2015

Guidance for Assessment of Sloshing Load and Structural Strength of Cargo Containment System

GC-17-E

KR

CONTENTS

I. GENERAL

1. Application

(1) This guidance deals with the sloshing load occurred by the liquid in cargo tank and 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 LNG carrier.
(2) In addition, this guidance applies to the calculation procedure of the sloshing load for the ship with cargo tank beyond the application range of 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.
(3) This guidance applies the evaluation procedure for the sloshing load and the structural strength of cargo containment system for marine LNG storage and regasification structures using the membrane technology.
(4) Requirement of this guidance shall apply in addition to the other requirement of the Rules.

2. Definitions

The definitions of terms, except otherwise specified, are to be in accordance with the Rules.
(1) "Sloshing" means the motion of the free fluid surface in LNG tank.
(2) "Potential flow" means the flow of idealized fluid without the viscosity effect.
(3) "Critical wave domain" means the wave range which generates the lifetime maximum sloshing loads.
(4) "Panel pressure" means the averaged pressure over each measured pressure signal of the sensor stack.
(5) "Critical sea state" means the sea state that generate the lifetime maximum sloshing loads.
(6) "Wave spectrum" means the graph showing the distribution of the wave energy over wave frequency.
(7) “Diffraction-Radiation Method” means the method to analyze the fluid motion phenomenon with the theory of diffraction-radiation.
(8) "Roll damping model" means the model including the hull viscous roll damping.
(9) "Triangular impulse pressure" means the sloshing loads which are idealized to have pressure shape over time in triangle shape.
(10) “Rising time” means the time during when triangular impact pressure increases from the lowest to the highest.
(11) “Drop time” means the time during when triangular impact pressure decreases from the highest to the lowest.
(12) “Skewness” means the ratio obtained by dividing the drop time with the rising time of triangular impulse pressure.
(13) "CFD" means the numerical analysis for fluid motion using computer program.
(14) “Sloshing model test” means the experiments to measure(estimate) the sloshing load by the small scaled cargo containment system with tank motion.
(15) "Pressure sensor" means the sensor attached to the tank model and used to measure the sloshing pressure.
(16) “Design sloshing load” means the design pressure used for the structural analysis of cargo containment system and obtained from the model test.
(17) “Comparative method” is 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.
(18) "Reinforced comparative method" is one method of comparative method and to consider the strength of cargo containment system.
(19) “Absolute method” is 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.
(20) “Membrane” means the film form substance used in the LNG cargo containment system.
(21) "Cargo containment system" is 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.
(22) "Primary barrier" means 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.

(23) "Secondary barrier" has 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.
(24) "Mark III" means the layered foam type cargo containment system with membrane developed by GTT which use STS 304L as the primary barrier.
(25) "CS 1" means the layered foam type cargo containment system with membrane developed by GTT , using invar as the primary barrier.
(26) "Polyurethane foam" means the filling material for the purpose of heat insulation at layered foam type cargo containment system(Mark III).
(27) "Mastic" means the material in contact with the hull directly in cargo containment system.
(28) "Upper plywood" means the plywood below the primary barrier and in contact with polyurethane foam at the layered foam type cargo containment system(Mark III).
(29) "Bottom plywood" means the plywood between insulation polyurethane foam and mastic at the layered foam cargo containment system(Mark III).
(30 "NO96" means the cargo containment system developed by GTT which is the box type membrane cargo containment system.
(31) "Primary insulation box" means the box between the primary and secondary barriers at the box type cargo containment system(NO 96).
(32) “Secondary insulation box” means the box in contact with hull through the mastic at the box type cargo containment system(NO 96).
(33) "Acceptance criteria" means the maximum stress, the maximum strain, the buckling and the service limit that cargo containment system can withstand without problems.
(34) "Strength of cargo containment system" means the maximum strength that cargo containment system withstand without problems.

3. General

The ship motion generates the motion of cargo tank and causes the sloshing phenomenon. Sloshing means the relative motion of fluid with the free surface within the cargo tanks, 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.
Sloshing in the real 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 due to the gas and the primary barrier.
Sloshing results in the high impact load at the inner structure and the support of cargo hold. Particularly the membrane type tank with the flat and the edge zone generates the high pressure by the sloshing impact. Structural safety issue of the LNG cargo containment system due to the sloshing pressure has become the important design factor. Various approaches have been made to predict the sloshing pressure to solve the problem caused by sloshing.
The sloshing load is generally estimated using the model test or sloshing simulations by using the computational fluid dynamics software.
During the model test, the model tank with partially filled with water is excited by the irregular motion obtained by the selection of sea condition and the RAO of tank. At this time, the pressure generated in the tank wall is measured.
Measured data is used to determine the design sloshing loads. The sloshing load measured is subject to the process to extract the design sloshing loads for finite element analysis. Once the design sloshing load is determined, the structure evaluation through the structural analysis is performed as needed.
As compared with the reference ship with the data of model test, if there is no significant design change of the ship and tank shape, the sloshing simulation is to be performed.
By performing the sloshing simulation for the reference design and the new design, the relative increase or the decrease of sloshing load is to be found. Critical wave conditions which can generate the lifetime maximum sloshing load are selected based on the amplitude of tank motion and the motion period.
After the critical sloshing wave condition is selected, the sloshing simulation is performed by using the validated computational fluid dynamics software.
After determining the design sloshing pressure, the structural analysis is performed in two steps. Step 1 is the static structural analysis to evaluate the safety of the cargo containment system by applying the maximum design sloshing load as the static load.

If the result of step 1 does not meet the acceptance criteria, step 2 should be performed. Step 2 process is the dynamic structural analysis to determine whether the result meets the acceptance criteria by applying the design sloshing load which has the triangular shape. If the analysis results meet the acceptance criteria, the design can be approved, otherwise the design shall be proceeded from the beginning.
The selection process of the design sloshing load and the structural analysis process are shown in Figure 1.
The structural strength assessment of cargo containment system is performed through the comparative method, the reinforced comparative method and the absolute method. The comparative method follows the dashed line, the reinforced comparative method proceeds following the long dashed line and the absolute method is performed by following the solid line.

(1) Comparative Method

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.
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 th reference ship, the design is approved. When it fails to meet this condition, the absolute method should be used.
The main design factor(size, arrangement and ratio) of the LNG cargo containment system of the target ship changes from those of the reference ship, the comparative method cannot be applied. In this case, the absolute method should be applied.

(2) Reinforced Comparative Method

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(NO 96) is improved by the enhanced box or the super-reinforced box, the reinforced comparative method can be applied.
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.
The dominant design parameter(size, arrangement and ratio) of LNG cargo containment system for the target ship changes significantly from those of the reference ship, the reinforced comparative method can not be applied. In this case, the absolute method should be applied

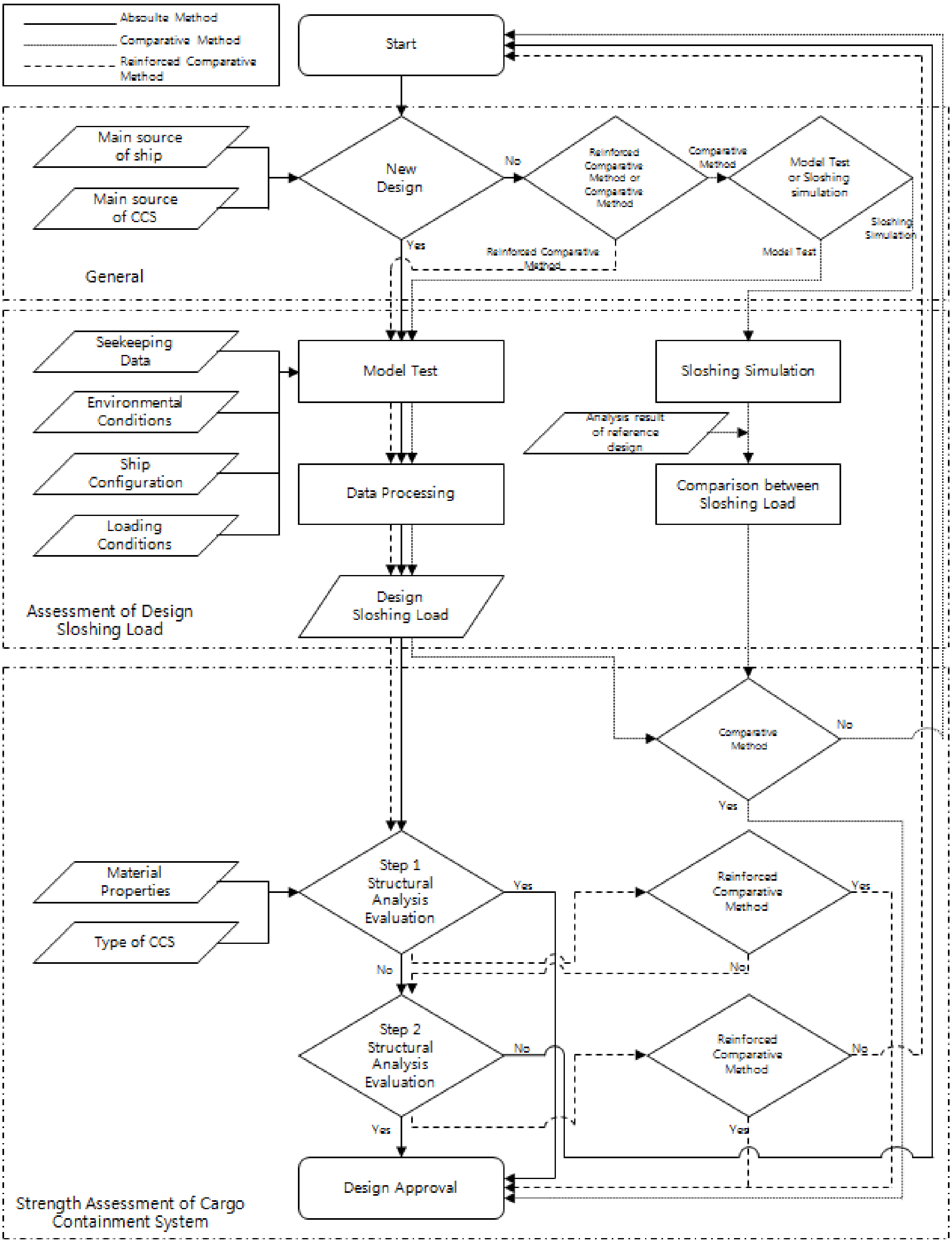

Figure 1 Flowchart of assessment of sloshing load and strength of cargo containment system

(3) Absolute Method

The absolute method is conducted through a two-step process as shown in Figure 2. The step 1 is to apply the maximum design sloshing load as the static load and to evaluate the safety. When the acceptance criteria is satisfied in the step 1, the design can be approved. If it fails to meet the acceptance criteria in step 1, the step 2 should be performed. It performs the dynamic nonlinear analysis by applying the design sloshing loads of triangular form and determine whether the analysis result meets the acceptance criteria. When it satisfies the acceptance criteria, the design can be approved, otherwise, the design should be started from the beginning.

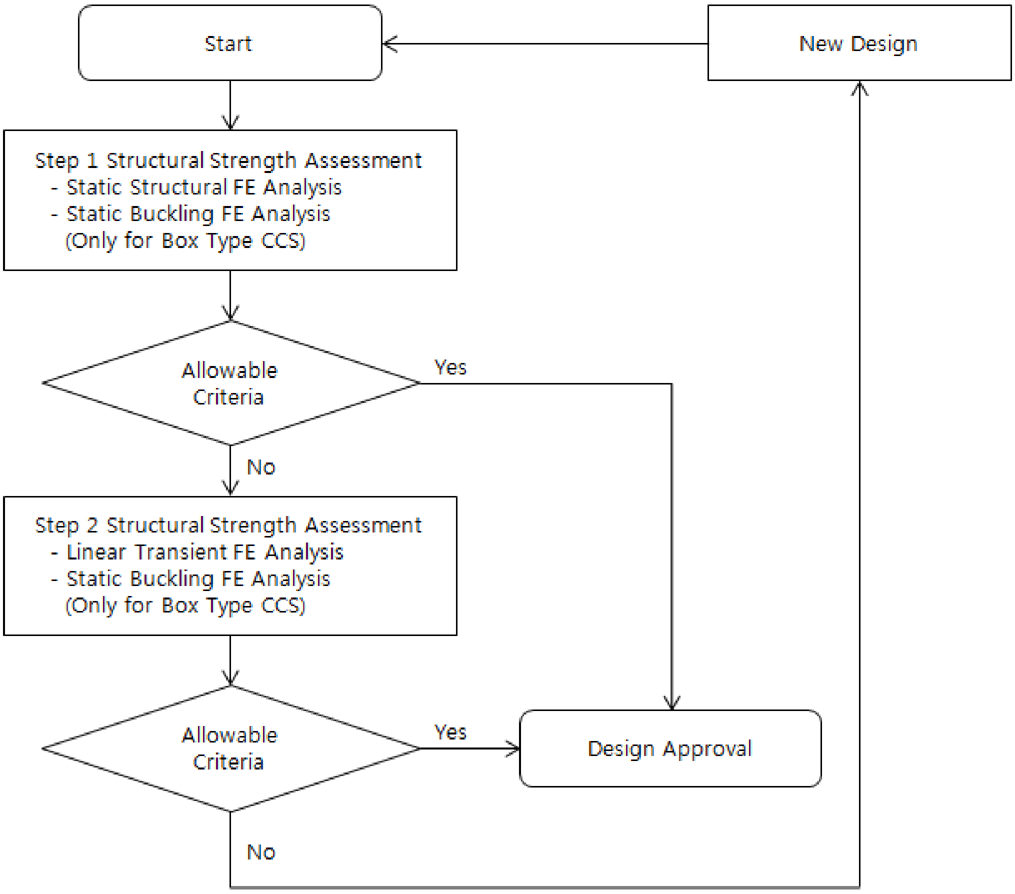

Figure 2 Flowchart of 2 step absolute method

4. Equivalence

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.

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.

5. Documentation

(1) Resource for approval

Depending on the assessment method of the cargo containment system, 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 date other than those specified below.

(A) The approval data for the comparative method performed by model test
- (a) Resource for approval of the cargo containment system of the reference ship
  - (i) The navigation information including the date, the filling level, the ship speed and the incident wave angle
  - (ii) The data for comparison and analysis between the sailing sloshing load and the design sloshing load
  - (iii) The design sloshing load of the reference ship
- (b) The motion analysis data of the target ship
  - (i) The input data of the motion analysis(loading conditions, the draft, the metacenter height and the gravity center of ship, etc)
  - (ii) The model of motion analysis
  - (iii) The detail result of motion analysis
  - (iv) The analysis data of critical sea state and wave condition for the model test.
- (c) The model test data of the target ship
  - (i) The model tank and the sensor specification
  - (ii) The specification of the motion generator and the data measuring system
  - (iii) The monitoring data of motion generator
  - (iv) The measured data
  - (v) The analysis data of the design sloshing load
  - (vi) The postprocessing method of the model test
- (d) The structural strength data of cargo containment system of the target ship
  - (i) Material properties and their basis
  - (ii) The acceptance criteria and its basis
  - (iii) The structural analysis result
  - (iv) The comparison evaluation data for the cargo containment system of the reference ship and that of the target ship
- (e) The drawing of cargo containment system and the related supports
  - (i) The data for type of cargo containment system
  - (ii) The detail drawing of representative basic model

(B) The approval data for the comparative method performed by the sloshing simulation
- (a) The motion analysis data of the reference ship
  - (i) The Input data of motion analysis(loading conditions, the draft, the metacenter height and the gravity center of ship, etc)
  - (ii) The model data of motion analysis
  - (iii) The detail result of motion analysis
  - (iv) The analysis data of critical sea states and wave conditions for the model test.
- (b) The model test data of the reference ship
  - (i) The model tank and sensor specification
  - (ii) The specification of motion generator and data measuring system
  - (iii) The monitoring data of motion generator
  - (iv) The measured data
  - (v) The analysis data of the design sloshing load
  - (vi) The postprocessing method of model test
- (c) The CFD data of the reference ship
  - (i) The verification data of CFD Software
  - (ii) The data of critical sloshing wave condition
  - (iii) The CFD analysis model
  - (iv) The CFD analysis result
  - (v) The analysis data of the design sloshing load
- (d) The CFD data of the target ship
  - (i) The verification data of CFD Software
  - (ii) The data of critical sloshing wave condition
  - (iii) The CFD analysis model
  - (iv) The CFD analysis result

(v) The analysis data of the design sloshing load
(vi) The data for comparison and analysis of the design sloshing load between the reference ship and the target ship
(e) The drawing and the related support data of cargo containment system
(i) The data for type of cargo containment system
(ii) The detail drawing of representative basic model
(C) The approval data for the reinforced comparative method
(a) The approval data of cargo containment system of the reference ship
(i) The navigation information including the date, the filling level, the ship speed and the wave angle of incidence
(ii) The comparison data and analysis data between the sailing sloshing load and the design sloshing load
(iii) The design sloshing load of the reference ship
(b) The motion analysis data of the target ship
(i) The input data of motion analysis(loading conditions, the draft, the metacenter height and the gravity center of ship, etc)
(ii) The model data of motion analysis
(iii) The detail result of motion analysis
(iv) The analysis data of critical sea states and wave conditions for the model test.
(c) The model test data of the target ship
(i) The model tank and the sensor specification
(ii) The specification of motion generator and data measuring system
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(i) The data for type of cargo containment system
(ii) The detail drawing of representative basic model
(D) The approval data for the absolute method
(a) The motion analysis data of the target ship
(i) The input data of motion analysis(loading conditions, the draft, the metacenter height and the gravity center of ship, etc)
(ii) The model data of motion analysis
(iii) The detail result of motion analysis
(iv) The analysis data of critical sea states and wave conditions for the model test.
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(2) The reference data

(A) The main source of the ship

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

(C) The layout of cargo containment system in each cargo hold

(D) The general arrangement of ship with the cargo containment system installed

(E) The design constraints of the cargo containment system

II. ASSESSMENT OF DESIGN SLOSHING LOAD

1. Analysis of Ship Motion

(1) General

(A) The long-term analysis of ship and tank motion should be calculated from the spectrum-based statical analysis based on the linear superposition principle of wave and ship motion.

(B) Sea states should be selected on the basis of the return period of sea state, the wave period close to the sloshing resonance period and major motion factors.

(2) Environmental Conditions

(A) Basic Considerations

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.

The wave diagram is used to calculate the extreme sea load with the return period of design life corresponding to the 10-8 probability of exceedance.

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

(B) Wave spectrum

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

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

S : Wave energy density(m2sec)

H_s : Significant wave height(m)

w : Angular wave frequency(rad/sec)

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

$$T_z = 2\pi\left(\frac{m_0}{m_2}\right)^{\frac{1}{2}}$$

The spectral moment of order n of the response process for a given heading may be described as

$$m_n = \int \sum_{w\theta_0 - 90^\circ}^{\theta_0 + 90^\circ} f_s(\theta) w^n S(w|H_s, T_z, \theta)$$

using a spreading function usually defined as $f_s(\theta) = k\cos^2(\theta)$ where k is selected such that :

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

θ_0 : Main wave heading(deg)

θ : Relative spreading around the main wave heading(deg)

(3) Loading Conditions

(A) Cargo Tank for analysis

Generally, the most severe sloshing phenomenon is considered to occur in No. 2 cargo hold because No. 2 cargo hold has the large size and is distant from the center of the ship motion.

This guidance continues to evaluate No. 2 cargo hold as the basic cargo hold. Figure 3 shows the typical membrane type LNG cargo hold and No. 2 Cargo hold.

(B) Filling Levels

The filling level for the sloshing analysis should be selected based on the loading manual presented by the designer. Otherwise, in addition to the standard filling level, the analysis should be performed for the partial filling level.

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

(a) The standard filling level means that more than 70%H and that lower than 10%H. The analysis should be performed for the filling level of 10%H, 70%H, 80%H, 90%H and 95%H.

(b) When there is no limit to the filling level, the sloshing analysis for the filling level of 25%H, 30%H, 40%H, 50%H and 60%H should be performed, in addition to the standard filling level.

(C) Loading conditions for the seakeeping analysis

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

If there is no limit to the filling level, the sloshing fluid of cargo hold and hull motion can be analyzed in couple.

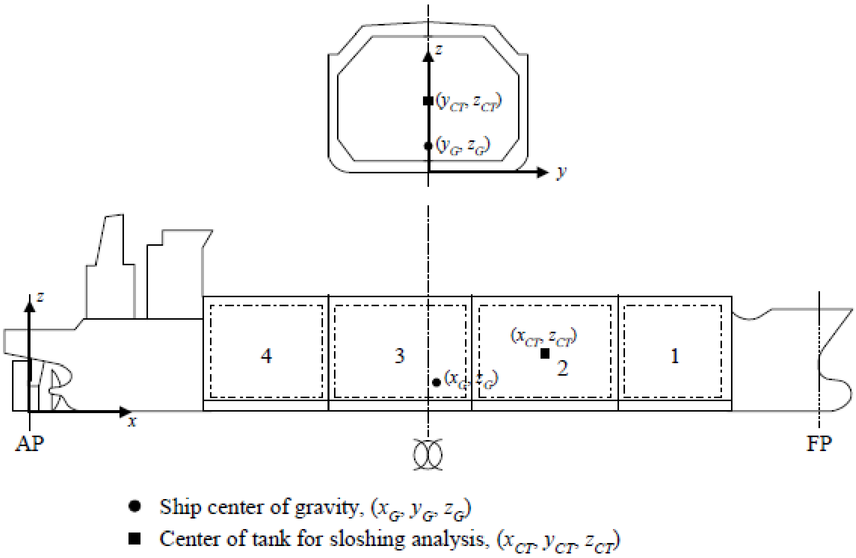

Figure 3 LNG cargo hold and No. 2 cargo hold location

(4) Ship motion and extreme value analysis

(A) General

(a) This calculation is performed by a spectrum-based approach based on the response amplitude operator. When applying the unit regular wave in the wave frequency and the wave direction range, the response amplitude operator should be calculated. The response amplitude operator of the tank motion is used to generate the random motion for the model test.

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

(B) Diffraction-Radiation Method

(a) The calculation of wave induced motion should be performed by applying the motion analysis code using the diffraction-radiation method based on the potential flow.

(b) If the different analysis code 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.

(C) Consideration of hydrodynamic model

(a) 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 level, the mass and the inertia radius should refer to the loading manual provided by the designer.

(b) 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.

(c) 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.

(d) 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.

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

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

$0.45B$: Ballast condition

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

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)

(D) The response amplitude operator of ship motion and tank acceleration.
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

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

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(9.8065m/s2)

$X_1, \ddot{X}_1$: Surge and longitudinal acceleration at the ship center of gravity(m, m/s2)

$X_2, \ddot{X}_2$: Sway and transverse acceleration at the ship center of gravity(m, m/s2)

$X_3, \ddot{X}_3$: Heave and vertical acceleration at the ship center of gravity(m, m/s2)

$X_4, \ddot{X}_4$: Roll and roll acceleration(rad, rad/s2)

$X_5, \ddot{X}_5$: Pitch and pitch acceleration(rad, rad/s2)

$X_6, \ddot{X}_6$: Yaw and yaw acceleration(rad, rad/s2)

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

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

(E) Ship speed
For the calculation of the amplitude response operator to be used for the long-term statistics of analysis for the hull motion and the sloshing, the 75% of the design speed of the ship speed should be considered. In order to calculate the amplitude response operator used in the motion of the model test, the various ship speed can be used for a variety of sea conditions.
The reduction of ship speed for severe sea conditions can be estimated from the towing tank experiments or the operation record of LNG carrier with similar structure.

(F) Roll damping model
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.

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.

(G) Extreme values for ship motion

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.

(5) Selection of critical sea state for the sloshing model test

(A) Selection of sea state

(a) The model test should be performed by selected the sea state with the probability of maximum sloshing motion during the lifetime of the ship based on the motion analysis. 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.

(b) 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 selection 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.

(i) The design sea state showing the most severe storm which the ship can meet during the life is defined. In the consideration of ship operation in the harsh sea state, the various sea state in heading sea and beam sea are used. Table 2 displays the sea conditions for sea conditions of 40 years and 1 year. These are based on the occurrence probability shown in wave dispersion table in Table 1. 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.

(ii) Based on the response of tank motion, the sloshing resonance period and the sloshing simulation results, the 40 year and 1 year sea condition for model tests are selected.

(iii) The model test for sea sate under the assumption of long crest wave is performed.

(iv) 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.

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

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

(B) Selection of regular wave conditions

In principle, the sloshing simulation for any sea state can be carried out in accordance with the same procedure of model tests. With the current development level of CFD software, it takes considerably longer than the model test to perform the sloshing simulation. Even the two-dimensional analysis takes a long time to get the proper sloshing loads processed statistically.

Alternatively, a regular wave approach to create a maximum sloshing loads at the design environmental condition is used. For each wave period and heading, the regular wave to make the maximum amplitude is derived. This time, there is a constraint that the ship motion and the acceleration response should not exceed a lifetime maximum response value in the environmental conditions and the design lifetime operation. The wave period and the heading should be selected on the basis of the magnitude of the tank center acceleration and the similarity of the sloshing resonance period to encountering period. Selected wave conditions is referred to the critical sloshing wave conditions, the selection process is as follows.

(a) The long-term extreme value of ship motion and acceleration with 10-8 probability level is calculated.

(b) The critical sloshing wave domain is defined.

(i) Encountering period shall be less than 30% range of sloshing resonance frequency.

(ii) The acceleration of the tank center should be at least 30% of the lifetime maximum acceleration response.

(c) The regular wave condition for the critical sloshing wave domain is to be determined.

(i) The wave direction and wave period should be within the critical sloshing domain.

(ii) While the conditions that the ship motion and the tank acceleration should not exceed the lifetime maximum value and be within the wave breaking limit are satisfied, the wave amplitude should be maximized.

(d) The wave amplitude in the beam sea and the vicinity of beam sea should be reduced to 72% value calculated by considering the rotational motion.

Table 2 40-year wave and 1-year wave for conditions of sloshing model test

T_z (sec)	H_s (m)	
	40-year wave	1-year wave
4.5	2.9	2.0
5.5	5.7	4.5
6.5	8.6	7.0
7.5	11.0	9.3
8.5	12.8	10.9
9.5	14.0	12.1
10.5	14.9	12.8
11.5	15.3	13.1
12.5	15.4	13.1
13.5	15.1	12.6
14.5	14.6	11.7
15.5	13.6	10.0
16.5	12.2	6.9

2. Sloshing Model Test

(1) General

(A) The model test should be carried out in all cases except for the case of performing the comparison method with the sloshing simulation.

(B) 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 1.

(2) Test equipment

(A) Tank Model

(a) Tank model should simulate the shape of the cargo tank accurately. If the hold surfaces have the waveform as in the Mark III, the flow interference due to the waveform can be ignored. Figure 4 shows an example of the model tank with the pressure sensor and the measuring wire installed.

(b) 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.

(c) 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.

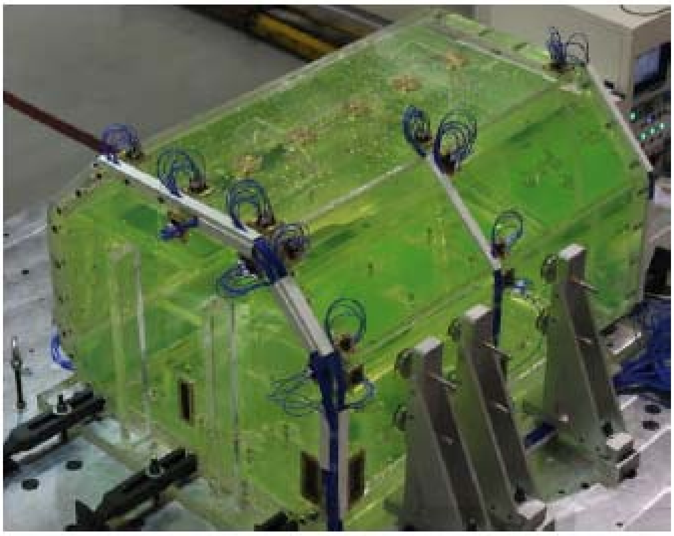

Figure 4 Model test and sensor installation

(B) Ullage and density effect

(a) Ullage and Scaling law of density effect

In principle, the similarity of ullage pressure and density ratio should be satisfied. If this is not possible, when calculating the actual pressure from the model test, the appropriate correction should be made to the scale law.

(b) Requirement of model tank

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.

(C) Pressure Sensor

(a) 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.

(b) The pressure sensor should be calibrated with the appropriate impact test. The experiment should be corrected using the impact pressure with the similar size and the duration to the model test. A wedge drop test with a more than 5° angle of incidence is recommended.

(c) A pressure sensor should be installed in the critical impact area of model tank. In general, the high impact area of the cargo tank with high filling level is the upper corner and edge. In the case of low filling of cargo tank, the critical area is near the sidewall of filling level and slightly higher area(100~133% of the cargo height).

(3) Tank Motion

(A) Generation of irregular tank motion

The response spectrum of tank motion should be generated by combining the response amplitude operator of the hull motion with the wave spectrum. The number of regular wave used to generate the irregular motion signal is selected not to repeat the motion sequence. The wave element should be sufficient for simulation of 5 hours and satisfy the assumption of longcrestedness of the sea surface.

(B) Duration of model test

The duration of model test should be long so as to generate a sufficient number of data for statistical analysis process. The duration of tank motion is to be at least not less than five hours. For the final selected conditions, at least five further model tests should be performed to generate a sufficient number of impact load and to obtain a reliable statistical analysis.

At the beginning of model test, the ramp start is used to avoid the excessive acceleration and transient state. Ramp duration of 10 tz is recommended.

(C) Capacity of motion generator

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, by numerical method or experimental method.

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

(4) Verification of Tank Motion

(A) Verification of global motion

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 1% or the power and torque of motion generator is outside the maximum capacity allowed, the measured data should be discarded.

(B) Verification of impact motion

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.

(5) Measurement of motion data

(A) System specification for data measurement

Measuring the frequency of motion, the channel number, the filtering frequency and the filter type should be reported. The number of channel should be enough to monitor the sloshing impact pressure and the tank motion simultaneously.

(B) Data filtering

The data filter frequency should be set higher than the duration of sloshing impact and structural
natural frequency.

(C) Data type submitted

The measured data type should be described surely. Data resolution higher than 10kHz is recommended.

(6) Selection of critical sea conditions

(A) Heading selection

The wave heading angle should be chosen based on the tank shape, the tank motion and the encountering frequency range for each filling level. For the high filling level(more than 70%H), the heading of 105°, 120°, 150° and 180° is generally used. For the low filling level(less than 10%H), the heading of 90°, 105° and 120° is used. For each heading angle, to evaluate the probability level corresponding, the two or three sea conditions should be chosen based on the tank motion response and that of encountering frequency to the tank resonant frequency.

By performing the sloshing simulation with the proven CFD software, the sea state to be tested can be determined.

(B) Selection of filling level
After running the model test of selected sea states, the maximum sloshing loads should be selected based on the pressure size. One heading generating the critical sloshing load for each filling level should be chosen. A model test of one additional sea state for each filling level should be performed in order to assess whether the sloshing load is maximized. Based on the additional model tests, the significant filling level should be selected.

(C) Repeating experiment of the critical state
For the filing level, the wave direction and the sea state of the critical sloshing load, two additional model tests should be performed to provide reliable statistic results.

(7) Panel pressure averaged spatially

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

(B) 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. The average pressure measurement by using the arranged group of more 3×3 sensors is recommended.

(C) Idealization of impact load
In order to evaluate the structural strength of cargo containment system, the time history of sloshing load is idealized as a triangle wave. The triangle wave is characterized by three factors, the maximum pressure, the rising time and the drop time as shown in Figure 5 and expressed by the following equation.

$$P_{rigid}(t) = P_{\max} t / T_{rise} \quad t < T_{rise}$$
$$P_{\max}(T_{rise} + T_{drop} - t)/T_{drop} \quad T_{rise} \le t < T_{rise} + T_{drop}$$

The skewness factor S is defined as follows in order to define a triangular impact pressure.

$$S = \frac{T_{drop}}{T_{rise}}$$

S : Skewness

T_{rise} : Rising time(msec)

T_{drop} : Drop time(msec)

$P_{\max}$: Maximum pressure(MPa)

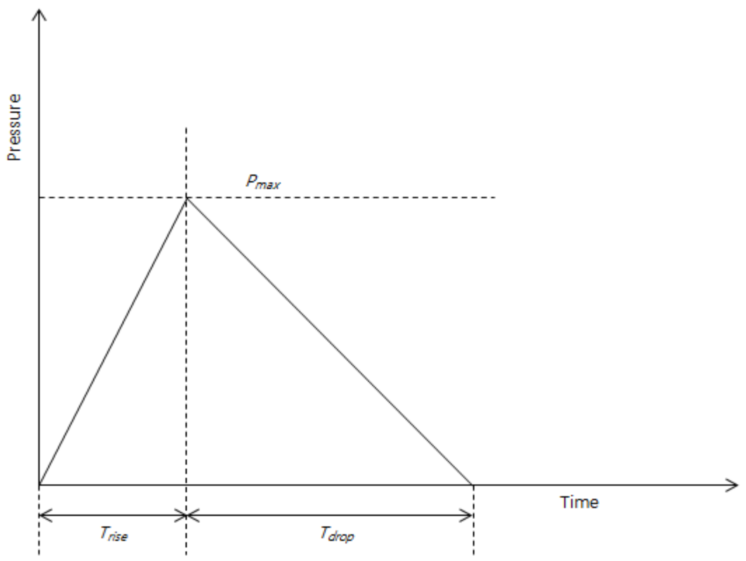

Figure 5 Definition of triangular impact pressure

For general impact signal, rising time and drop time is to be calculated using the appropriate algorithm.
The skewness factor changes to various values in accordance with the impact pressure form. When the skewness factor is greater than 1, it shows a impact pressure with a short rising time and occurs typically in an incompressible fluid. The wave with skewness factor close to 1 is symmetric and often observed when the gas is trapped in the impact between the fluid and the tank wall. The impact pressure with skewness factor less than 1 has a longer rising time.

3. Sloshing Simulation

(1) General
(A) As compared with the model data of the reference ship, if there is no significant change in the LNG carrier and the tank shape, the sloshing simulation should be carried out.
(B) By performing simulations with respect to the reference design and the new design, the relative increase or decrease of the sloshing load should be analyzed by comparative method.

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

(3) Modeling
(A) Tank Modeling
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.
(B) Element division
(a) The element size should be able to simulate the spatial distribution of impact pressure accurately. The element size less than 20cm is recommended for use in areas that generate the maximum pressure.
(b) 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.
(c) In the two-dimensional analysis, the longitudinal bulkhead and the inner bottom should be divided into the size of 2m.
(C) Time step and duration
(a) The increment of time step is to be sufficiently fine in order to maintain the stability and the accuracy of the analysis result.
(b) 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.

(4) Wave condition for sloshing analysis
CFD simulation must be performed within the following conditions.
(A) Critical wave domain
(a) Transverse motion
(i) The heading is greater or equal to 90° and less or equal to 120°.
(ii) The encountering period is to be less than 30% range of sloshing resonance frequency.
(iii) The transverse acceleration is to be more than 30% of lifetime maximum of transverse acceleration.

$$\left| T_y - \frac{2\pi}{\omega_e} \right| < 0.3\,T_y$$

$$a_w(\omega,\theta) RAO_1(\omega,\theta) > 0.3A_1,\ 90^\circ \le \theta \le 120^\circ$$

T_y : Transverse sloshing resonance period(sec)

w_e : Encountering frequency(rad/sec)

a_w : Wave amplitude(m)

$RAO_1(\omega,\theta)$: Transverse acceleration response amplitude operator

A_1 : Maximum lifetime transverse acceleration(m/sec2)

(b) Longitudinal motion
  (i) The heading is greater or equal to 150° and less or equal to 180°.
  (ii) The encountering period is to be less than 30% of sloshing resonance frequency.
  (iii) The longitudinal acceleration is to be more than 30% of lifetime maximum of transverse acceleration.

$$\left| T_x - \frac{2\pi}{\omega_e} \right| < 0.3\,T_x$$

$$a_w(\omega,\theta) RAO_2(\omega,\theta) > 0.3A_2,\ 150^\circ \le \theta \le 180^\circ$$

T_x : Longitudinal sloshing resonance period(sec)

$RAO_2(\omega,\theta)$: Longitudinal acceleration response amplitude operator

A_2 : Maximum lifetime longitudinal acceleration(m/sec2)

(B) Critical wave condition
  (a) The sinusoidal wave amplitude in the longitudinal direction is as follows and the wave amplitude belong to the critical wave region and shall not exceed the wave breaking limit.

$$a_w(\omega,\theta) = \min \frac{A_j}{RAO_j(\omega,\theta)}$$

$$a_w(\omega,\theta) \le \frac{\pi}{7}\frac{g}{\omega^2}$$

A_j : Lifetime maximum response of jth motion parameter of 10-8 probability (m/sec2)

$RAO_j(\omega,\theta)$: Response amplitude operator of jth motion parameter at frequency of w and heading of θ

g : Gravitational acceleration (9.8065m/s2)

  (b) For the transverse motion, the wave amplitude should be reduced to 72% to consider the rotational motion of LNG carrier in beam sea. The wave amplitude belongs to the critical wave range and does not exceed the 72%of wave breaking limit.

$$a_w(\omega,\theta) = 0.72\min \frac{A_j}{RAO_j(\omega,\theta)}$$

$$a_w(\omega,\theta) \le \frac{0.72\pi}{7}\frac{g}{\omega^2}$$

(5) Results of numerical analysis
  (A) The analysis result should be able to obtain from CFD analysis.
    (a) The time history of impact pressure and maximum
    (b) The impact pressure value averaged over 2m panel along the bulkhead and tank top(2-dimensional analysis)
    (c) The impact pressure value averaged over 1m2 panel along the bulkhead and tank top(3-dimensional analysis)
  (B) The average panel pressure history and the maximum for each loading condition should be provided to the Society.
  (C) By comparing the sloshing load of the new design and the reference design, the relative increase/decrease of sloshing load should be analyzed.

III. STRENGTH ASSESSMENT OF LNG CONTAINMENT SYSTEM

1. Containment System Configuration

(1) Layered Foam Type Containment System

(A) The Layered foam type containment system was first introduced in 1970. Gaztransport & Technigaz(GTT)'s Mark III and CS 1 are present.

(B) Membrane tank type of Mark III

(a) The membrane tank composed of a thin membrane is liquid tight. Unlike the independent tank, the membrane tank does not handle the cargo load. Instead the inner hull adjacent to the insulation outside the membrane tank support the load.

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

(c) The secondary barrier and the secondary insulations 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. Figure 6 shows a typical cargo containment system of Mark III.

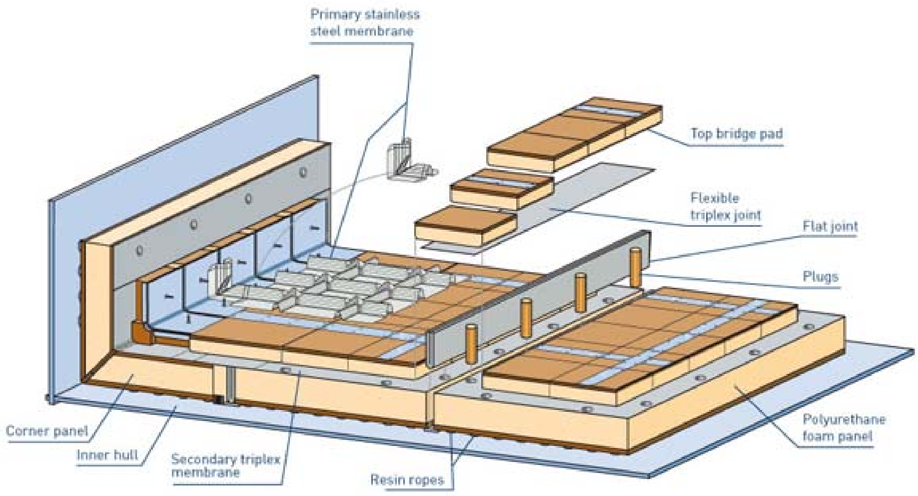

Figure 6 Cargo containment system of Mark III

(C) Membrane tank type of CS 1

(a) Invar is used as the primary barrier.

(b) Triplex is used as a secondary barrier.

(c) The cargo containment system consists of a pre-fabricated panel to support a load. The panel is composed of polyurethane foam and first layer and second layer and the secondary barrier. The panel thickness may vary from 250mm to 350mm in order to meed the BOR requirement. The panel gets in contact with the hull by the mastic. Figure 7 shows a typical cargo containment system of CS 1.

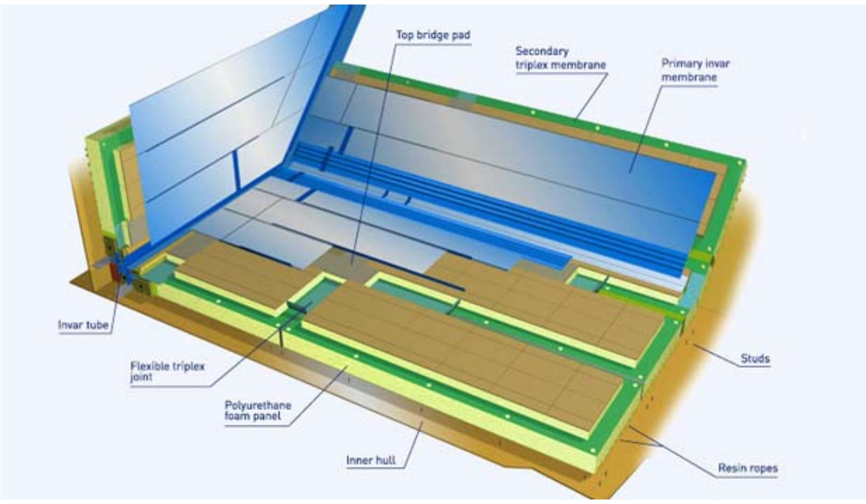

Figure 7 Cargo containment system of CS I

(2) Box Type Containment System

(A) The box type containment system, introduced in 1960, is a typical product of NO 96 by Gaztransport & Technigas(GTT).

(B) Membrane tank type of NO 96

(a) The membrane tank composed of a thin membrane is liquid tight. Unlike the independent tank, the membrane tank does not handle the cargo load. Instead the inner hull adjacent to the insulation outside the membrane tank support the load.

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

(c) The membrane stress is hardly generated, and not influenced by the external force to generate the stress in the adjacent hull structure. Figure 8 shows a general cargo containment system of NO 96.

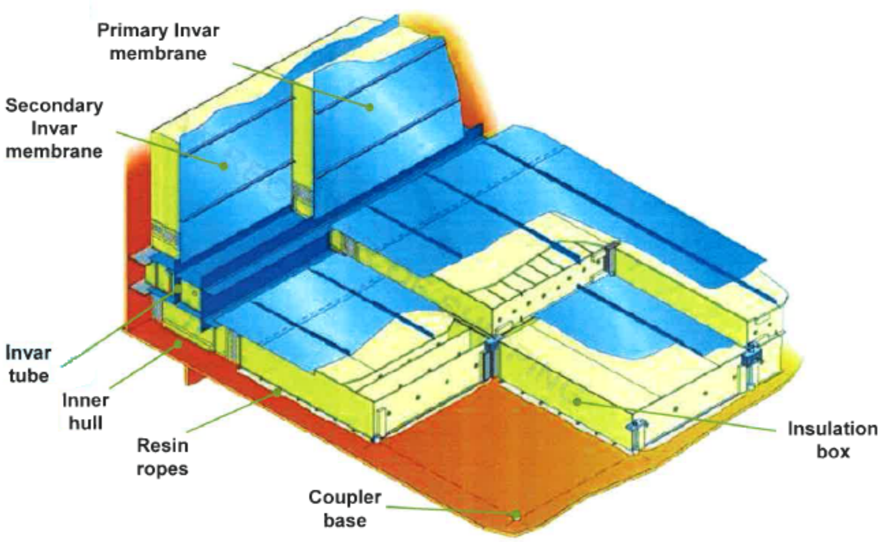

Figure 8 Cargo Containment System of NO 96

(3) Other Type Containment Systems

The design of cargo containment system shall comply with the international gas code(IGC) and shall be approved by the Society.

2. Comparative Method

(1) General

(A) 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.

(B) The comparative method is applied when the strength of cargo containment system of the reference ship is same with that of the target ship.

(C) 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.

(2) Application conditions

(A) In order to apply the comparative method or the reinforced comparative method, the following should be proved.

(a) The cargo containment system of the reference ship and that of the target ship should be substantially equal.

(b) The hull structure supporting the cargo containment system should be quite similar.

(c) The verified navigation record should exist for the cargo containment system of the reference ship or that of similar ship.

(B) If it does not meet the above criteria, the designed cargo containment system is determined to be new design.

(3) Selection of Target Ship

(A) When the reference ship meet the following conditions, it is recognized to have the proved operating record.

(a) The important damage or repetitive damage at cargo containment system should not occur. All the environmental conditions for each filling level should be considered.

(b) 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.

(B) 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.

(4) Comparative Method

(A) 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.

(B) 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.

(C) If the design sloshing load of the target ship is lower than that of the reference ship as shown in Figure 9, the design can be approved.

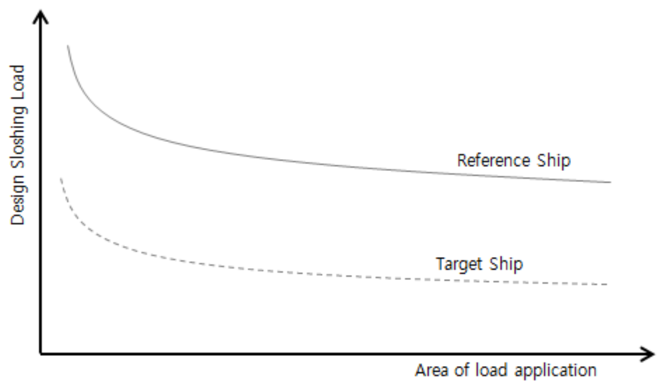

Figure 9 Schematic drawing of comparative method

(5) Reinforced Comparative Method

(A) The reinforced comparative method include the strength of the cargo containment system in the evaluation process. It is suitable for the case that the structural strength of cargo containment system of the target ship increases from that of the reference ship. In the case that the standard box of box type cargo containment system(NO 96) is improved by the reinforced box or the super-reinforced box, this method can be applied.

(B) 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.

(C) 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.

(D) 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 10 shows this conceptually.

$$\frac{Design\,sloshing\,load_{target\,ship}}{Structural\,strength\,of\,CCS_{target\,ship}} < \frac{Design\,sloshing\,load_{reference\,ship}}{Structural\,strength\,of\,CCS_{reference\,ship}}$$

(E) 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 reinforced comparative method cannot be applicable. This design as determined as new design is assessed through the absolute method.

(F) If the approved design for the reference ship is not present, the absolute method should be applied.

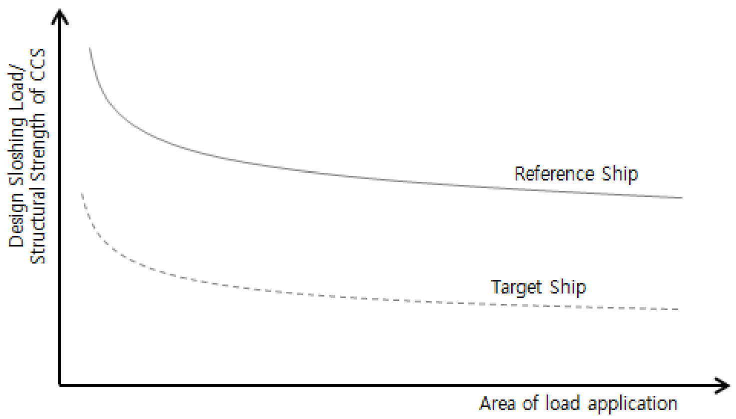

Figure 10 Schematic drawing of enhanced comparative method

3. Absolute Method

(1) Step 1 Finite element analysis

(A) General

(a) By applying the maximum load obtained through the sloshing model test as quasi-static load, static analysis is performed.

(b) The analysis target is generally the pre-fabricated unit at manufacturing process step.

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

(B) Element and material properties

(a) In step 1 finite element analysis, modeling does not include LNG.

(b) The layered foam type cargo containment system is composed of the polyurethane foam(PUF), the plywood and the mastic as a laminated structure. Figure 11 shows the model section.

(c) 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.

(d) The layered foam type cargo containment system(Mark III) does not include the primary barrier(STS 304L) and the secondary barrier(Triplex) in the finite element model. These two barriers are not included in the analysis model due to minor contribution to supporting the structural stress caused by sloshing.

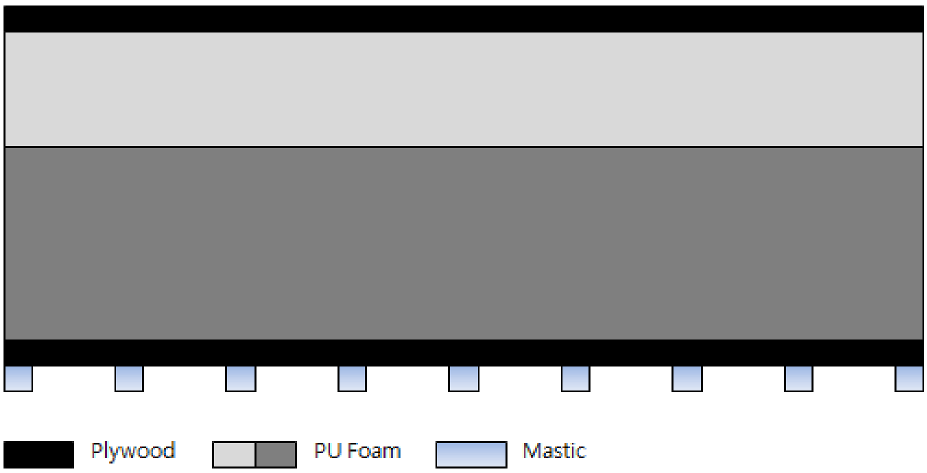

Figure 11 Configuration of layered foam type cargo containment system(Mark III)

(e) The box type cargo containment system is composed of the primary insulation box, the secondary insulation box and the mastic as three main elements. Figure 12 show the model geometry.

(f) It is assumed that the mastic is isotropic and the plywood constituting the insulation box has the orthotropic behavior.

(g) Invar forming the primary barrier and the secondary barrier of the box type cargo containment system is not included 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 caused by sloshing.

(h) Material properties of the mastic, the plywood and the polyurethane foam necessary for step 1 finite element analysis should be provided by the manufacturer. It is a principle.

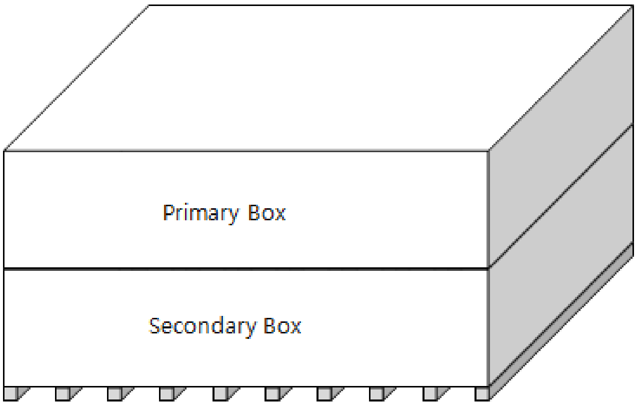

Figure 12 Configuration of box type cargo containment system(NO 96)

(C) Finite element mesh

(a) The three-dimensional finite element model of the layered foam type cargo containment system should use the hexa solid element as the default. The finite element mesh should be sufficiently dense to obtain the converging result for the layered foam type cargo containment system and the box type cargo containment system.

(b) The mastic should be divided into two or more elements in the thickness direction and the width direction. The upper plywood should be divided at least one or more element in the thickness direction. Lower plywood should have at least three or more elements in the thickness direction. The plywood elements between the two mastic should be at least seven or more elements. Polyurethane foam should be divided into elements with a length of about 10mm in the thickness direction.

(c) The box type cargo containment system should be modeled using the shell elements. The enhanced plywood can be considered by increasing the thickness of shell element. The perlite in the box is not considered because they do not affect the strength of cargo containment system.

(d) For the box type cargo containment system, space between two mastics should be divided into at least seven or more shell elements. The primary box and the secondary box should be divided into elements with a length of about 10mm in the thickness direction.

(e) The finite element model for the layered foam type cargo containment system is shown in Figure 13.

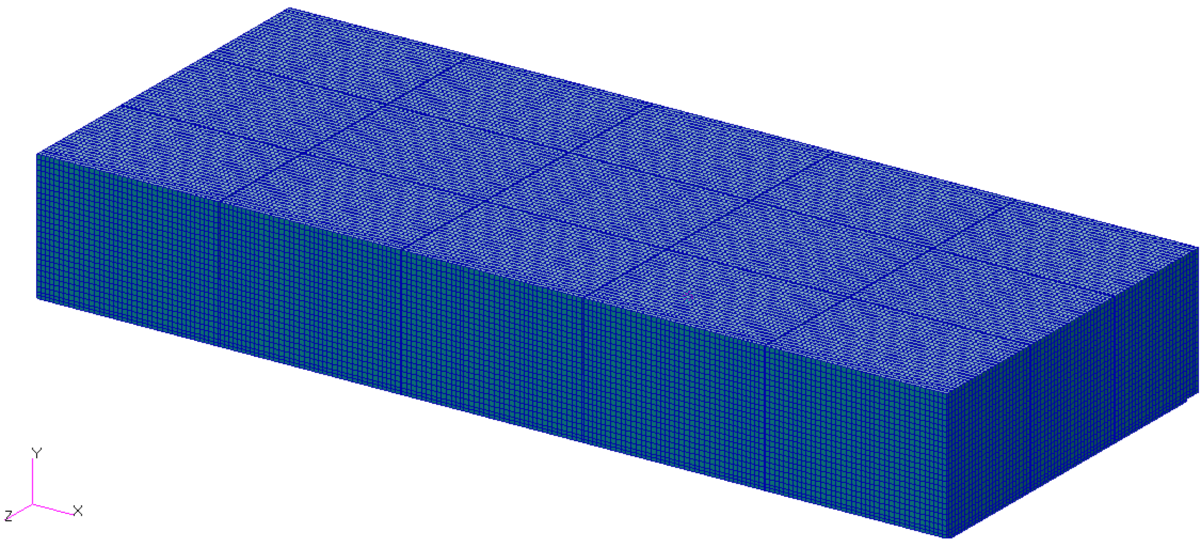

Figure 13 The finite element 3-D mesh model of cargo containment system

(D) Loading and boundary conditions
  (a) The height direction of the mastic part in contact with hull is restrained. Figure 14 shows an example which is fixed on mastic in the height direction in the layered foam type cargo containment system.
  (b) The mastic part closest to the four vertices of the cargo containment system are constrained in three directions so at to avoid the rigid body motion. Figure 15 is an example to show the three direction constraints of the four part of mastic in the layered foam type cargo containment system. The boundary conditions of (a) and (b) are indicted in detain in Table 3.
  (c) The static load is applied on the top plywood of cargo containment system. Figure 16 shows an example applying a static load on the layered foam type cargo containment system. The static load is obtained from the model test, which means P_{max} defined in Figure 5.

Table 3 Boundary Conditions

Position	Displacement			Rotation		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Mastic nodes in contact with hull	0	1	0	0	0	0
Mastic nodes closest to the four vertices of cargo containment system	1	1	1	0	0	0
(Notes) 1 : Constrained 0 : Free						

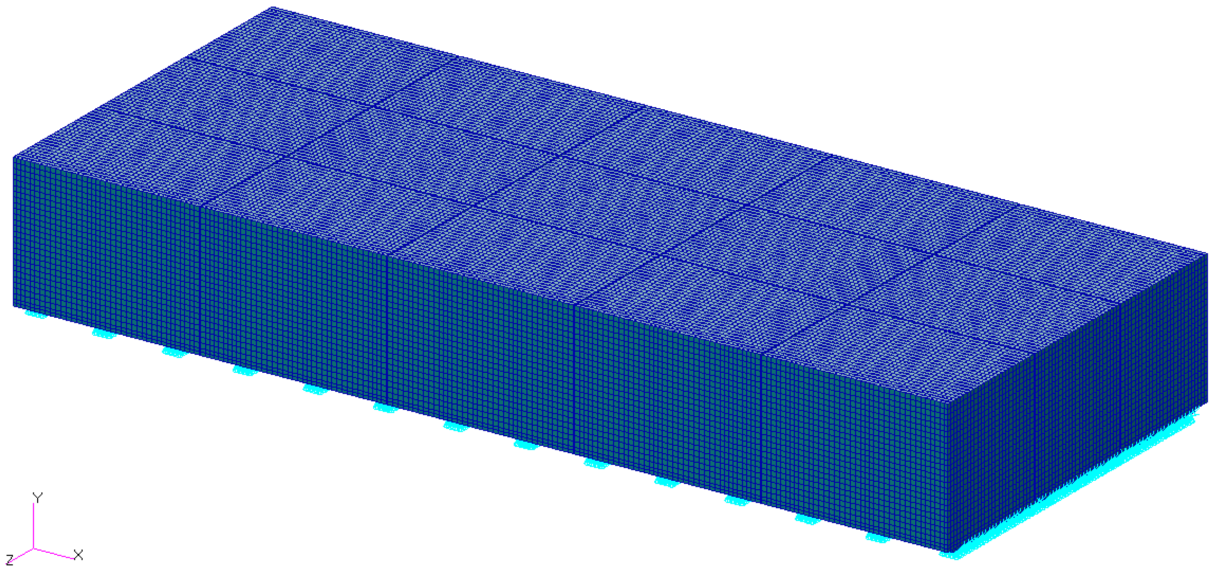

Figure 14 The constrained boundary conditions of mastic in height direction in cargo containment system

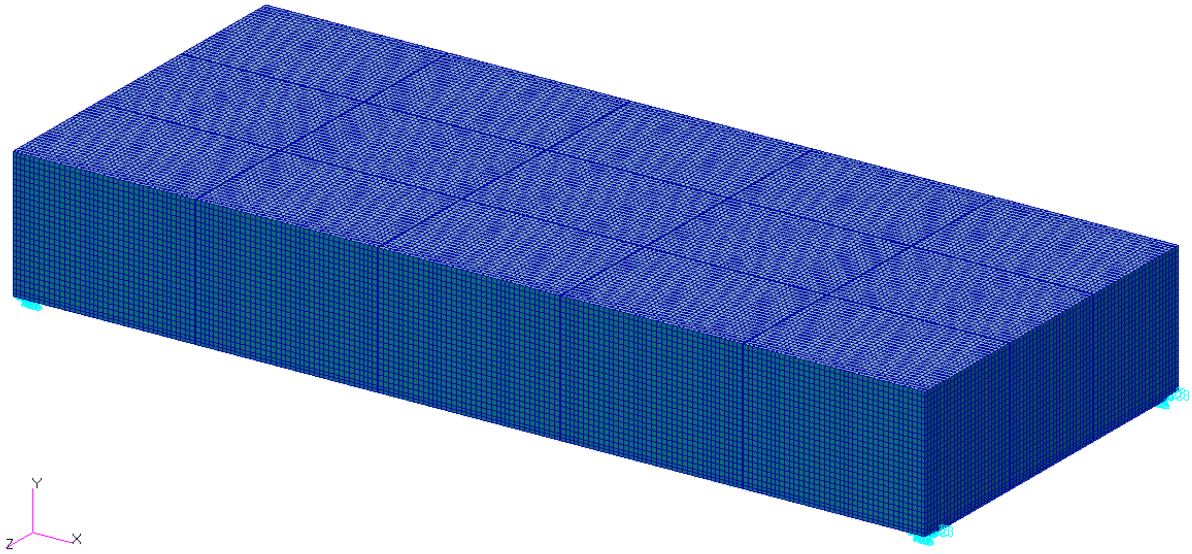

Figure 15 The constrained boundary conditions of mastic corner area of cargo containment system

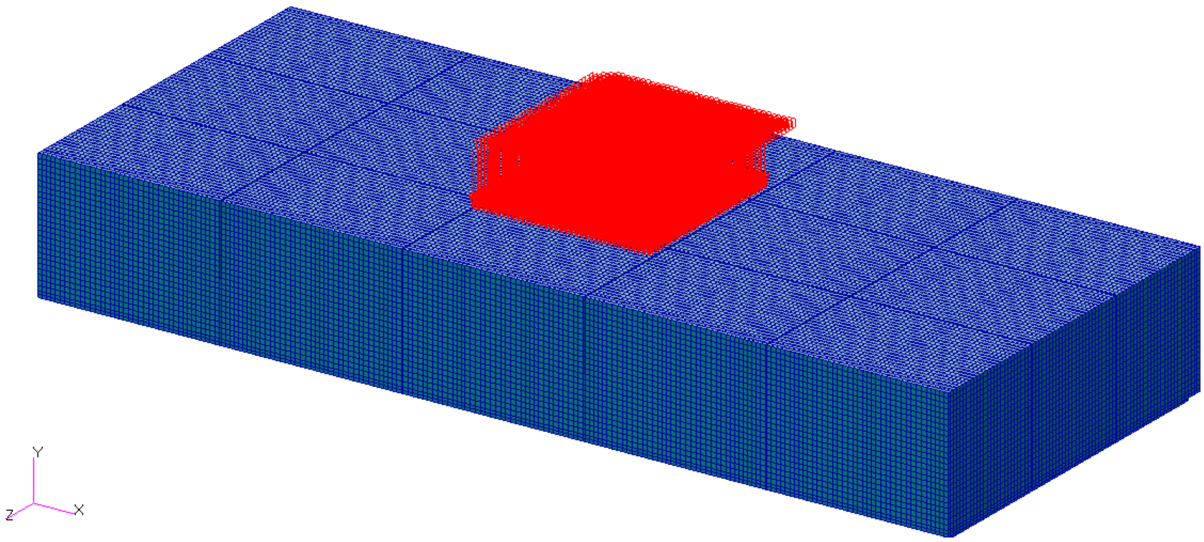

Figure 16 Loading conditions of sloshing for cargo containment system

(d) Application location of static load is to be determined with reference to the model test. In general, the pressure sensor is arranged in a 3×3 or 4×4 panel with respect to the surface area of 1m2 in the model test. In this condition, the combination of the pressure sensor shown in Figure 17 is obtained. The static analysis should proceed considering this combination.

(i) 1×1 sensor array : 9set
(ii) 3×1 or 1×3 sensor array: 6set
(iii) 2×2 sensor array: 4set
(iv) 3×2 or 2×3 sensor array: 4set
(v) 3×3 sensor array: 1set

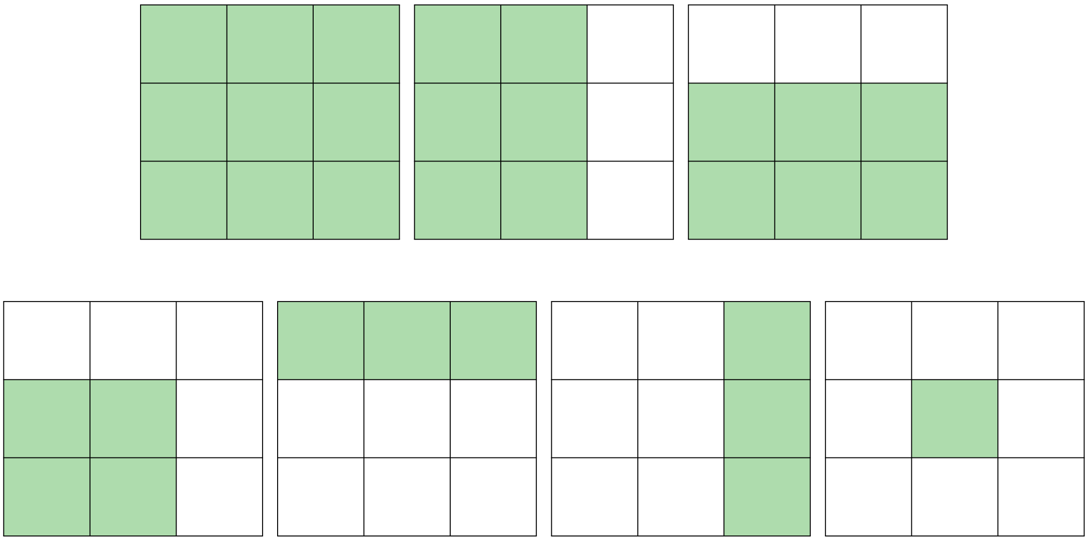

Figure 17 Examples of applied area combination for sloshing loads

(E) Buckling Strength of Box Type Containment System(NO 96)

Because of the characteristics of box type cargo containment system, the buckling occurs. The linear buckling analysis is carried out with the finite element model in order to evaluate the static strength of the box type cargo containment system. Figure 18 shows an example of buckling analysis.

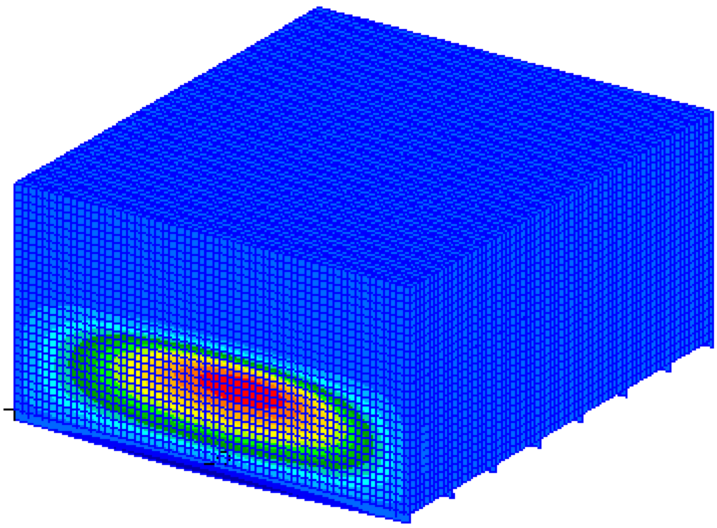

Figure 18 Analysis example of linear static buckling of box type cargo containment system(NO 96)

(F) Analysis Procedure

In step 1 of finite element analysis, the static analysis for the model not including LNG by using a approved code by the Society is to be performed.

It is possible to obtain stress, strain and displacement from the result of finite element analysis. The analysis procedure is as follows.

(a) The polyurethane foam, the plywood and the mastic of the layered foam type cargo containment system are to be modeled according to (B) and (C). The boundary condition in accordance with (D) is applied to the mastic and the sloshing load is applied to the upper plywood as the quasi-static pressure.

(b) The box type cargo containment system is to be modeled as the primary insulation box, the secondary insulation box and the mastic according to (B) and (C). According to (D), the boundary condition is applied to the mastic and the sloshing load is applied to the upper surface of the primary insulation box as the quasi-static pressure. The static structural finite element analysis is to be performed. A linear buckling analysis is to be conducted.

(c) Based on the analysis result, the process of structural evaluation for each element proceeds.

(d) The analysis result should not be more than the acceptance criteria according to 4.

(e) If the result exceed the acceptance criteria, step 2 finite element analysis proceeds.

(2) Step 2 finite element analysis

(A) General

(a) The finite element shape, the element partitioning and the size, material properties and boundary conditions should be accordance with (1).(A)~(D).

(b) The analysis target generally refers to the pre-fabrication unit in the manufacturing process step.

(c) If necessary, it may include a hull in the analysis and consider the temperature of the cargo containment system and motion of cargo hold

(d) By applying the triangular impact pressure obtained from the sloshing model test, the dynamic analysis is to be performed.

(e) Since the step 2 finite element analysis is the dynamic process, the time increment should be small enough that analysis result such as the stress, the strain and the displacement is possible to obtain. Time increment shall be suitably selected based on the analysis code used. In the implicit code, the time increment should be less than 1/20 of the natural period of the analysis model. The time increment in the explicit code should be determined in proportion to the finite element mesh size. For example, the sound speed in the steel and aluminum is 5mm/1μs. Thus, if the steel structure finite element model is modeled by 5mm, time increment is 1μs. Elements of material having a smaller sound speed can have a larger time increments. Table 4 shows the sound wave velocity for various materials.

Table 4 Sound speed for various materials

Material	Sound speed(m/s)
Air	331
Water	1478
Steel	5240

Since the sound speed of the material with a constant elasticity modulus is calculated as follows, the appropriate size for each of the finite element should be modeled based on this.

$$c = \sqrt{\frac{E(1-\nu)}{(1+\upsilon)(1-2\upsilon)\rho}}$$

E : Material elasticity modulus

υ : Material poisson's ratio

ρ : Material density

(f) The analysis time should be more than three times the duration of sloshing load. If the desired analysis result is not obtained, the analysis duration is to be adjusted.

(B) Element shape and material properties

It proceeds following (1)(B).

(C) Finite element mesh

It proceeds following (1)(C).

(D) Loading and boundary conditions

(a) Boundary conditions follows (1)(D)(a) and (b).

(b) The dynamic triangular wave as design sloshing load is applied on the top plywood of cargo containment system. This pressure is determined by the model test. The sloshing dynamic triangular wave is defined by the maximum pressure, the rising time, the drop time and the skewness. Figure 5 shows an example of dynamic sloshing triangular wave.

(c) The sloshing impact pressure has a variety of effects on the cargo containment system as various parameters(the maximum sloshing pressure, the rising time, the drop time and the skewness) defined in Figure 5 changes. In order to investigate it, the parametric study for each factor should be performed. It is possible to investigate the influence of the factors for each acceptance criteria and parameter range to be considered may be selected. In applying the parametric study, the designer should consult with the Society in advance and determine how to apply the each parameter, etc.

(d) The area applied by the sloshing impact pressure should be consistent with the model test. In model test, area of 1m2 is usually covered with a pressure sensor of 3×3 or 4×4 panel. Various combinations of the pressure sensor are described in (1)(D)(d). By implementing the dynamic finite element analysis for the various combination, the structural assessment for cargo containment system should be proceeded.

(E) Buckling of Box Type Containment System(NO 96)

It proceeds following (1)(E).

(F) Analysis Procedure

Step 2 finite element analysis is performed according to the following sub steps.

(a) As described in the previous part, the layered foam type cargo containment system (Mark III) should include a polyurethane foam, plywood and mastic, the box type cargo containment system(NO 96) is to include the primary insulation box, secondary insulation box and mastic. Boundary conditions described in previous part are applied to the lower part of mastic and the sloshing dynamic triangular pressure to the top plywood of cargo containment system as loads. The dynamic structural finite element analysis is to performed.

(b) The box type cargo containment system is to perform a linear buckling analysis, also.

(c) Time history for stress/displacement by calculating the stress distribution and the displacement distribution for each component of cargo containment system are obtained.

(d) It proceeds by performing the parametric studies with factors of sloshing load on the effects of the stress/displacement.

(e) The structural strength assessment of cargo containment system should be proceeded by performing the finite element analysis for various combinations of applied area for sloshing impact load according to (1)(D)(d).

(f) The analysis results should be less than or equal to acceptance criteria according to 4. Figure 19 shows an example of comparing the strength of cargo containment system to the sloshing load of cargo containment system conceptually.

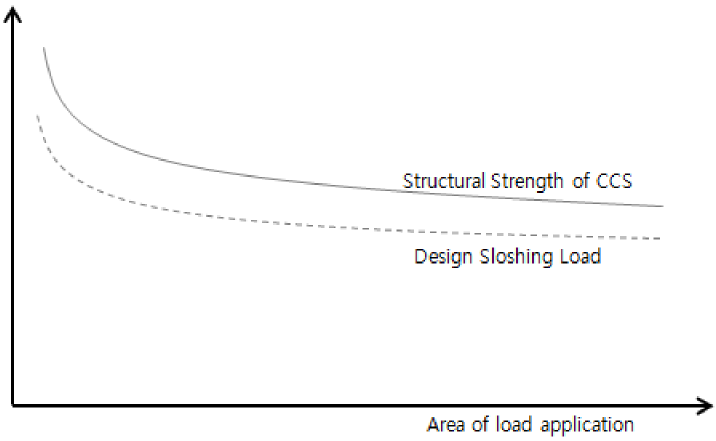

Figure 19 Comparison between structural strength of cargo containment system and sloshing load

4. Acceptance Criteria

(1) General

(A) 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.

(B) A typical failure type of layered foam type cargo containment system under the sloshing loads are as follows. A common occurrence position of the damage is shown in Figure 20.

(a) Failure of polyurethane foam
(b) Plywood distortion
(c) Peeling of lower plywood
(d) Breaking of plywood at the connection between mastic and lower plywood
(e) Breaking of polyurethane foam at the connection between mastic and lower plywood

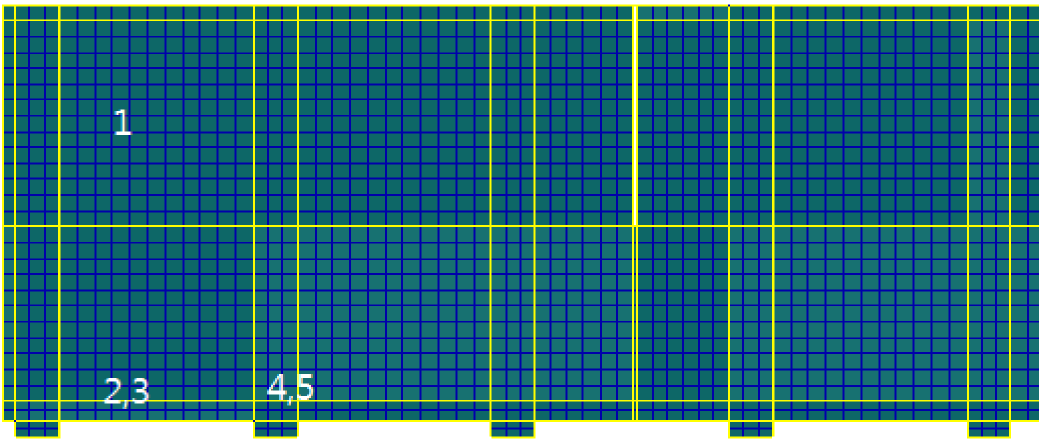

Figure 20 Typical damage location of layered foam type cargo containment system

(C) The typical damage in the box type cargo containment system is as follows.

(a) Buckling of the primary insulation box or the secondary insulation box
(b) Failure due to the bending/shear of the top plywood

(D) 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.

(E) For the viewpoint of yield/fracture and damage, the maximum tensile/compressive stress and the shear stress of plywood is evaluated. The von-mises stress of polyurethane foam and mastic is compared to its tensile strength for the assessment of structural strength.

(F) 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.

(G) 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.

(H) Evaluation method of 2 should satisfy the acceptance criteria of (2) and (3), The evaluation method of 3 should be in accordance with the acceptance criteria of (4).

(2) Comparative method

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.

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

P_{target} : Design sloshing load of target ship

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

This criteria should be satisfied for the area/sloshing loads as shown in Figure 9.

(3) Reinforced Comparative Method

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.

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

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

This criteria should be satisfied for the area/sloshing loads as shown in Figure 10.

(4) Absolute Method

(A) 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.

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

P : It is the design sloshing load which includes the effect of loading area, rising time and drop time, etc.

C : It means the structural strength of cargo containment system and evaluated by the structural analysis.

UF : As the 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.

(B) In order to evaluate the structural strength of cargo containment system, the analysis should be performed based on the following criteria. The designer is responsible for the selection of criteria.

(a) The maximum normal stress : The maximum normal tensile/compressive stress in three direction(X, Y, Z coordinate) shall satisfy the following conditions.

$$\sigma_{\max} \leq \sigma_c$$

σ_c : It is the allowable normal stress which represents $S_m \sigma_y$ or $S_m \sigma_u$.

σ_y : It is the yield strength which should be based on the acknowledged experimental data for each material and the standard recognized by the Society

σ_u : It is the tensile strength which should be based on the acknowledged experimental data for each material and the standard recognized by the Society

S_m : It is a strength reduction factor given in Table 5.

(b) The maximum shear stress : The maximum shear stress should satisfy the following conditions.

$$\tau_{\max} \leq \tau_c$$

τ_c : It is the allowable shear stress which represents $S_m \tau_u$.

τ_u : It is the shear strength which should be based on the acknowledged experimental data for each material and the standard recognized by the Society.

S_m : It is a strength reduction factor given in Table 5.

(c) The maximum equivalent stress : The maximum equivalent stress should meet the following conditions.

$$\sigma_{\max}^{eq} \leq \sigma_c$$

σ_c : It is the allowable equivalent stress which represents $S_m \sigma_y$ or $S_m \sigma_u$.

σ_y : It is the yield strength which should be based on the acknowledged experimental data for each material and the standard recognized by the Society

σ_u : It is the tensile strength which should be based on the acknowledged experimental data for each material and the standard recognized by the Society

S_m : It is a strength reduction factor given in Table 5.

(d) Buckling criteria : By performing the buckling analysis for the box type cargo containment system, the allowable buckling pressure should be obtained. The maximum pressure applied to the top box should satisfy the following conditions.

$$P_{\max} \leq P_c$$

P_c : It is the allowable buckling pressure which represents $S_m P_{cr}$.

P_{cr} : It is the critical buckling pressure which should be based on the acknowledged experimental data for each material and the standard recognized by the Society

S_m : It is a strength reduction factor given in Table 5.

Table 5 Strength reduction factors

SRF	Tensile strength	Shear strength	Yield strength	Buckling pressure
Sm	0.8 ~ 1.0	0.8 ~ 1.0	0.9 ~ 1.0	0.9 ~ 1.0

(e) Service limit criteria : If there is a maximum displacement recommended by designer for each component of cargo containment system, it should satisfy the following conditions.

$$u_{\max} \leq u_c$$

$u_{\max}$: It is a analysis result which represents the maximum displacement.

u_c : It is allowable service displacement which should be recommended by the designer.

5. Material Properties

(1) General

(A) 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.

(B) 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.

(C) Material properties can be obtained through the material supplier, the promulgated experimental data or the material experiments. They should be sought in accordance with (2), (3), (4) and (5).

(2) Primary and secondary barriers

(A) Primary and secondary barriers(Membrane and Triplex of Mark III, Invar of NO 96 and invar and triplex of CS 1) should be modeled as a linear isotropic elastic material. It is necessary to enter the following properties.

(a) Density(kg/m^3)
(b) Young's Modulus(MPa)
(c) Poisson's ratio

(B) If necessary, the analysis shall include the change of material properties with the change of temperature.

(3) Polyurethane Foam

(A) 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(MPa)
(c) Poisson's ratio
(d) Shear modulus(MPa)

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

(4) Plywood

(A) 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)

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

(5) Mastic

(A) 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
(d) Shear modulus(MPa)

(B) The parameters for the ambient temperature is used for the analysis.

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