the fluid in the model tank as real is to replace the air by a suitable ullage gas which is heavier than air.
3. A mixture of sulfur hexafluoride (SF6) and nitrogen (N2) can be used instead of ambient air. The mixed gas has a ratio of SF6 of about 57% and N2 of about 43%, and their respective densities are shown in **Table 4**.
4. It is known that when the density ratio is adjusted to the realistic value by using a heavy gas mixture, the sloshing impact load can be reduced by about 40%-60% compared to the test case of using ambient air (**Figure 5**).

Table 4 Material properties of heavy gases at 25 ° C, 1atm

| Products | Density | Ratio (%) |
|---|---|---|
| Sulfur Hexafluoride (SF6) | 6.16 | 56.9 |
| Nitrogen (N2) | 1.15 | 43.1 |
| Mixture | 4.00 | - |

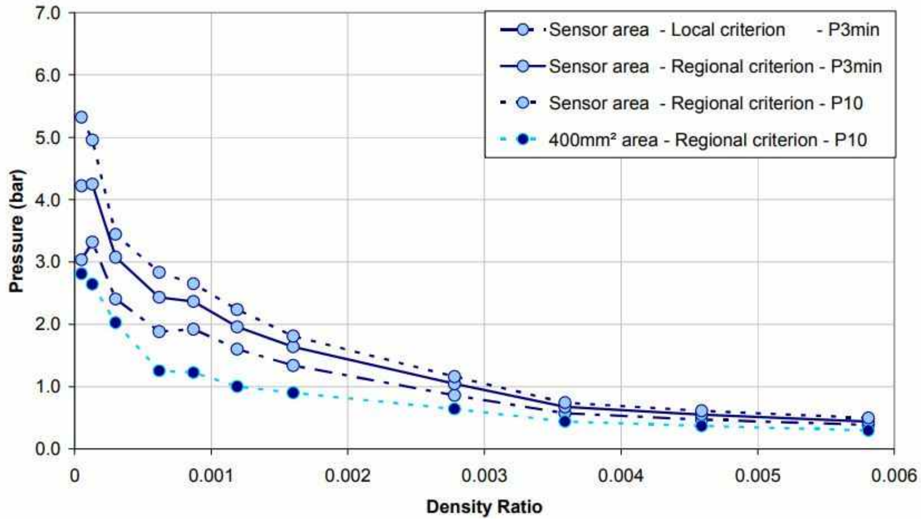



**Figure 5 Influence of fluid density ratio in tank on sloshing load**

5. When using a heavy gas mixture, it is essential to ensure that the gas density in the tank is adjusted to the desired level. When using a heavy gas mixture, it is essential to ensure that the gas density in the tank is adjusted to the desired level. In addition, it is necessary to check whether the airtightness in the tank is well maintained. During the model test, the air dissolved in the water may escape and change the density ratio in the tank, so saturation work is also necessary before the test.

### 208. Data submission

1. System specification for data measurement

   (1) Measuring the frequency of motion, the channel number, the filtering frequency and the filter type should be reported.

   (2) The number of channel should be enough to monitor the sloshing impact pressure and the tank motion simultaneously.

2. Data type submitted

   (1) The measured data type should be described surely.

   (2) Data resolution higher than 10kHz is recommended (in model scale).

# Section 3 Data analysis

## 301. General

1. General procedure of data-post processing of pressure data from the test is shown in **Figure 6**.
2. The pressure time series obtained from individual sensors are converted into load time series for each load application area. After that, statistical samples to be used for statistical analysis are acquired through the process of detecting and idealizing sloshing peaks in the load time series.
3. After the post-processed sloshing peak samples are approximated to the extreme distribution function, the design sloshing load of a design exceedance probability level can be estimated based on the approximated function.
4. To convert to interacted load, FE analysis data base for target CCS model is required, and in this case, additional extreme function fitting is required.

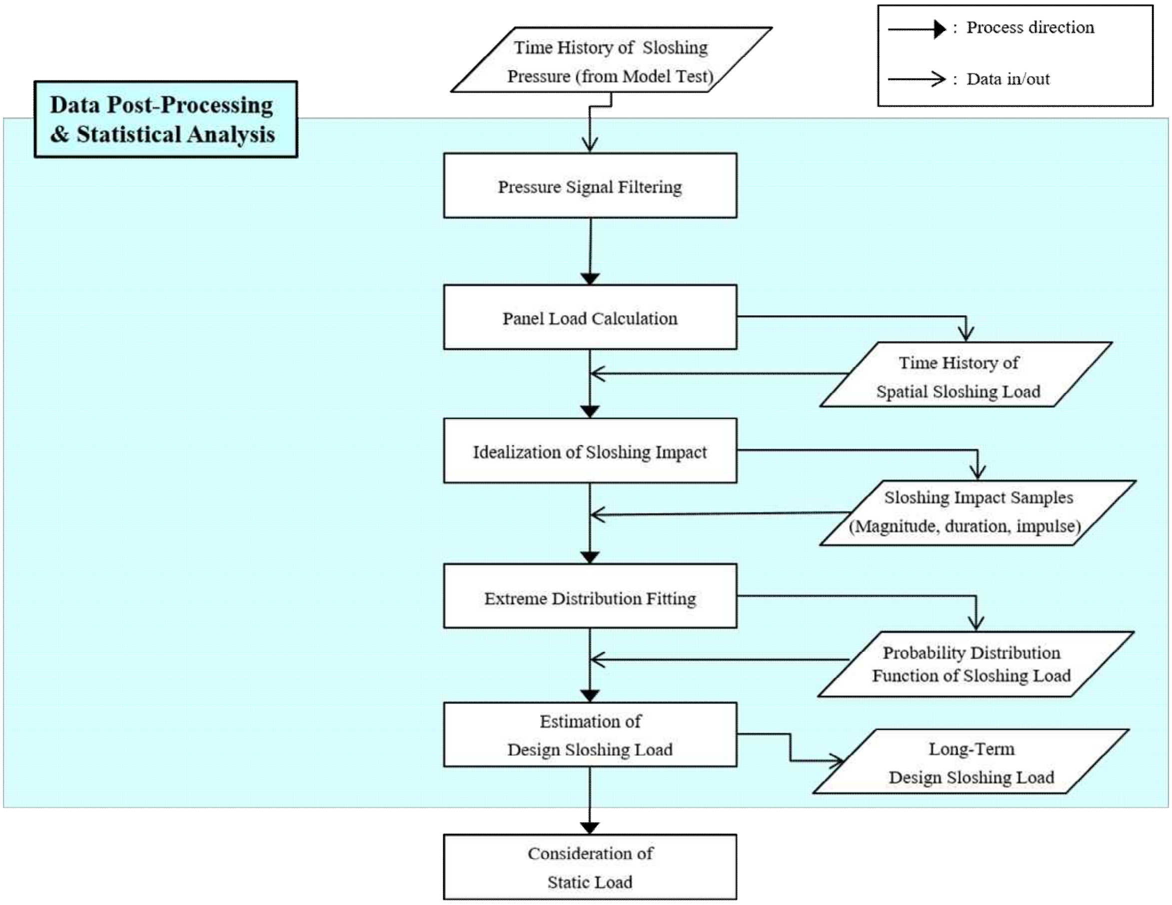



Figure 6 Statistical post-processing of experimental pressure for design sloshing load

## 302. Data filtering

1. A high pass filter could be applied to obtain impulse signals; hydrostatic pressure and low frequency components are to be removed. Cut-off frequency should be defined based on the response period of sloshing event, structural natural frequencies, and properties of pressure sensor. The filtering frequency should be reported.

## 303. Consideration of panel load

1. The average pressure over a certain area should be processed through statistics and used as the design sloshing load.

2. The spatial averaging of sloshing pressure is a method of calculating the panel pressure by configuring the array group of sensors. The panel pressure can be calculated by combining the pressure signal of the individual pressure sensor. By using the installed cluster sensor, the panel load for various areas such as 0.25$m^2$(1x1 array), 1.00$m^2$(2x2 array), 2.25$m^2$(3x3 array) should be evaluated.

### 304. Identifying sloshing events

1. Peak over threshold method

   (1) From the measure pressure signal, sloshing event can be identified by peak over threshold method (**Figure 7**).

   (2) Pressure peaks which exceed the pressure threshold value are to be extracted as temporal peaks. Threshold value should be large enough to eliminate experimental noise and should be smaller than pressure maxima induced by sloshing events.

   (3) Within a moving time window, the largest temporal peak is collected as the global sloshing peak. Sampling time window should be wide enough to catch only one peak at a single sloshing event (single sloshing event can bring multiple pressure peak especially for the impact with gas entrapment).

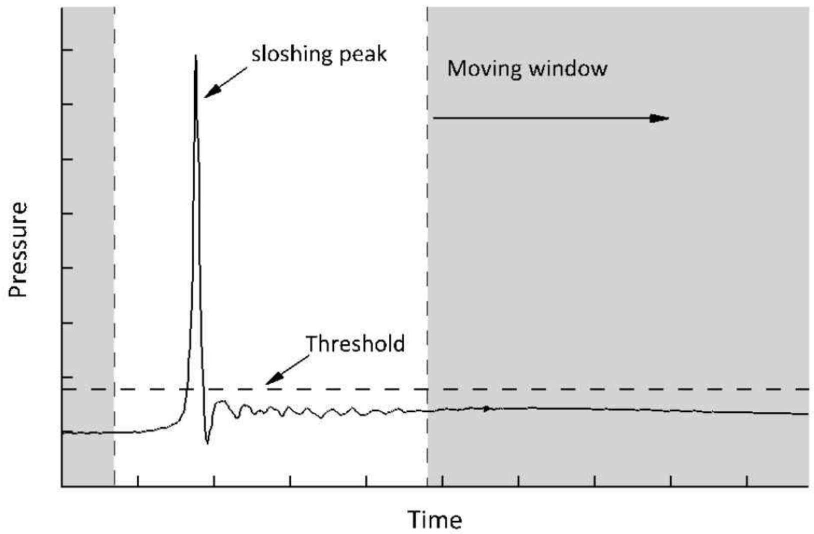



**Figure 7 Identifying sloshing events using peak over threshold method**

2. Maximum per events method

   (1) Due to strong locality of the sloshing impact, it may be more meaningful to consider the analysis results by collecting the impact pressure from the sensors located on the specific sensor panel.

   (2) In this case, the sloshing impact sample of the multi-channel pressure time series can be extracted by collecting only the impact where the largest sloshing pressure peak occurs for each sloshing impact (**Figure 8**).

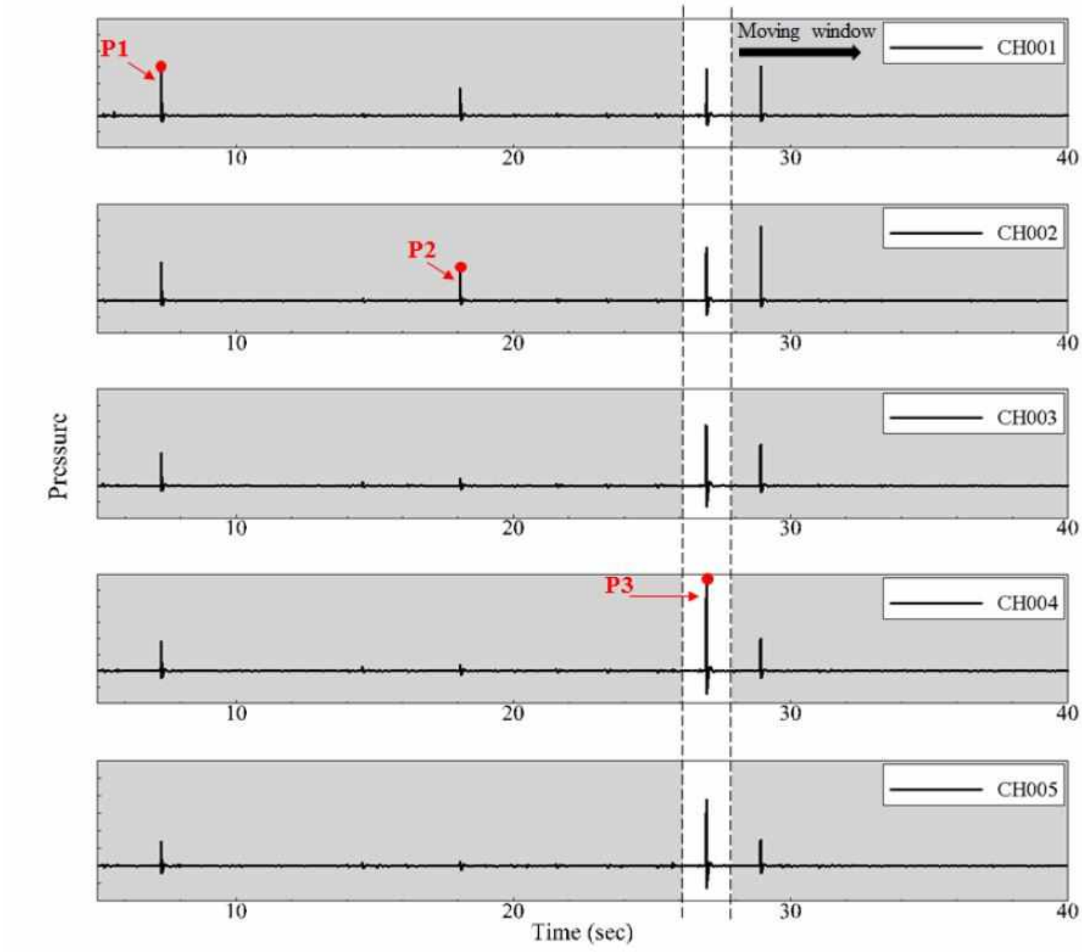



Figure 8 Identifying sloshing events from multiple channel data

3. In order to evaluate the structural strength of CCS, the time history of sloshing load is idealized as a triangular shape (**Figure 9**) which can be characterized by several parameters such as a peak pressure (or load) $P_{peak}$, a rise time $t_{rise}$, a decay time $t_{decay}$, a an impulse area $A$. Peak pressure means maximum value of each sloshing event. The rise time and the decay time can be defined as twice the time duration from pressure up-crossing or down-crossing half of the peak pressure to reaching the peak pressure which can be expressed as bellows:

$$t_{rise} = 2(t_p - t_{(0.5P)up-crossing})$$

$$t_{decay} = 2(t_{(0.5P)down-crossing} - t_p)$$

4. $t_P$ refers to the time instant when the $P$ is measured. $t_{(0.5P)up-crossing}$, $t_{(0.5P)down-crossing}$ can also be interpreted in the same manner. The impulse areas can be defined by modelling parameters.

$$A_r = \frac{1}{2}P_{peak} \cdot t_{rise}$$

$$A_d = \frac{1}{2}P_{peak} \cdot t_{decay}$$

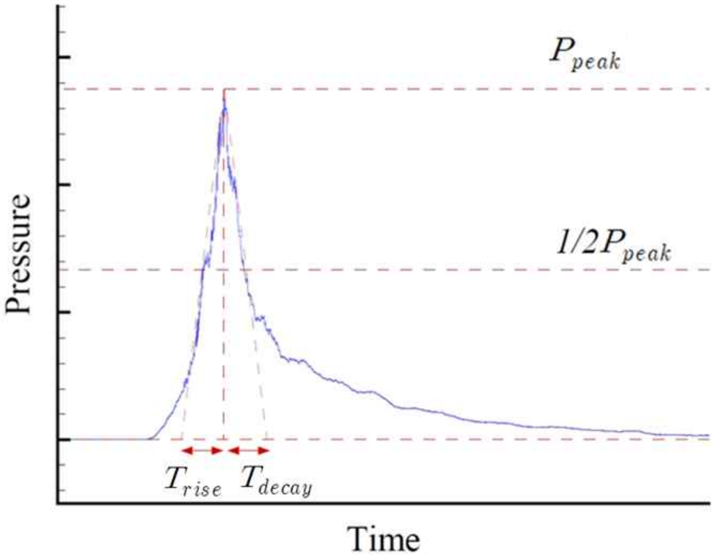



Figure 9 Idealization of sloshing impact as triangular shape

### 305. Consideration of interacted load

1. Structural strength evaluation can be assessed by two methods;"Level 1 evaluation" and "Level 2 evaluation". Level 1 evaluation uses interacted load ($P_{is}$). Level 2 evaluation is described in **Ch 3, Sec 6**.
2. Level 1 evaluation is based on interacted load. Which means statistical analysis for design load derivation (**Ch 2 Sec 3 306, 307**) should be performed for $P_{is}$, not $P_{peak}$ . Since The interacted load should include the dynamic response effect of the cargo hold, it is obtained by multiplying $P_{peak}$ and $DAF_{is}$. $DAF_{is}$ means the envelop of maximum curves for all failure modes of a structure considered, which can be obtained from the DAFs by multiplying its own natural period. For the details of DAF derivation, see **Ch 3, Sec 3**.

### 306. Estimation of probability distribution of sloshing impact load

1. In order to examine various statistical characteristics of sloshing loads, it is necessary to approximate the probability distribution of sampled sloshing peaks to the extreme distribution function.
2. The most commonly used at this time is three-parameter Weibull distribution function. Probability density function (PDF, $f$), cumulative distribution function (CDF, $F$), and exceedance probability distribution (POE, $Q$) of Weibull function are described as bellows:

$$f(P) = \frac{\gamma}{\beta}\left(\frac{P-\delta}{\beta}\right)\exp\left\{-\left(\frac{P-\delta}{\beta}\right)^{\gamma}\right\}$$

$$F(P) = 1 - \exp\left\{-\left(\frac{P-\delta}{\beta}\right)^{\gamma}\right\}$$

$$Q(P) = 1 - F(P) = \exp\left\{-\left(\frac{P-\delta}{\beta}\right)^{\gamma}\right\}$$

### 307. Estimation of long-term probability distribution

1. A long-term probability distribution of sloshing load should be derived based on the probability distribution of every condition that the model test is performed.
2. The long-term exceedance probability of sloshing load can be expressed as follows.

$$Q(P) = \sum_{k=1}^{NF} \sum_{k=1}^{NH} \sum_{k=1}^{NS} p_{ijk} \cdot \frac{R_{ijk}}{R} Q_{ijk}(P)$$

where,

$NF$ : Number of considered filling conditions.

$NH$ : Number of considered heading conditions.

$NS$ : Number of considered sea states.

$p_{ijk}$ : Occurrence probability of filling $i$, heading $j$, sea state $k$ condition.

$R_{ijk}$ : Event rate of $ijk$ condition.

$R$ : Average event rate.

$Q_{ijk}(P)$ : Exceedance probability of sloshing load $ijk$ condition.

# Section 4 Sloshing simulation using CFD

## 401. General

1. The sloshing analysis using CFD should be used only as an auxiliary role in deriving the sloshing design load through model tests, such as for screening purposes.
2. Which means that the design sloshing load derived only through CFD can not be accepted.

## 402. Requirements for CFD tool

1. The CFD tool for sloshing simulation is to be verified and must satisfy the following criteria.
   (1) The governing equation of liquid motion must be satisfied in real liquid domain. The linearization of the liquid domain is not allowed.
   (2) Six degree of freedom motion of tank for the three-dimensional model is to be considered.
   (3) Three degree of freedom motion of tank for the two-dimensional model is to be considered.
   (4) The CFD tool shall be able to present the pressure, the velocity and the acceleration of all the point inside the tank.
2. Verification of CFD tool
   (1) The CFD Tool is to be verified by comparing with the existing experimental and/or theoretical results.

## 403. Modeling

1. Tank modeling
   (1) The tank of LNG Carrier is to be modeled accurately. When performing the two-dimensional simulation, the transverse and the longitudinal section is to be modeled accurately.
2. Element division
   (1) The element size should be able to simulate the spatial distribution of impact pressure accurately. The element size less than $20cm$ in real scale is recommended for use in areas that generate the maximum pressure.
   (2) The average pressure for a given panel area because of the position of the local impact pressure, the sensitivity to the element size and the size increment of time division, is to be calculated. The panel is to include all of the tank surface area expected to have the large sloshing load.
   (3) In the two-dimensional analysis, the longitudinal bulkhead and the inner bottom should be divided into the size of $2m$.
3. Time step and duration
   (1) The increment of time step is to be sufficiently fine in order to maintain the stability and the accuracy of the analysis result.
   (2) The duration of sloshing simulation is to be enough that sloshing simulations are steady state. The duration of steady state response should be at least 5 to 10 periods to the longitudinal and transverse directions.

## 404. Results of numerical analysis

1. The analysis result should be able to obtain from CFD analysis.
   (1) The time history of impact pressure and maximum
   (2) The impact pressure value averaged over $2m$ panel along the bulkhead and tank top (2-dimensional analysis)
   (3) The impact pressure value averaged over $1m^2$ panel along the bulkhead and tank top

(3-dimensional analysis)

2. The average panel pressure history and the maximum for each loading condition should be provided to the Society.

# CHAPTER 3 STRENGTH ASSESSMENT OF LNG CCS

## Section 1 General

### 101. Application

After data post-processing & statistical analysis of model tests or CFD simulations, the structural analysis is performed in two levels.

Level 1 evaluation is the structural analysis to evaluate the safety of the cargo containment system by applying the sloshing load as the static load. Level 1 evaluation including the use of a DAF along with quasi-static response analyses should be used to assess the dynamic responses of the membrane type insulation systems. The details of Level 1 evaluation are described in **Ch 3, Sec 3**.

If the result of Level 1 evaluation does not meet the acceptance criteria, Level 2 evaluation should be performed. Level 2 evaluation is the advanced dynamic analysis to determine whether the result meets the acceptance criteria by applying the design sloshing load. If the analysis results meet the acceptance criteria, the design can be approved, otherwise the design shall be proceeded from the beginning. The details of Level 2 evaluation are described in **Ch 3, Sec 6**.

Sloshing loads may cause deformations of primary membranes of containment systems, but are not to cause significant damage of membranes of the cargo containment system. The main purpose of the structural analysis of LNG cargo containment system is to ensure the structural strength of the insulation panels.

If necessary, it may include a hull in the structural analysis and consider the motion of cargo hold. The structural assessment of primary membranes may be required to ensure that membrane deformations are in the acceptable limit. In these cases, methods of analyses shall be approved by the Society.

## Section 2 Configuration of CCS

### 201. General

The LNG cargo containment system should keep the LNG cargo in liquid state and insulate the hull structure from the low temperature. The two major types of membrane containment systems are layered foam type containment system and box type containment system. Both containment systems provide primary and secondary barriers in compliance with the “International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)”, Volume III of SOLAS 1974 and consist of a two-layer system to prevent cargo leakage and maintain the cryogenic temperature.

### 202. Layered foam type containment system

MarkⅢ and MarkⅢ flex designed by GTT and KC-1 by KC LNG TECH are typical of layered foam type containment system.

1. MarkⅢ and MarkⅢ flex

The material of primary barrier is austenitic stainless steel 304L which is possible to expand and contract in order to absorb the thermal deformation and hull deformation.

The secondary barrier is a membrane called Triplex which consists of the aluminum foil attached with glass fiber in and out for watertightness. The secondary insulation is composed of the reinforced polyurethane foam as same as the first insulation and the plywood. All of the contact surfaces are glued and mastic ropes are positioned between the back plywood and the inner hull. **Figure 1** shows MarkⅢ containment system.

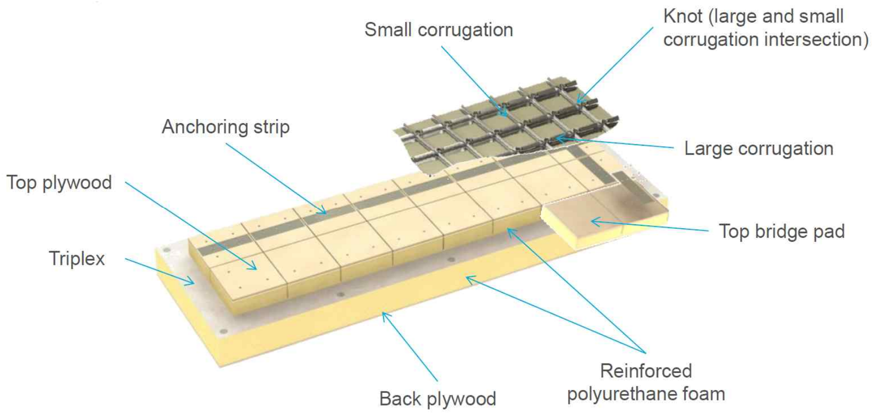



**Figure 1 MarkⅢ containment system**

MarkⅢ flex containment system is reinforced by increasing the thickness of secondary insulations and reducing the gap of strips of mastic. **Figure 2** shows MarkⅢ flex containment system.

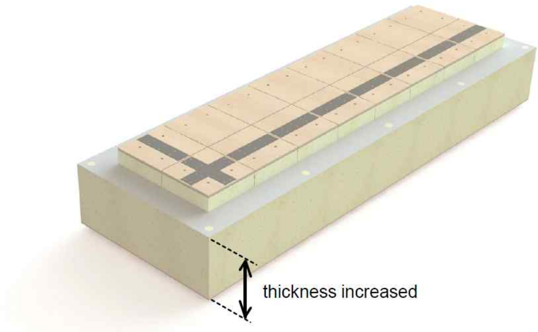



**Figure 2 MarkⅢ flex containment system**

2. KC-1

KC-1 cargo containment system has double metal barriers as shown in **Figure 3**.

The primary and secondary membrane are made of austenitic stainless steel 304L. The primary membrane has arch-shaped end corrugations with 3 lanes. Secondary membrane has identical thickness and corrugation structure but a slightly different size and shape in order to ensure a certain amount of space between them.

The insulation system is a bonded sandwich structure with single layer including back plywood, rigid closed cell foam panel and top plywood. The insulation panels are made of polyurethane foam and fixed to the inner hull by means of stud bolts. Mastic attached to the inner hull serves only load bearing members from cargo tanks because of anti-sticking paper inserted between mastic and inner hull.

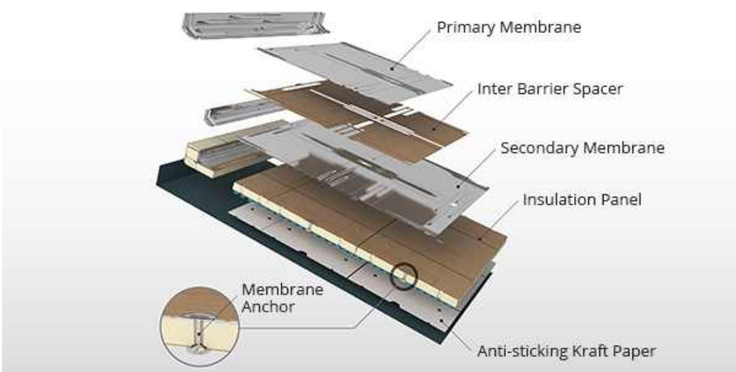



**Figure 3 KC-1 containment system**

## 203. Box type containment system

1. NO96 and NO96 reinforcement

NO96 and NO96 reinforcement designed by GTT are typical box type containment system.

The membrane material is invar which has the extremely low thermal expansion coefficient and the stress does not occur due to the thermal expansion and contraction.

The insulation system consists of two plywood boxes filled with an insulation material called perlite. These boxes are stiffened by internal partitions. All plywoods are fixed by the staples and strips of mastic are glued between the secondary box and the inner hull. **Figure 4** shows a general containment system of NO96.

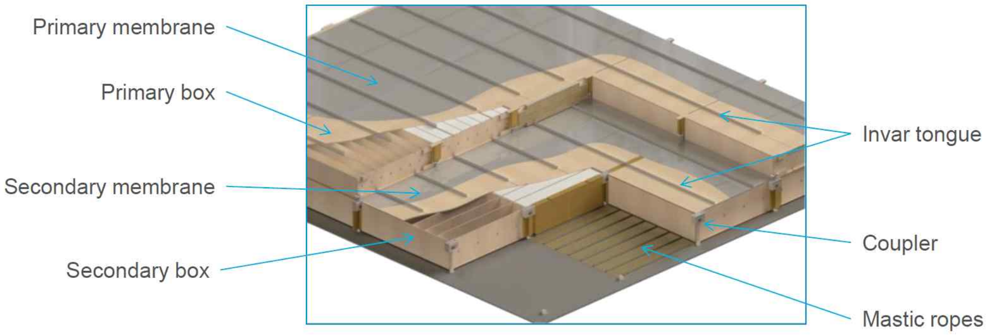
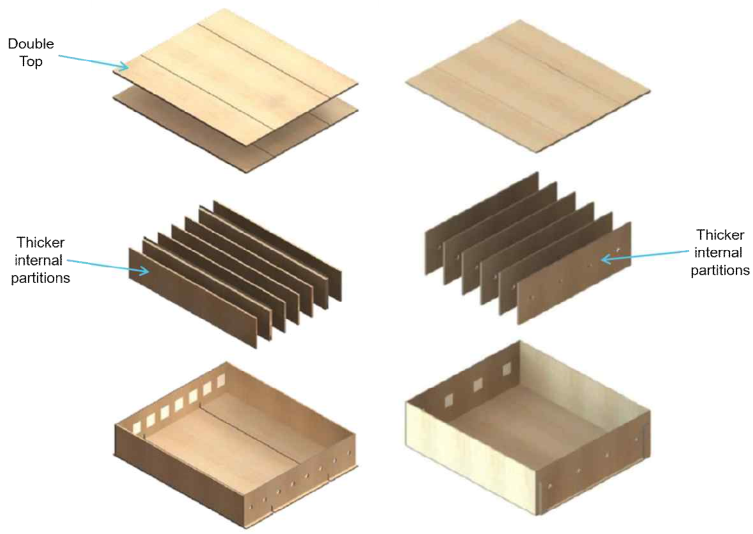



**Figure 4 NO96 containment system**

NO96 reinforcement containment system is reinforced by increasing the thickness of the internal partitions and designing the double top plates. The plates are connected by the staples. **Figure 5** shows NO96 reinforcement containment system.




Primary boxes Secondary boxes

**Figure 5 NO96 reinforcement containment system**

## 204. Other types of containment systems

The design of cargo containment system shall comply with the “The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)” and shall be approved by the Society.

# Section 3 Analysis based on static load

## 301. General

1. The dynamic response should be considered when performing the analysis based on static load. The dynamic response is determined from the quasi-static response through the application of dynamic amplication factor (DAF), given in **Ch 3, Sec 3, 305**.

2. If necessary, it may include a hull in the analysis and consider the temperature of the cargo containment system, the motion of cargo hold and the thermal analysis.

3. New types of cargo containment systems should be modeled using sufficient mesh size to reflect the structural response for the expected failure types. The loading and boundary conditions of the aforementioned systems should reflect realistic conditions as much as possible.

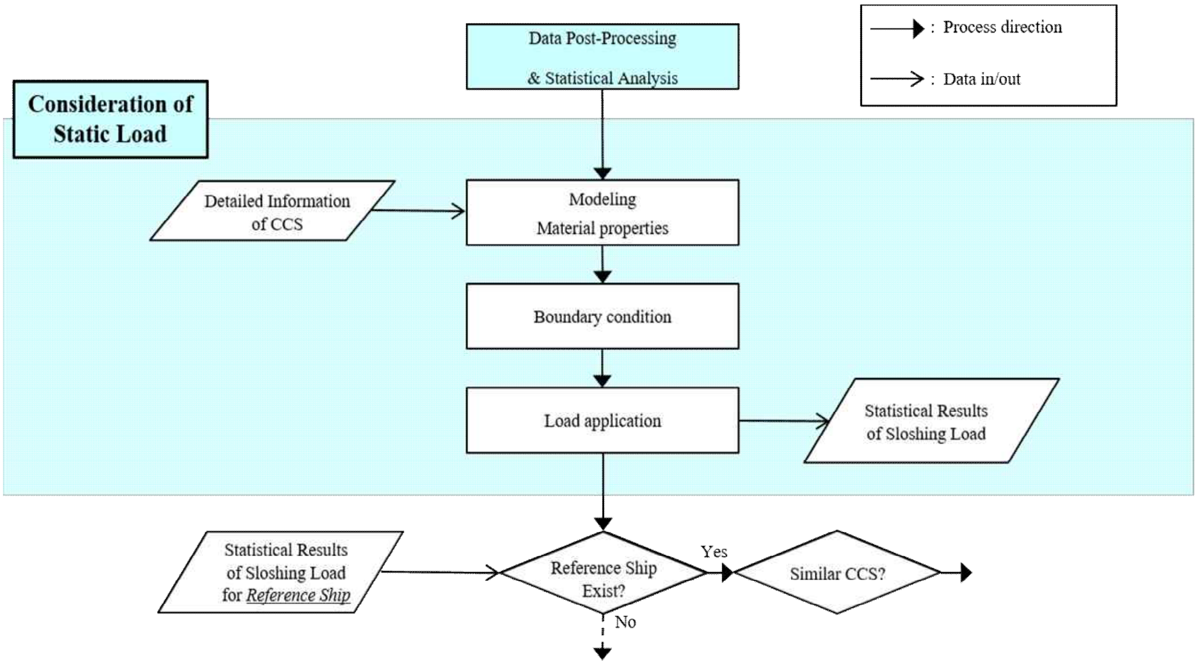



Figure 6 Flowchart of consideration of static load

## 302. Modeling

1. MarkⅢ and MarkⅢ flex

(1) The three-dimensional finite element models of MarkⅢ and MarkⅢ flex should use the hexa solid elements as the default. The finite element mesh should be sufficiently dense to obtain the converged result.

(2) MarkⅢ and MarkⅢ flex are composed of the reinforced polyurethane foam (RPUF), the plywood and the mastic as laminated structures. **Figure 7** and **Figure 8** show the structural models of MarkⅢ and MarkⅢ flex.

(3) The finite element models of MarkⅢ and MarkⅢ flex do not include the primary barrier (STS 304L) and the secondary barrier (Triplex) in the finite element models due to minor contribution to supporting the structural stress caused by sloshing.

(4) It is assumed that the mastic is isotropic and the plywood is orthotropic. Polyurethane foam can be selected to be isotropic or orthotropic as needed. See **Ch 3, Sec 3, 303**.

(5) The mastic should be divided into two or more elements in the width direction. At least three elements should be used along the thickness of the back plywood. Reinforced polyurethane foam should be divided into elements with a length of about 10mm in the thickness direction.

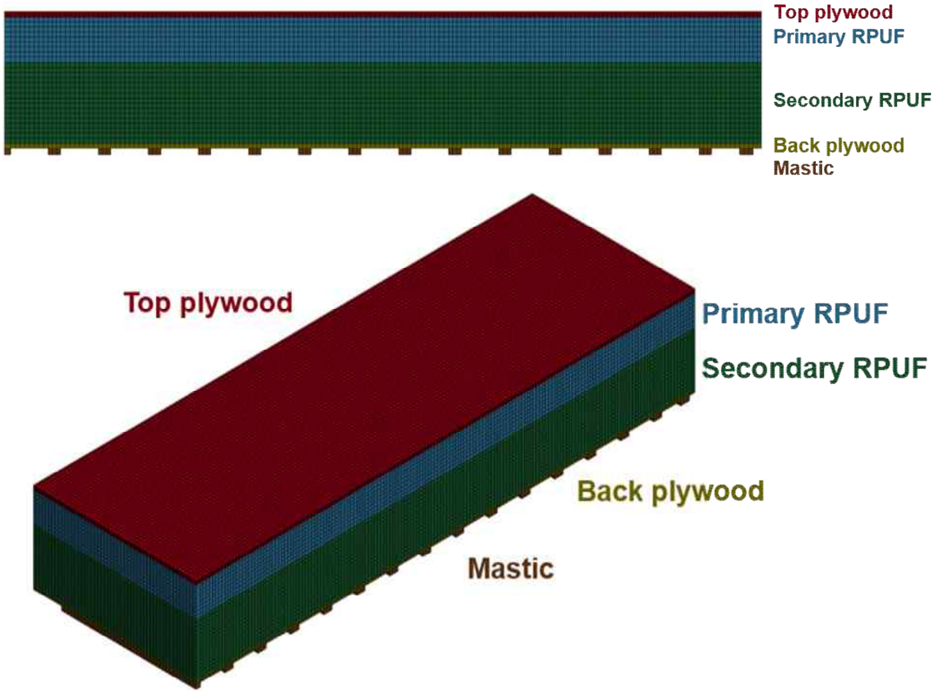



Figure 7 Structural model of MarkⅢ

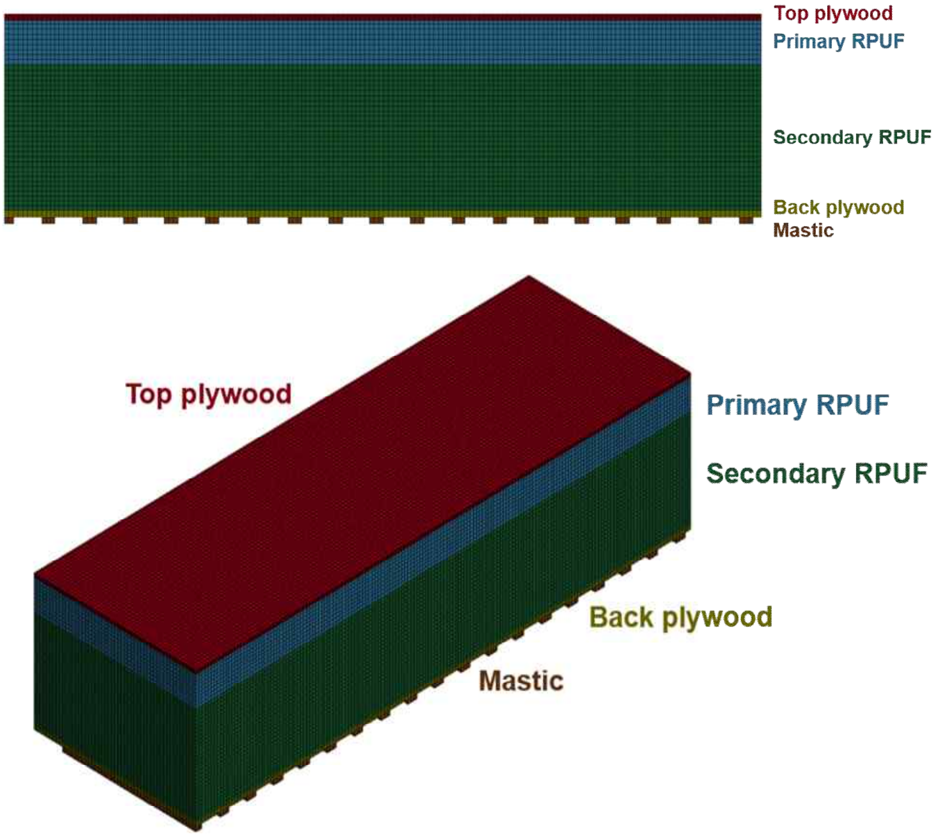



Figure 8 Structural model of MarkⅢ flex

2. KC-1

(1) The three-dimensional finite element model of KC-1 should use the hexa solid elements as the default. The finite element mesh should be sufficiently dense to obtain the converged result.

(2) KC-1 is composed of the polyurethane foam (PUF), the plywood and the mastic as a laminated structure. **Figure 9** shows the structural model of KC-1.

(3) The finite element model of KC-1 does not include the primary membrane and the secondary membrane in the finite element model due to minor contribution to supporting the structural stress caused by sloshing.

(4) It is assumed that the mastic is isotropic and the plywood is orthotropic. Polyurethane foam can be selected to be isotropic or orthotropic as needed. See **Ch 3, Sec 3, 303**.

(5) The mastic should be divided into two or more elements in the width direction. At least three elements should be used along the thickness of the back plywood. Polyurethane foam should be divided into elements with a length of about 10mm in the thickness direction.

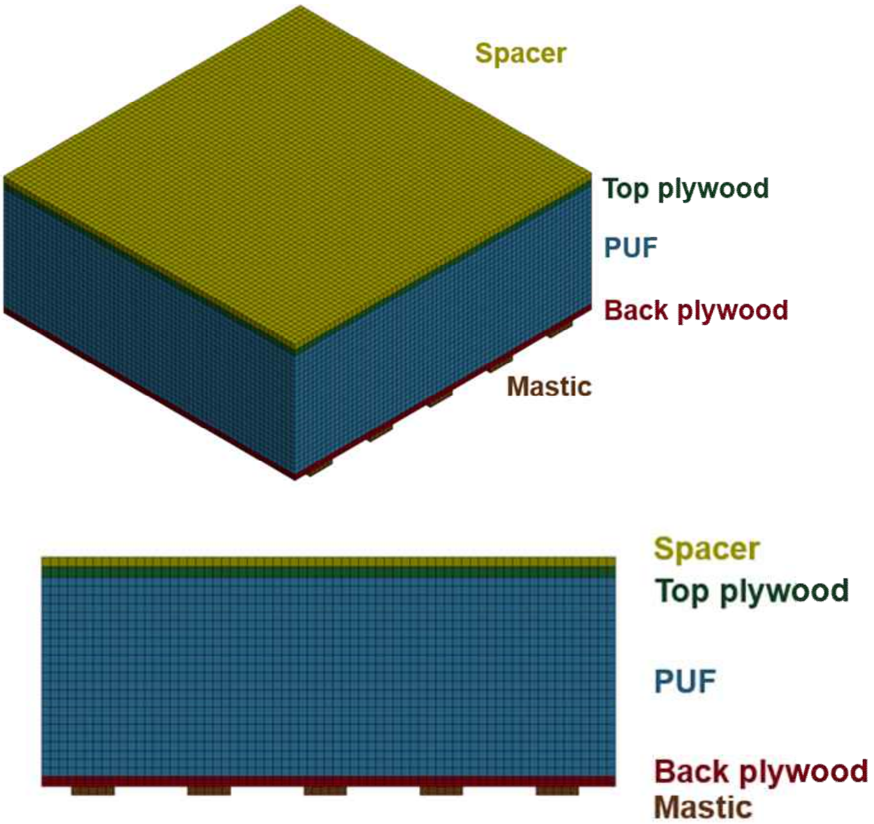



Figure 9 Structural model of KC-1

3. NO96 and NO96 reinforcement

(1) NO96 and NO96 reinforcement should be modeled using the 4 node shell elements. The enhanced plywood can be considered by increasing the thickness of shell element. The aspect ratio of the shell elements is in general not to exceed 3. The elements in the bulkhead plates should as far as possible be square. The finite element mesh should be sufficiently dense to obtain the converged result.

(2) NO96 and NO96 reinforcement are composed of the primary insulation box and the secondary insulation box. **Figure 10** and **Figure 11** show the structural models of NO96 and NO96 reinforcement.

(3) The perlite in the box is not considered because they do not affect the strength of cargo containment system. Also, invar forming the primary barrier and the secondary barrier of the box type cargo containment system is not considered in the finite element model. The primary barrier and the secondary barrier is not included in the analysis model due to its minor contribution to supporting the structural stress due to sloshing load.

(4) It is assumed that the plywood constituting the insulation box has the orthotropic behavior. See **Ch 3, Sec 3, 303**.

(5) In the case of the NO96 reinforcement with double top plates, the upper and lower plates should be modelled as separate entities. The plates should be connected using RBEs at the positions of the staples as indicated in **Figure 12**.

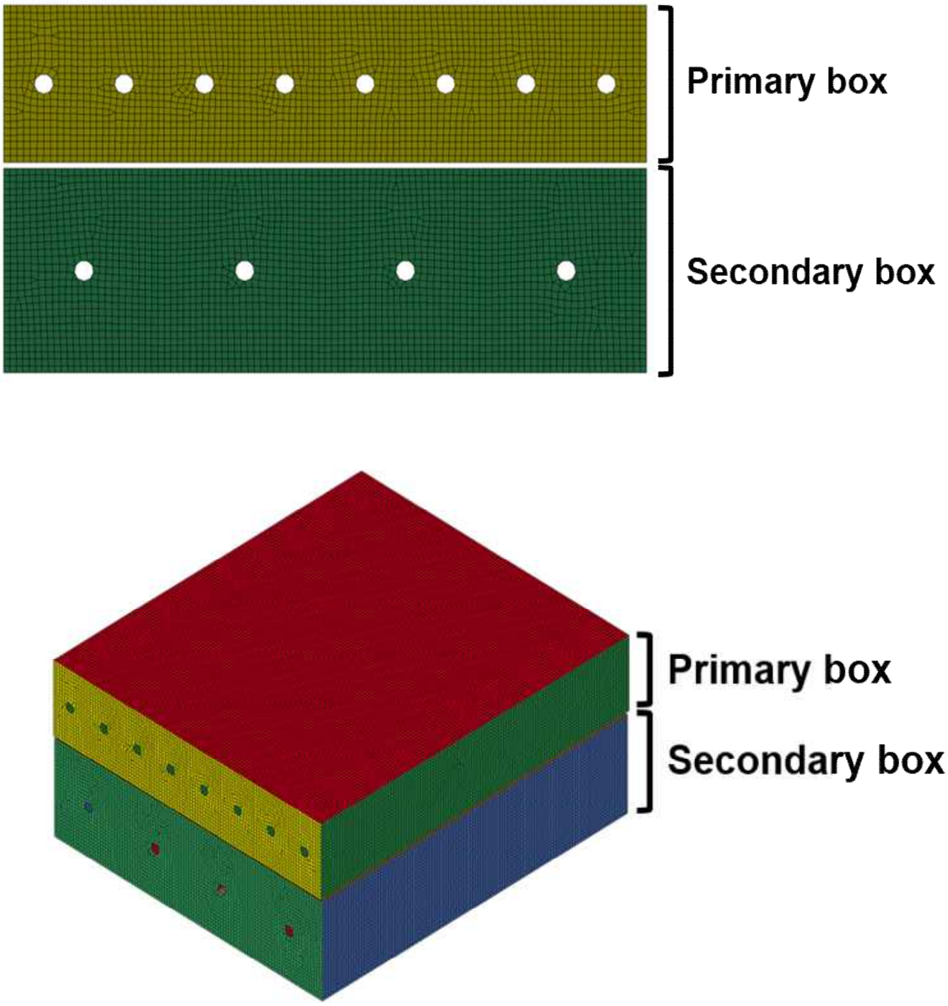



**Figure 10 Structural model of box type containment system (NO96)**

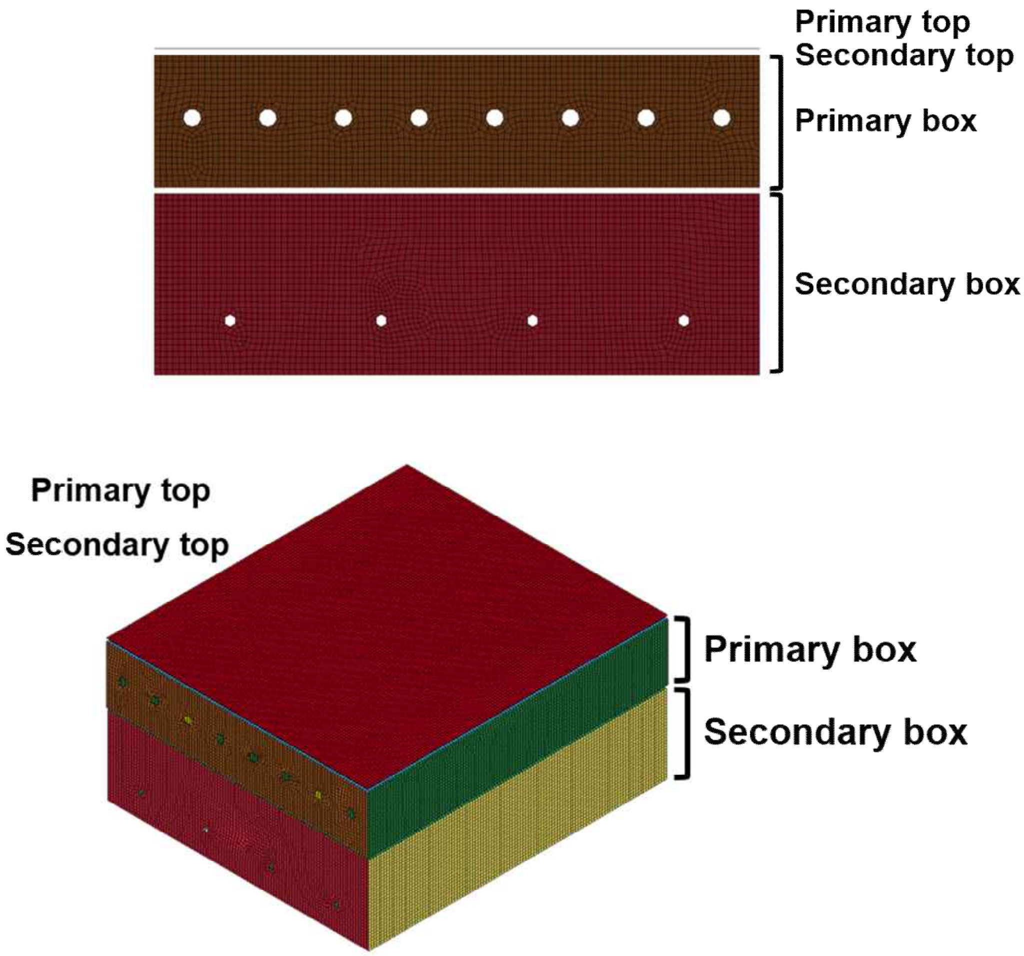



Figure 11 Structural model of box type containment system
(NO96 reinforcement)

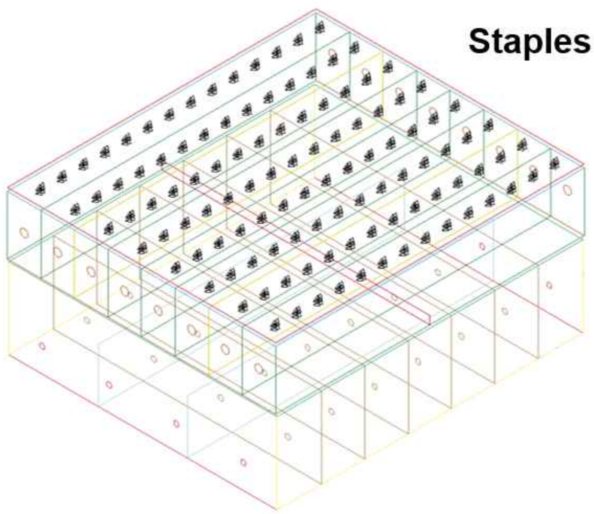



Figure 12 Staples modeling
(NO96 reinforcement)

## 303. Material properties

1. General

(1) The designer is responsible for getting the material properties used in the structural analysis. The purposes of this section is to provide the guidance to draw material properties.

(2) To evaluate the material mechanical properties including a dynamic effect due to the sloshing loads and the cryogenic environment of LNG (approximately -163°C) is the responsibility of the designer.

(3) Material properties can be obtained through the material supplier, the promulgated experimental data or the material experiments. They should be sought in accordance with **Ch 3, Sec 3, 303, 2**, **3** and **4**.

2. Polyurethane foam

(1) The layered foam cargo containment system shall be modeled as a linear isotropic elastic material, it is necessary to enter the following properties. The polyurethane foam can be modeled to have a perpendicular anisotropy, if necessary.

(a) Density ($kg/m^3$)

(b) Young's Modulus in three direction ($MPa$)

(c) Poisson's ratio

(d) Shear modulus ($MPa$)

(2) The analysis shall include the change of material properties with the ambient temperature and a cryogenic temperature.

3. Plywood

(1) The plywood is a composite material consisting of several layers of wood. The behavior of the plywood should be modeled to have a perpendicular anisotropy, the following properties should be entered.

(a) Density ($kg/m^3$)

(b) Young's Modulus in three direction ($MPa$)

(c) Poisson's ratio

(d) Shear modulus ($MPa$)

(2) Analysis shall include the change of material properties with ambient temperature and a cryogenic temperature.

4. Mastic

(1) The mastic to connect the hull structure to the cargo containment system shall be modeled using a linear isotropic elastic material. The following properties is needed to be entered.

(a) Density ($kg/m^3$)

(b) Young's Modulus ($MPa$)

(c) Poisson's ratio

(2) Analysis shall include the change of material properties with ambient temperature and a cryogenic temperature.

## 304. Loading and boundary conditions

1. MarkⅢ and MarkⅢ flex

(1) Application location of static load is to be determined with reference to the model test. In general, the 3x3 pressure sensor is arranged in a panel with respect to the surface area of 1.5$m$ x1.5$m$ in the model test. The static load is applied on the top plywood of MarkⅢ and MarkⅢ flex. The static load, shown in **Figure 13**, **Figure 14** and **Figure 15**, is to be taken as:

$$P_{static} = P_{unit}$$

(3) The boundary conditions described in this section are to be applied to the structural model of MarkⅢ and MarkⅢ flex, as shown in **Table 1**, **Figure 16** and **Figure 17**.

(4) When setting up a contact method of components, the method should reflect realistic condition as much as possible.

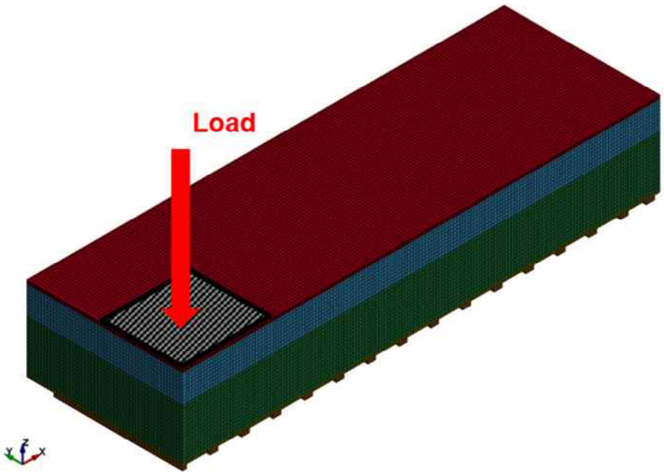



Figure 13 Loading condition of 1x1 sensor array
in MarkⅢ and MarkⅢ flex

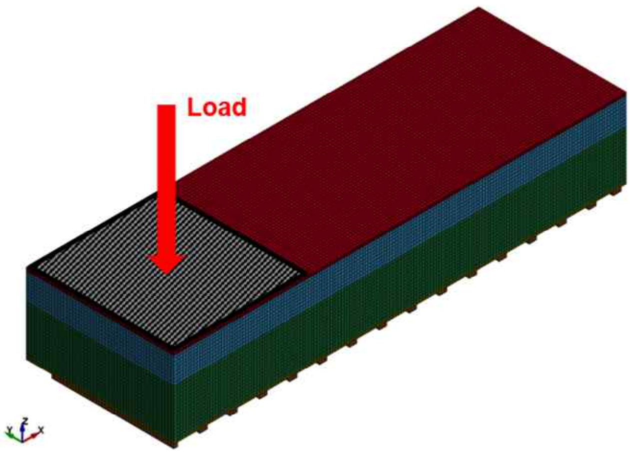



Figure 14 Loading condition of 2x2 sensor array
in MarkⅢ and MarkⅢ flex

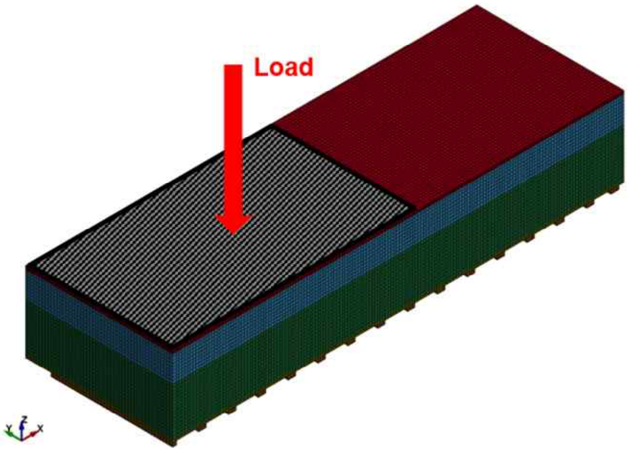



Figure 15 Loading condition of 3x3 sensor array
in MarkⅢ and MarkⅢ flex

Table 1 Boundary conditions in MarkⅢ and MarkⅢ flex

| Position | Displacement | | | Rotation | | |
|---|---|---|---|---|---|---|
| | $\delta_x$ | $\delta_y$ | $\delta_z$ | $\theta_x$ | $\theta_y$ | $\theta_z$ |
| Mastic nodes in contact with hull | 1 | 1 | 1 | 0 | 0 | 0 |
| x-symmetry plane | 1 | 0 | 0 | 0 | 1 | 1 |
| y-symmetry plane | 0 | 1 | 0 | 1 | 0 | 1 |
| (Notes)<br>1 : Constrained<br>0 : Free | | | | | | |

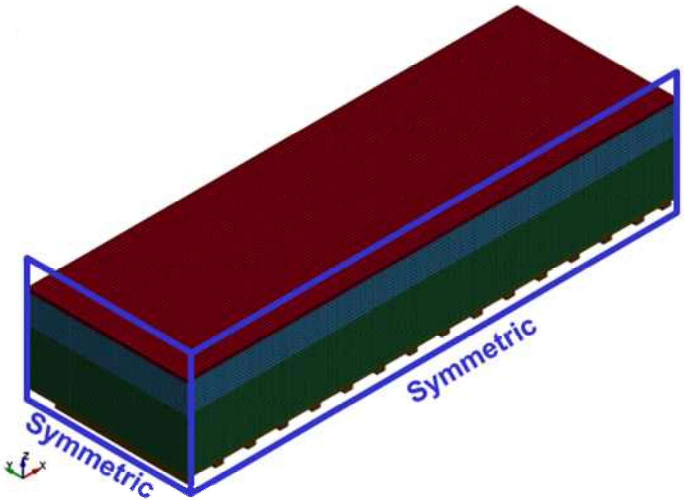



Figure 16 The symmetry planes in MarkⅢ and MarkⅢ flex

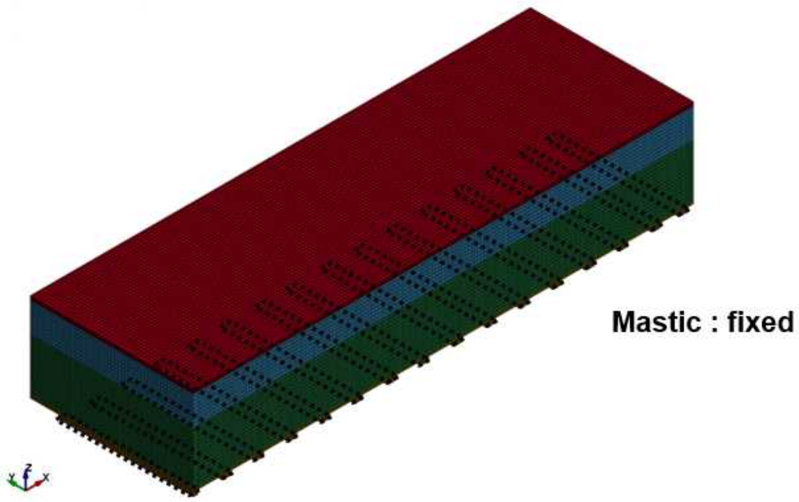



Figure 17 The boundary conditions of mastic in MarkⅢ and MarkⅢ flex

2. NO96 and NO96 reinforcement

(1) Application location of static load is to be determined with reference to the model test. In general, the 3x3 pressure sensor is arranged in a panel with respect to the surface area of 1.5$m$ x1.5$m$ in the model test. Because it is assumed that one flat panel is independent, loading conditions of 2x2 sensor array and 3x3 sensor array have the same results when the same load is applied. The static load is applied on the top plywood of NO96 and NO96 reinforcement. The static load, shown in **Figure 18** and **Figure 19**, is to be taken as:

$$P_{static} = P_{unit}$$

(3) The boundary conditions described in this section are to be applied to the structural model of NO96 and NO96 reinforcement, as shown in **Table 2**, **Figure 20** and **Figure 21**.

(4) When setting up a contact method of components, the method should reflect realistic condition as much as possible.

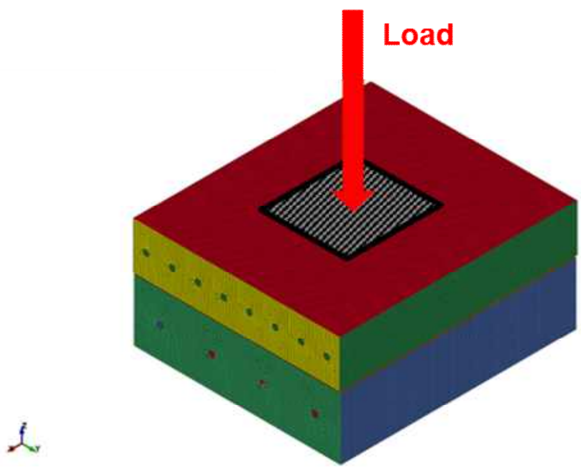



Figure 18 Loading condition of 1x1 sensor array in NO96 and NO96 reinforcement

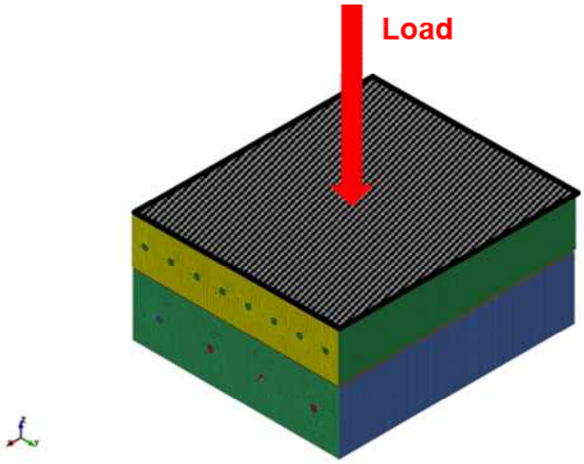



Figure 19 Loading condition of 2x2 or 3x3 sensor array in NO96 and NO96 reinforcement

Table 2 Boundary conditions in the box type containment system

| Position | Displacement | | | Rotation | | |
|---|---|---|---|---|---|---|
| | $\delta_x$ | $\delta_y$ | $\delta_z$ | $\theta_x$ | $\theta_y$ | $\theta_z$ |
| Mastic nodes in contact with hull | 0 | 0 | 1 | 0 | 0 | 0 |
| 4 corner nodes in the secondary box | 1 | 1 | 1 | 0 | 0 | 0 |
| 4 tied nodes in the primary box and secondary box | 1 | 1 | 1 | 0 | 0 | 0 |
| (Notes)<br>1 : Constrained<br>0 : Free | | | | | | |

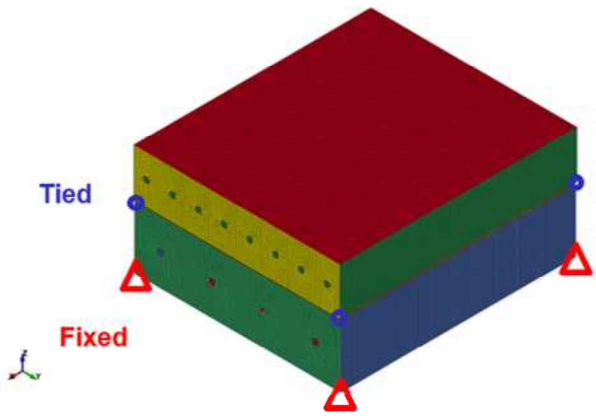



Figure 20 The fixed and tied boundary conditions in NO96 and NO96 reinforcement

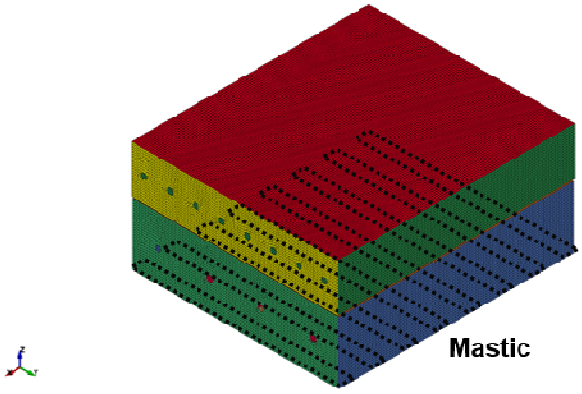



Figure 21 The boundary conditions of mastic in NO96 and NO96 reinforcement

### 305. Dynamic amplification factor

1. Dynamic amplication factor(DAF) is the ratio of the dynamic response to the static response for unit load with particular rise time. Therefore DAF is a function of the ratio between the rise time and the natural period for characteristic of the cargo containment system being considered.
2. DAF curves depend on the structural models and loading conditions of 1x1, 2x2 or 3x3 sensor array, so the analyses should be conducted respectively. DAF curves may differ each component of the cargo containment system and for different failure types.
3. In order to obtain the robust DAF curve for the target cargo containment system, sufficient number of dynamic analyses should be conducted for various load cases. Peak is the rise time divided by the natural period, provided that DAF reaches maximum value. The examples of the sloshing loads for the derivation of DAF are shown in **Figure 22**.

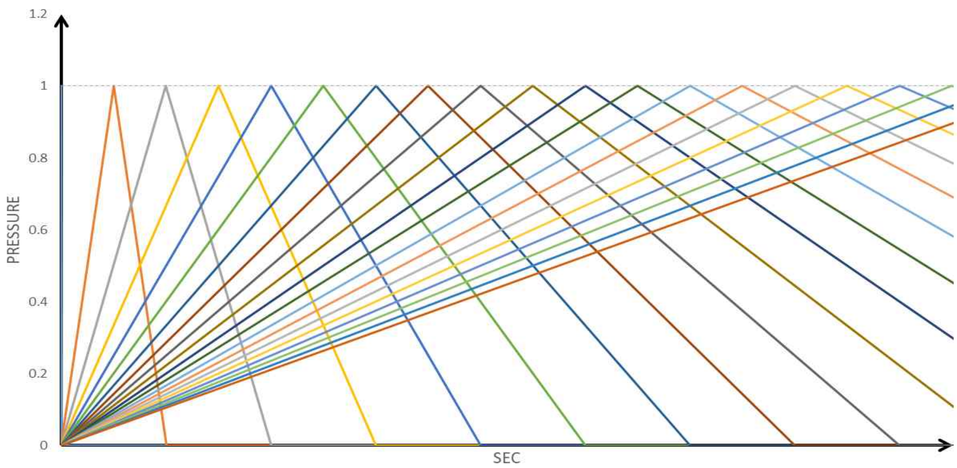



**Figure 22 Sloshing load profiles for derivation of DAFs**

4. Typical failure types of MarkⅢ and MarkⅢ flex under the sloshing loads are as follows. Examples of locations where major damage occurs in cargo containment system are shown in **Figure 23**, **Figure 24** and **Figure 25**.
   (1) Crushing of reinforced polyurethane foam
   (2) Plywood distortion
   (3) Bending failure of back plywood
   (4) Shear failure of plywood at the connection between mastic and back plywood
   (5) Crushing of reinforced polyurethane foam at the connection between mastic and lower plywood

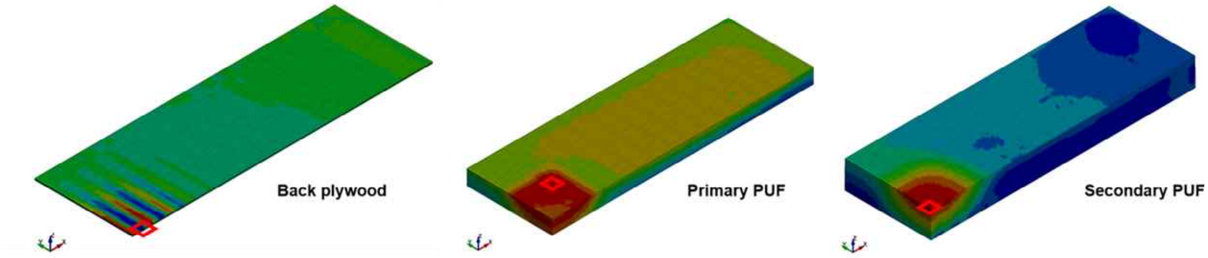



Figure 23 Typical damage location of MarkⅢ and MarkⅢ flex (1x1 array)

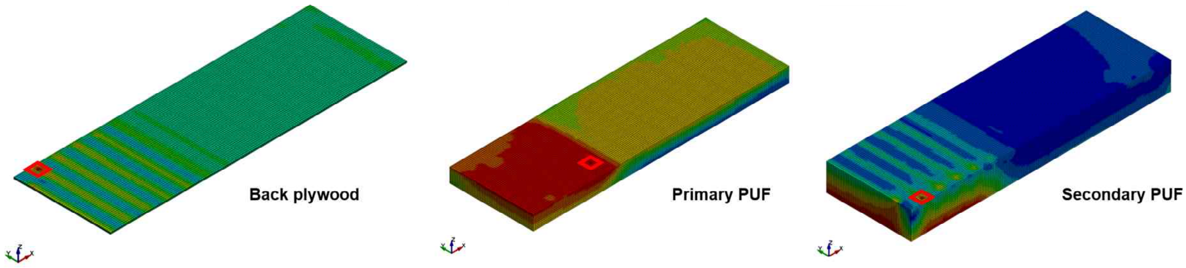



Figure 24 Typical damage location of MarkⅢ and MarkⅢ flex (2x2 array)

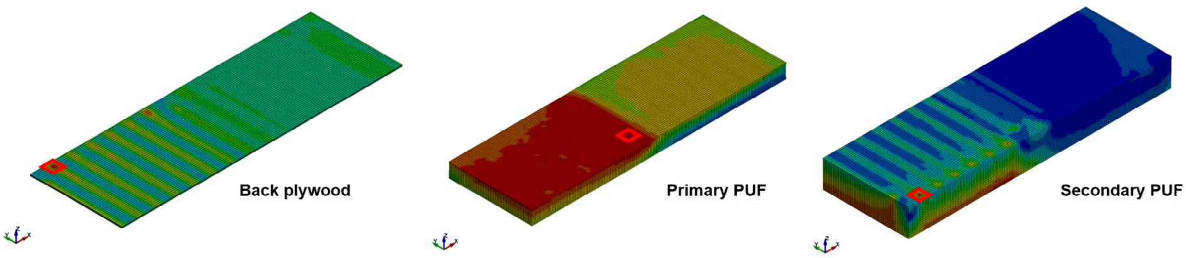



Figure 25 Typical damage location of MarkⅢ and MarkⅢ flex (3x3 array)

5. Typical failure types of NO96 and NO96 reinforcement under the sloshing loads are as follows. Examples of locations where major damage occurs in cargo containment system are shown in **Figure 26** and **Figure 27**.
   (1) Shear failure of the cover plywood
   (2) Bending failure of the cover plywood
   (3) Crushing of internal bulkheads of the primary insulation box at bulkhead intersections.
   (4) Crushing of internal bulkheads of the secondary insulation box at bulkhead intersections.
   (5) Buckling of internal and external bulkheads of the primary insulation box.
   (6) Buckling of internal and external bulkheads of the secondary insulation box.

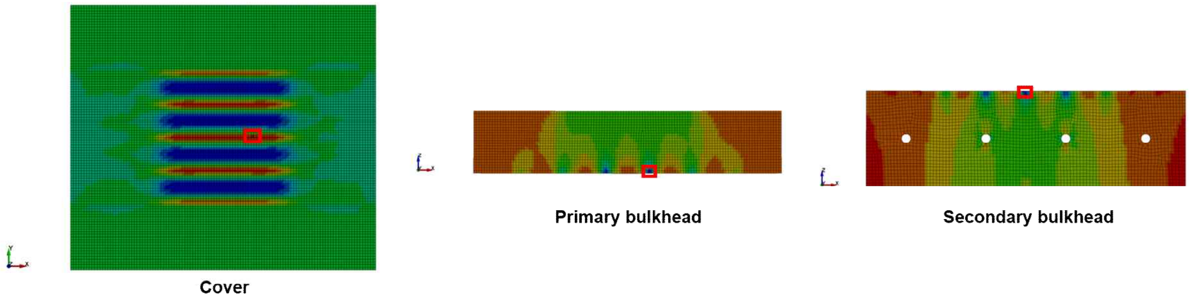



Figure 26 Typical damage location of NO96 and NO96 reinforcement (1x1 array)

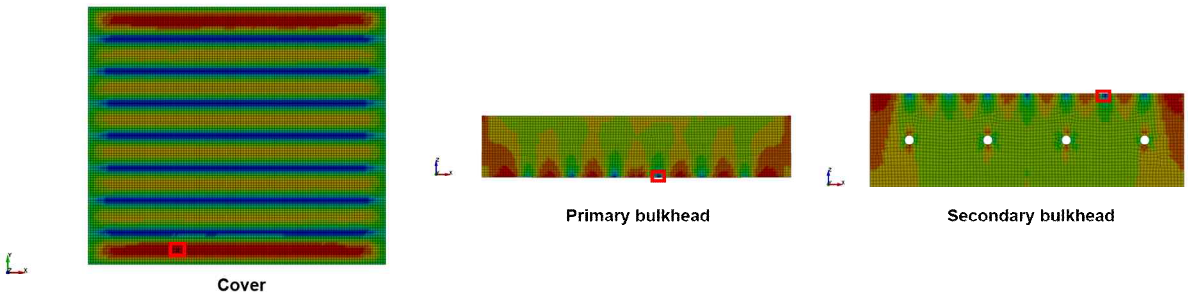



Figure 27 Typical damage location of NO96 and NO96 reinforcement (2x2 or 3x3 array)

6. Reference for DAFs

(1) Designer is responsible for deriving the DAF and the purpose of reference DAF is to provide the guidance.

(2) DAF for the typical layered foam type or box type cargo containment system may be taken as follows. The reference DAF is to be taken as:

$$DAF = \frac{(DAF_{\max} - 1)}{Peak}\left(\frac{t_{rise}}{T_{natural}}\right) + 1 \qquad \text{for} \quad 0 \le \frac{t_{rise}}{T_{natural}} < Peak$$

$$DAF = \frac{(1 - DAF_{\max})}{(1 - Peak)}\left(\frac{t_{rise}}{T_{natural}}\right) + \frac{(DAF_{\max} - Peak)}{(1 - Peak)} \qquad \text{for} \quad Peak \le \frac{t_{rise}}{T_{natural}} < 1$$

$$DAF = 1 \qquad \text{for} \quad 1 \le \frac{t_{rise}}{T_{natural}}$$

where,

$t_{rise}$ : Rise time $(\sec)$.

$T_{natural}$ : Natural period $(\sec)$.

$DAF_{\max}$ : Maximum DAF to be obtained from **Table 3**.

$Peak$ : Rise time divided by the natural period, provided that DAF reaches the maximum value to be obtained from **Table 3**.

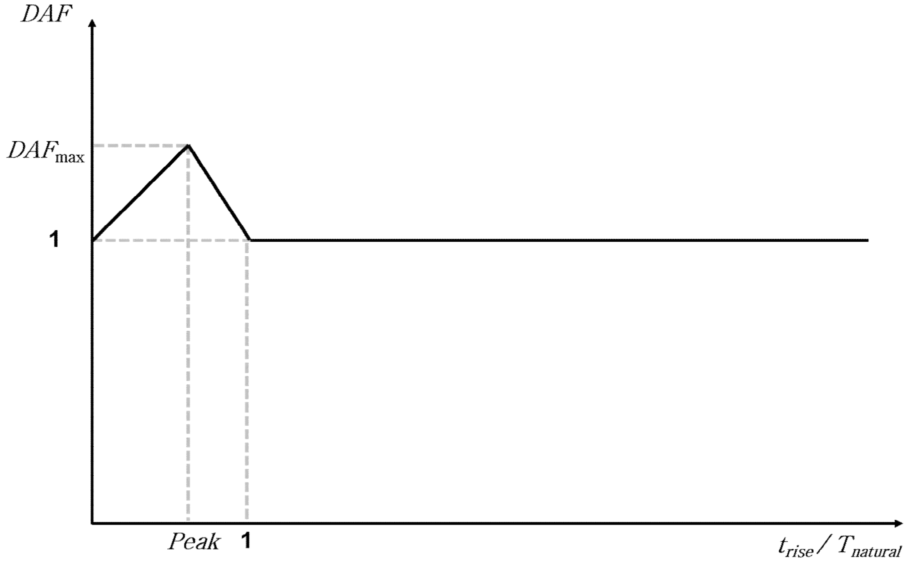



Figure 28 Distribution of DAF

Table 3 Maximum DAFs and peaks

| Type | Array | Part | Failure | Max DAF | Peak |
|---|---|---|---|---|---|
| Mark Ⅲ | 1x1 | Primary RPUF | Crushing | 1.0 | 0.5 |
| | | Secondary RPUF | Crushing | 1.3 | 0.4 |
| | | Back plywood | Bending | 1.5 | 0.3 |
| | 2x2 | Primary RPUF | Crushing | 1.1 | 0.5 |
| | | Secondary RPUF | Crushing | 1.6 | 0.3 |
| | | Back plywood | Bending | 2.0 | 0.3 |
| | 3x3 | Primary RPUF | Crushing | 1.1 | 0.5 |
| | | Secondary RPUF | Crushing | 1.7 | 0.3 |
| | | Back plywood | Bending | 2.0 | 0.3 |
| Mark Ⅲ flex | 1x1 | Primary RPUF | Crushing | 1.0 | 0.5 |
| | | Secondary RPUF | Crushing | 1.2 | 0.4 |
| | | Back plywood | Bending | 1.7 | 0.3 |
| | 2x2 | Primary RPUF | Crushing | 1.1 | 0.5 |
| | | Secondary RPUF | Crushing | 1.1 | 0.4 |
| | | Back plywood | Bending | 1.9 | 0.3 |
| | 3x3 | Primary RPUF | Crushing | 1.1 | 0.5 |
| | | Secondary RPUF | Crushing | 1.1 | 0.4 |
| | | Back plywood | Bending | 1.9 | 0.3 |
| NO96 | 1x1 | Cover | Bending | 1.2 | 0.1 |
| | | Primary BHD | Crushing | 1.5 | 0.1 |
| | | Secondary BHD | Crushing | 1.5 | 0.1 |
| | 2x2 | Cover | Bending | 1.1 | 0.1 |
| | | Primary BHD | Crushing | 1.4 | 0.1 |
| | | Secondary BHD | Crushing | 1.9 | 0.1 |
| | 3x3 | Cover | Bending | 1.1 | 0.1 |
| | | Primary BHD | Crushing | 1.4 | 0.1 |
| | | Secondary BHD | Crushing | 1.9 | 0.1 |
| NO96 reinforcement | 1x1 | Cover | Bending | 1.3 | 0.2 |
| | | Primary BHD | Crushing | 1.4 | 0.2 |
| | | Secondary BHD | Crushing | 1.4 | 0.2 |
| | 2x2 | Cover | Bending | 1.3 | 0.2 |
| | | Primary BHD | Crushing | 1.6 | 0.2 |
| | | Secondary BHD | Crushing | 1.6 | 0.1 |
| | 3x3 | Cover | Bending | 1.3 | 0.2 |
| | | Primary BHD | Crushing | 1.6 | 0.2 |
| | | Secondary BHD | Crushing | 1.6 | 0.1 |

## Section 4 Methods of assessment

### 401. General

1. The comparative method refer to a method to evaluate the target ship by selecting the reference ship with a proven service history among the LNG membrane ships.
2. The comparative method is applied when the strength of cargo containment system of the reference ship is same with that of the target ship.
3. The reinforced comparative method is one of the comparative method and is applied when the structural strength of cargo containment system of the target ship increases from that of the reference ship.
4. If the approved design for the reference ship is not present, the absolute method should be applied.

### 402. Application conditions

1. In order to apply the comparative method or the reinforced comparative method, the following should be proved.
   (1) The cargo containment system of the reference ship and that of the target ship should be substantially equal.
   (2) The hull structure supporting the cargo containment system should be quite similar.
   (3) The verified navigation record should exist for the cargo containment system of the reference ship or that of similar ship.
2. If it does not meet the above criteria, the designed cargo containment system is determined to be new design.

### 403. Selection of target ship

1. When the reference ship meet the following conditions, it is recognized to have the proved operating record.
   (1) The important damage or repetitive damage at cargo containment system should not occur. All the environmental conditions for each filling level should be considered.
   (2) Proven service history can be approved for each load height. For example, a good performance for the high filling level can be approved, independent of the good performance for the low filling level.
2. In order to establish a proven performance record for the new design of cargo containment system, the information from all sail should be recorded. The minimum required information should include the date, the filling level, the sea state, the ship speed and the wave incident angle. This information is used to evaluate the expected sloshing loads in navigation and compared to the design sloshing load. If the sloshing load during the voyage is similar to the design sloshing load and the cargo containment system is operating as predicted, the Society can approve that the designed cargo containment system have been proven.

### 404. Comparative method

1. The comparative method is to select the membrane LNG ship with the good service history as the reference ship and to evaluate the design of LNG cargo containment system similar to the reference ship.
2. The design sloshing load of the reference ship is obtained and the design sloshing load of target ship is obtained in the same way. If the design sloshing load of the target ship is lower than that of the reference ship, the design is approved. When it fails to meet this condition, the absolute

method should be used.

3. In order to proceed the comparative method, only the design sloshing load of the reference ship and that of target ship is needed. The design sloshing load is obtained through the CFD analysis or the model test, the structural analysis is not required.

4. The design sloshing loads of the reference ship and that of the target ship should be obtained in the same manner. The model test should proceed following the same procedure with the same model test facility.

5. If the design sloshing load of the target ship is lower than that of the reference ship as shown in **Figure 29**, the design can be approved. Refer to **Ch 3, Sec 5, 502, 1**.

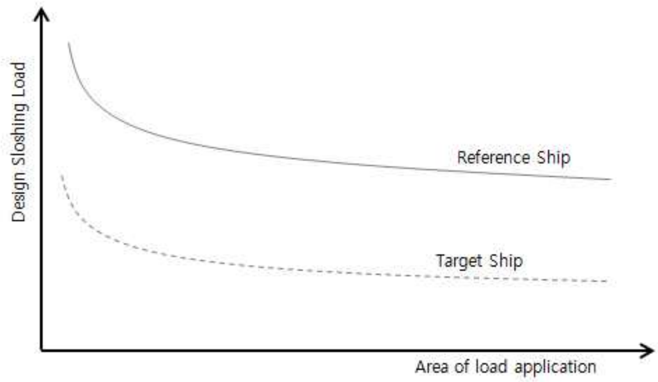



**Figure 29 Schematic drawing of comparative method**

### 405. Reinforced comparative method

1. The reinforced comparative method is one of comparative method and applied to the case where the structural strength of cargo containment system of the target ship increases from that of the reference ship. If the standard box of the box type cargo containment system (NO96) is improved by the enhanced box or the super-reinforced box, the reinforced comparative method can be applied.

2. The design sloshing load and the structural strength of cargo containment system for the reference ship and the target ship should be obtained. If the ratio of the structural strength of cargo containment system divided by the design sloshing load for the target ship is lower than that of the reference ship, the design of cargo containment system of the target ship can be approved. When it does not meet the acceptance criteria, the absolute method should be used.

3. For the reinforced comparative method, the design sloshing load and the strength of cargo containment system for the reference ship and the target ship should be obtained. The design sloshing loads are usually obtained through the model test. It should comply with the same test procedure with the same model facility for the target ship and the reference ship.

4. The strength change of cargo containment system are generally obtained by using the finite element analysis or the model test or both method at the same time. The critical failure mode of cargo containment system between the reference ship and the target ship should be assessed and documented. Although the structural change of the target cargo containment system is to change the critical failure mode, it should be demonstrated that its performance has not been further degenerated by the additional strength increment.

5. If the ratio of strength of cargo containment system to the design sloshing load for the target ship is lower than that for the reference ship, the cargo containment system of the target ship can be approved. **Figure 30** shows this conceptually. Refer to **Ch 3, Sec 5, 503, 1**.

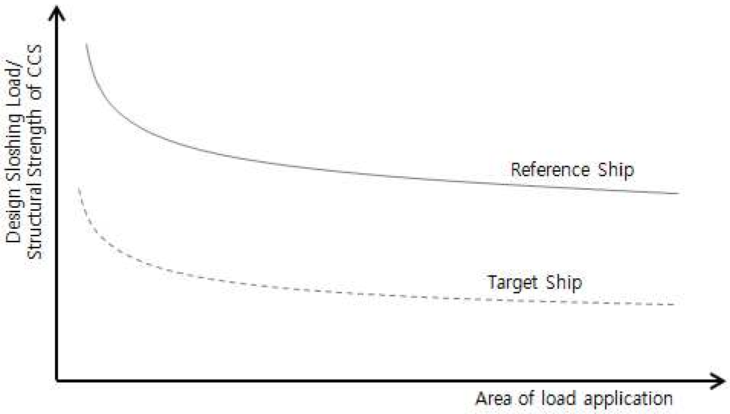



Figure 30 Schematic drawing of reinforced comparative method

### 406. Absolute method

1. If the main design factor (size, arrangement and ratio) of cargo containment system of the target ship change significantly as compared to the that of the reference ship, the comparative and reinforced comparative method cannot be applicable. This design as determined as new design is assessed through the absolute method.
2. When it satisfies the acceptance criteria, the design can be approved, otherwise, the design should be started from the beginning.
3. **Figure 31** shows an example of comparing the strength of cargo containment system to the sloshing load of cargo containment system conceptually. Refer to **Ch 3, Sec 5, 504, 1**.

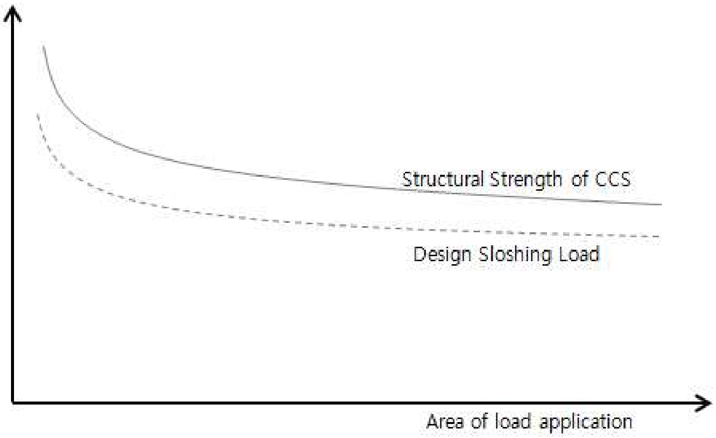



Figure 31 Comparison between structural strength of cargo containment system and sloshing load

# Section 5 Acceptance criteria

## 501. General

1. The designer is responsible for deriving the acceptance criteria and the purpose of this section is to provide the guidance to derive the acceptance criteria.
2. A typical failure type of layered foam type and box type cargo containment system under the sloshing loads is given in **Ch 3, Sec 3, 305, 4** and **5**.
3. The damage of cargo containment system may be evaluated from the point of yield/fracture, buckling and service limit. The damage type is related with material properties such as the relationship between stress and strain, yield strength and tensile strength.
4. For the viewpoint of yield/fracture and damage, the maximum bending stress of plywood is evaluated. The von-Mises stress of mastic and compressive stress of polyurethane foam are evaluated for the assessment of structural strength.
5. If the sloshing load exceeds the critical buckling load from the viewpoint of assessment of buckling failure, the cargo containment system is deemed to be broken.
6. Related to the service limit, the polyurethane foam, the plywood and the mastic has the allowable maximum displacement. If this limit is exceeded, the system becomes unstable and results in failure finally.

## 502. Comparative method

1. In the case that the design sloshing load of the target ship is less than that of the reference ship, the cargo containment system of the target ship may be approved.

$$P_{target} < P_{reference}$$

where,

$P_{target}$ : Design sloshing load of target ship.

$P_{reference}$ : Design sloshing load of reference ship.

2. This criteria should be satisfied for the area/sloshing loads as shown in **Figure 29**.

## 503. Reinforced comparative method

1. If the ratio of structural strength of cargo containment system to the design sloshing load for the target ship is less than that of the target ship, the cargo containment system of the target ship can be approved.

$$\frac{P_{target}}{C_{target}} < \frac{P_{reference}}{C_{reference}}$$

where,

$P_{target}$ : Design sloshing load of target ship.

$P_{reference}$ : Design sloshing load of reference ship.

$C_{target}$ : Structural strength for cargo containment system of target ship.

$C_{reference}$ : Structural strength for cargo containment system of reference ship.

2. This criteria should be satisfied for the area/sloshing loads as shown in **Figure 30**.

### 504. Absolute method

1. In the case that the ratio of design sloshing load to the structural strength of cargo containment system is less than the utilization factor selected appropriately, the cargo containment system can be approved. This criteria should be satisfied for the area/sloshing loads as shown in **Figure 31**.

$$\frac{P}{C} < UF$$

where,

$P$ : Design sloshing pressure. In case of Level 1 evaluation, it is interacted load referred to **Ch 2, Sec 3, 305**.

$C$ : Structural capacity of cargo containment system and calculated by the structural analysis. In case of Level 1 evaluation, it is to be taken as:

$$C = \min\left(\frac{\sigma_{y,i}}{\sigma_{unit,i}}\right)$$

where,

$\sigma_{unit}$ : Maximum stress which is obtained by the static analysis while applying the unit load.

$\sigma_y$ : Allowable stress , which is related with failure mode, which should be based on the acknowledged experimental data for each material and the standard recognized by the Society.

$i$ : One of failure modes which should be considered.

$UF$ : Utilization factor, the value less than 0.60 is generally used. 0.60 is determined by the approximation of 1/(1.1×1.5). 1.5 is commonly used parameter for the dynamic load and 1.1 is a normally used factor for strength. Application of the utilization factor will vary depending on whether or not the cargo containment system is verified design. For the new cargo containment system, the utilization factor less than 0.5 is generally used.

2. Because of the characteristics of box type cargo containment system, the buckling can be occur. The buckling analysis is carried out with the finite element model in order to evaluate the strength of the box type cargo containment system.

(1) Assuming that the bottom part of the bulkhead is fully supported, the elastic buckling allowable stress is to be taken as:

$$\sigma_{buckling} = K\frac{\pi^2 E_{buckling}}{12(1-\nu^2)}\left(\frac{t_{BHD}}{b_{BHD}}\right)^2$$

where,

$\sigma_{buckling}$ : Elastic buckling allowable stress of plate limit state.

$K$ : Buckling coefficient K.

$$K = \left(\frac{h_{BHD}}{b_{BHD}} + \frac{b_{BHD}}{h_{BHD}}\right)^2 \quad \text{for } \frac{h_{BHD}}{b_{BHD}} < 1$$

$$K = 4 \quad \text{for } \frac{h_{BHD}}{b_{BHD}} \geq 1$$

$E_{buckling}$ : Young's modulus of the bulkhead in the direction of the sloshing load.

$\nu$ : Poisson's ratio.

$h_{BHD}$ : Height of bulkheads.

$b_{BHD}$ : Breadth of bulkheads.

$t_{BHD}$ : Thickness of bulkheads.

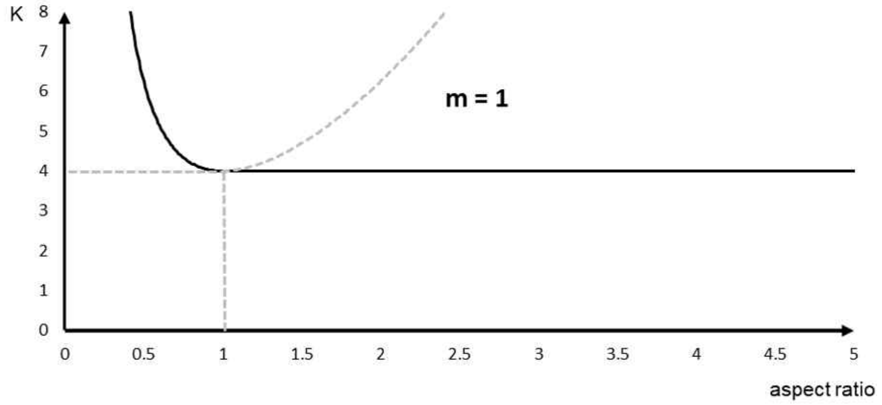



Figure 32 Buckling coefficient K

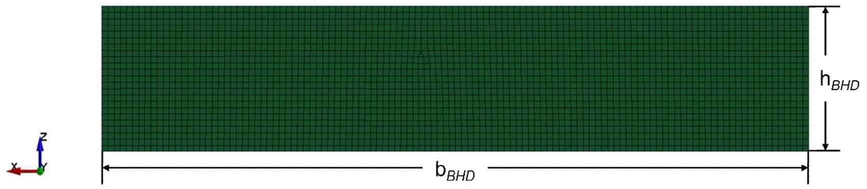



Figure 33 Height and breadth of the primary bulkheads

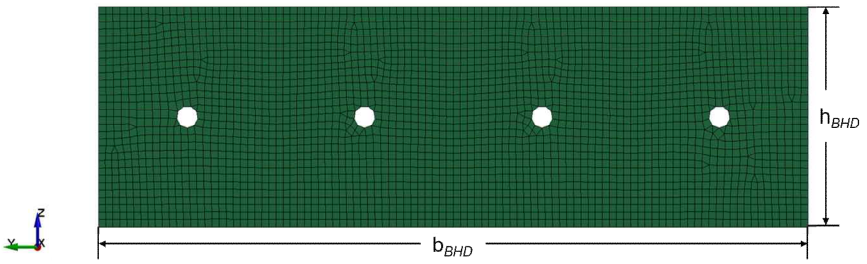



Figure 34 Height and breadth of the secondary bulkheads

(2) Buckling criteria : By performing the buckling analysis for the box type cargo containment system, the elastic buckling allowable stress should be obtained. The mean stress in internal and external bulkheads of the primary and secondary insulation box should satisfy the following conditions.

$$\sigma_{mean} \le \sigma_{c,\,buckling}$$

where,

$\sigma_{c,\,buckling}$ : Elastic buckling allowable stress which represents $f_{sr}\sigma_{buckling}$.

$\sigma_{buckling}$ : Elastic buckling allowable stress of plate limit state.

$f_{sr}$ : Strength reduction factor is to be taken as between 0.9 and 1.0.

# Section 6 Advanced dynamic analysis

## 601. General

1. The advanced analysis should be conducted when the results of analysis considering the static load do not satisfy the criteria of either reinforced comparative or absolute method. The advanced analysis is defined as analyses performed to obtain more accurate results than that of the analysis considering the static load.

2. The dynamic load profile to be applied to the structure should correspond to the interacted load applied at Level 1 evaluation. For this case, the rise time of the load profile should be considered as conservative as possible considering the natural period of the structure.

3. The advanced dynamic analysis of the containment system may consider fluid-structure interaction between LNG and the cargo containment system. The sloshing of the LNG cargo containment system occurs by the complicated relation of the fluid and structure. The fluid-structure interaction analysis can consider the dynamics of the fluid and the deformation of the structure at the same time.

4. The viscoelastic effect may be also considered for polyurethane foam material in the advanced analysis. As the sloshing load is a short duration impact load, the rate effects can be included for the viscoelastic materials for evaluating the strength of the cargo containment system. Also non-linearity of material property and strain rate can be considered. However the analysis becomes more complicated and therefore, the assumptions and parameters of the analysis should be applied accurately.

5. The procedures and acceptance criteria of the advanced dynamic analysis should be submitted to the Society and to be approved by the Society.

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# Guidance for Strength Assessment of Membrane-Type LNG Tanks under Sloshing Loads

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