First principle-based analysis procedure for strength assessment of membrane-type
LNG containment system due to sloshing impact

Y. S. Shin, PhD, J. W. Kim, PhD, and B. Wang, PhD

American Bureau of Shipping, USA

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SYNOPSIS

As the oil and gas industry is building much larger LNGC than so called standard size and is also considering operation in
partially filled condition, a more accurate and realistic assessment method and criteria are needed. In the past, a simple
methodology has been used to define the load and strength of the containment system to evaluate the factor of safety of
the system. To meet the new demand of the industry, ABS has developed a procedure for the strength assessment of a
membrane type containment system based on the combination of numerical analysis and experimental study. This paper is
to present the technical background of the analysis procedure. The method for determining the load and strength of an
LNG containment system and the acceptance criteria are to be described. For load, sloshing model test requirement and
procedure to determine the critical load cases and test conditions using sloshing simulation are to be presented with
experimental results. Strength side of the equation, dry and wet drop test procedure and how these test results are used in
the determination of realistic impact strength including the interaction between the fluid and containment structure and
dynamic structure analysis utilizing dynamic material characteristics and structure damping. The analysis procedure to
evaluate two main containment systems will be presented with an example analysis. Results are summarized in the
conclusions and recommendations are made for further study.

INTRODUCTION

The hull structure of the LNG ships has been designed and constructed based on applicable classification rules. However,
the containment systems of the LNG ships are made of quite different materials and are exposed to a cryogenic
environment. Therefore, in the past, a simple assessment method [1, 2] has been used to evaluate the adequacy of the
containment system based on a comparative approach and corresponding factor of safety based on a previous successful
operational record. Recently, the ship size has been increased from standard or conventional size of 138,000-150,000 m³

Author’s Biography

Yung Sup Shin is a technical advisor, ABS Technology. He received a Ph.D. in Hydrodynamics from the Department of Naval
Architecture from the University of Michigan. Since joining ABS 26 years ago, Dr. Shin has led a number of hydrodynamic projects
for theoretical development of ships and offshore structures of semisubmersible, tension leg platform, and FPSO. Also, he has led an
R&D team for the development of tanker and LNG sloshing analysis, pump tower analysis system and procedure. He serves as
chairman of the PRECAL working group of MARIN Cooperative Research for Ships and SNAME H-7 Seakeeping panel.

Jang Whan Kim is a Senior Research Engineer in the ABS Technology Department. He earned his Ph.D. degree in Naval Architecture
from the Seoul National University, Korea in 1991. He worked as Post Doc. and Researcher in the Seoul National University,
University of California at Berkeley and University of Hawaii. He joined ABS in 2001. His research interests are in the fields of linear
and nonlinear wave modeling, hydrodynamic impact, fluid-structure interaction and sloshing phenomena in LNG tanks.

Bo Wang is a Research Engineer in the ABS Technology Department. He received his Ph.D. in Engineering Mechanics in 1990. Dr.
Wang worked as a research faculty in the School of Mechanical and Aerospace Engineering at Oklahoma State University before
joining ABS in 2005. His research interests include FE modeling, structural analysis and material science.
First Principle-based Analysis Procedure for Strength Assessment of Membrane-type LNG Containment System due to Sloshing Impact

Size of 138,000-150,000 m$^3$ to 250,000 m$^3$ plus, and tank design, size, and configuration have been changed significantly. Also, a new operational condition at partial filling is being considered for the spot market or offloading operation at an offshore terminal [3]. To meet the special needs of the industry, a direct calculation-based strength assessment procedure has been developed and presented in the paper based on the earlier framework of the analysis approach [4, 5, 6].

Inside of the membrane type LNG tank hull structure, there are two major structural systems - LNG containment system and pump tower structure. The proposed analysis procedures focused on the determination of the sloshing load inside of LNG cargo tanks and the subsequent strength assessment of the membrane type containment system. The membrane type LNG containment system consists of thin metal membranes to prevent cargo leakage, form or powdery insulation material to maintain the low temperature to keep the LNG cargo in liquid state, and an associated structure to retain the membrane and insulation material and to secure them to the hull structure. Sloshing of LNG cargo can cause high impact loads on the supporting and containing structures. This is particularly critical for membrane type tanks since these will have flat surfaces and corner regions leading to increased peak pressures for sloshing impacts. Sloshing loads are typically estimated using a scaled model test or numerical simulation such as the computational fluid dynamics (CFD) method. In the scaled model test, a partially filled tank with water is subjected to oscillatory motions to simulate the ship motions, and the resulting pressures on the tank wall are then measured. Sloshing in a real LNG tank involves many complicated physical phenomena such as wave breaking, phase transition between liquid and gas during the impact, gas entrapment, cushioning effect due to corrugation, etc. The membrane type containment system is much more flexible compared to the steel hull structure. As a result, the fluid-structural interaction plays an important role in the structural analysis of LNG containment systems under sloshing load. Furthermore, the property of foam material is viscoelastic and the structural response is dependent on the dynamic loading rate. It is a challenging task to consider the complicated sloshing load and structural responses in designing the containment systems. Therefore, a comparative method has often been used to determine the acceptance of the new design compared to previously known design. The comparative method is an attractive and practical approach when the new design is not significantly different from the known design with a proven service record. The comparative method may not be reliable when the major design parameter, such as the size of cargo tanks, changes beyond the proven design range. Furthermore, the comparative method cannot provide detailed information that is needed to optimize the design.

The proposed direct calculation-based method is prepared in response to the needs of having a more advanced strength assessment of the containment system for unique or novel design or an unusually large tank beyond the comparative method. The technical approach adopted in these procedures is based on the direct calculation method of applying sloshing load to the containment system using finite element analysis. Determination of sloshing load from numerical simulation and scaled model test is presented. The structural analysis of the containment system considers fluid-structure interaction between liquid cargo and the LNG containment system. The analysis procedure also considers the effect of viscoelasticity when the containment system is partly made of foam material. The acceptance criteria are provided for different members of the containment system, considering the material properties and possible failure modes. However, there are still many technical issues that require further studies although some research and progress have been made on the effect of entrapped gas and compressibility on sloshing pressure [7], scale law to extend the model test pressure to full scale [2], and ship motion/sloshing interaction [8], etc. These effects are not directly considered in the direct calculations of load and structure responses.

An overview of the sloshing analysis and containment system strength assessment is summarized in the flow shown in Fig 1. The proposed direct calculation-based procedure is to be used for the new novel design or when the design is significantly changed from conventional tank design and configuration. For the standard size or conventional design, a simplified traditional comparative assessment method has been used [2].
For the proposed analysis procedure, the load is determined based on sloshing load measurement, which is conducted in small model scale theoretically using a rigid tank structure. The sloshing load is to be evaluated based on the structure response to determine the critical load cases using a simpler response analysis considering the fluid-structure interaction and viscoelastic property of the containment systems. Sloshing impact pressure is represented by a triangular impact pattern to account for impact duration and rising time. Once the design sloshing load is determined, nonlinear FE analysis using the coupled fluid-structure model is performed to calculate the critical responses for various failure modes. The final strength assessment is made based on the acceptance criteria for approval.

**DESIGN SLOSHING LOAD**

**Environmental Condition and Seakeeping Analysis**

To reach the design objective of a nominal 25-year service life in the North Atlantic Ocean, the extreme sloshing loads during the lifetime of LNGC need to be evaluated for the structural assessment of the containment system. The IACS
Recommendation 34 is used to define the wave conditions during the service life. The number in each cell gives a probability of the sea states for the given zero-crossing period, $T_z$, and significant wave height, $H_s$. The probability of each sea states is given in terms of number of occurrence among 100,000 occasions. The two-parameter Bretschneider spectrum is used to model open sea wave conditions in the seakeeping analysis and the “cosine squared” spreading is applied to model short crest waves. The motion of ship and LNG tank can be calculated by spectral-based statistical analysis, which relies on linear superposition principle of wave and ship motion. Ship and tank motion Response Amplitude Operator (RAO) for each wave heading and frequency are calculated by a three-dimensional panel method. The hull-geometry of LNGC is to be accurately modeled from the offset data provided by the designer. The location of center of gravity, mass and mass moment of inertia for each loading condition and filling level are to be obtained from the loading manual provided by the designer. For the calculation of RAO to be used for the tank motion in the sloshing model test, different ship speed may be used for different sea states. The reduction of ship speed at severe sea states may be estimated from towing tank test or operational experience of LNGC with similar hull form and propulsion system. Alternatively, if those data are not available, ship speed of 5 knots may be used for sea states with significant wave height, $H_s$, higher than 12 m. For milder sea states, ship speed of 75% of design speed is used.

Sea States for Sloshing Model Test

Sloshing model tests are to be performed with irregular tank motion corresponding to the most severe sea conditions that can occur during the lifetime of LNGC. The severity of sea condition should be judged based on the severity of sloshing load on the containment system, which means that the most severe sea conditions can be identified only after sloshing model tests are performed. As a result, a group of sea states are selected for the model test based on probability of occurrence of the sea states, tank motion response and proximity of encountering wave period to the tank natural period. Qualified sloshing simulation tool [9, 10] can also be used to pre-screen the sea states to cause the most significant sloshing loads.

The design sloshing load should be defined based on the probability level of $10^{-8}$ in the long-term sense. Unlike the ship motion, spectral-based long-term statistical analysis [11] is not available for sloshing load due to its high nonlinearity. Alternatively, an equivalent short-term approach is introduced to estimate the long-term extreme value. The procedure can be summarized as

- Definition of sea states with probability of occurrence equal to $10^{-5}$.
- Sloshing model test for each selected sea state under long-crested assumptions.
- Evaluation of short-term extreme value of sloshing load of probability level of $10^{-3}$ for each sea state
- Take maximum value among the short-term extreme values

To consider the weathervane operation in severe sea states, the sea states for head- and beam seas are selected on different probability levels. Head sea conditions are selected at a probability level of 0.5 x $10^{-5}$, and beam sea conditions are selected from 2x$10^{-4}$, which represents the nominal 40-year and 1-year wave conditions, respectively. Table 1 shows the wave data with schematics of 40-year and 1-year sea conditions, which are selected based on the occurrence (or probability) level given by the wave scatter diagram provided by the IACS Recommendation No. 34. The 40-year sea conditions are utilized for head seas (180 – 150 deg) and the 1-year sea conditions are utilized for beam seas (90 – 120 deg). For quartering seas, one may use an interpolated wave height. It has also been the model-test practice to assume a long-crested wave when calculating tank motion for the sloshing model test, which will give a more conservative response than the more realistic short-crested sea.

Model Test

Sloshing model tests are to be performed for the selected loading and wave conditions (filling levels, sea states and headings). For each condition, model tests are performed for five hours to evaluate the extreme value of sloshing load of probability level of $10^{-3}$. A detail model test procedure including requirements on test facilities, pressure measurement and statistical analysis of impact load can be found in ABS [5]. Fig 2 shows a model test set-up with model tank, pressure sensors and wiring for measurement.
Table 1 Wave scatter diagram by IACS Rec. 34. Red cell denotes nominal 40 year wave and yellow cell denotes nominal 1 year wave

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Fig 2 Model tank and pressure sensor set up

Sloshing Panel Pressure by measurement

The sloshing impact load recorded by a single pressure sensor provides impact load on a restricted area. The diameter of the sensing area of the modern pressure sensor is only a couple of millimeters, at most. For 1:50 scale model, this area covers about 10cm in the full scale LNG tank, which will not significantly affect structural response if the load is concentrated only on that area. There is also a scale-law issue when evaluating the localized pressure value at full-scale LNG tank from the model test measurements [8]. There are many controversial theories about which scale law should be used for the local impact pressure. The local pressure is very sensitive to local flow phenomena such as air trapping, liquid jet impact and capillary waves, which cannot be covered by existing scale laws based on Euler (Pressure scale is proportional to tank length and liquid density) and Froude (Time scale is proportional to square root of tank length) scaling.
For these reasons, panel pressure is preferred to the local impact pressure when defining design sloshing load for the structural assessment of the LNG membrane system. The size of the panel should be large enough such that the averaged pressure will be affected not by local flow phenomena but by the global liquid motion, which is governed by the conventional scale law based on Euler and Froude scaling. At the same time, the panel size should not be too large to lose the main characteristics of sloshing load for structural analysis. Currently, ABS uses panel averaging performed over a square area of 1 meter by 1 meter size. Panel averaging is usually made by clustered sensors. Fig 3 shows an example of clustered sensors installed at a tank top corner. A total of 16 sensors made of 4 by 4 array have been used.

Fig 3 Clustered sensor at tank corner

**Idealization of Sloshing Pressure Load**

Due to the structural response of the LNG containment system, the sloshing load on the full-scale LNG tank wall is different from that on the rigid tank wall in the test model. The sloshing load on the flexible full-scale LNG tank, $p_{flex}(t)$ is decomposed into two parts: $p_{flex}(t) = p_{rigid}(t) + p_{hydroelasticity}(t)$, where $p_{rigid}(t)$ and $p_{hydroelasticity}(t)$ denote the sloshing load on the rigid wall and additional sloshing load component due to structural response, respectively. Note that $p_{hydroelasticity}(t)$ has to be calculated from dynamic structural analysis with $p_{rigid}(t)$ as the input load.

For the simplicity of structural analysis, the time history of a panel load around its peak is idealized by a triangular pulse, which can be characterized by three parameters – magnitude, duration and rise time.

$$p_{rigid}(t) = \begin{cases} P_{max} t / T_{rise}, & t < T_{rise}; \\ P_{max} (T_{duration} - t) / (T_{duration} - T_{rise}), & T_{rise} \leq t < T_{duration}; \\ 0, & \text{otherwise}. \end{cases}$$

Fig 4 shows the definition sketch of a triangular pulse. A skewness parameter, $\sigma$, is introduced to define the pattern of the triangular pulse, which is defined by Sigma ($\sigma$) = (Rise time) / (2 x Duration). For a general impact signal, the duration and rise time are defined from the time moments when the impact pressure reaches half of the maximum value, as depicted in Fig 5.
The skewness parameter varies from 0 to 2, depending on the shape of the impulse. If the skewness parameter is less than 1, it represents the impulse with a short rise time, which is a typical pressure pattern for the hydrodynamic impact of the incompressible fluid. The pressure pattern with skewness close to 1 represents a symmetric impulse that is often observed when gas is trapped in between fluid and tank wall during the impact. The general pattern of sloshing impact load from the model test can be visualized by pattern plots such as Fig 6. This figure shows the pattern of panel pressure measured at 95%H filling level at head sea. Every sloshing impact is different. Most of the significant or high impact have a symmetric pattern or skewness close to 1, as can be seen in Fig 6(a), and have a short duration as can be seen in Fig 6(c).

Damage Index based on Structure Response for Screening Sloshing Impacts

Because of the dynamic nature of a sloshing impact load with short duration, the influence of such an impact load on the structure depends on the shape and duration of the impact. When evaluating impact loads, the severity of each impact should be evaluated based on the structural response, not simply by the magnitude of the impact load. A damage index is introduced to measure the severity of impact based on the structural response. The damage index is defined as the ratio between the magnitude of the measured impact load and the minimum magnitude of impact load that causes the failure of structure with the same skewness and duration. The damage index, $D_{ij}$, of $i$-th impact with magnitude, $P_i$, duration, $T_i$, and skewness, $\sigma_i$, is given by

$$D_{ij} = \frac{P_i}{P_{ij,\text{failure}}(\sigma_i, T_i)}.$$  

$P_{ij,\text{failure}}$ is the minimum magnitude of impact load which causes the structure to fail in each mode. $i$ denotes the individual impact load and $j$ denotes the individual failure mode. $P_{ij,\text{failure}}$ can be obtained by simple linear dynamic structural analysis based on failure modes for screening.

Statistical Analysis and Critical Design Sloshing Load for FEA

Statistical analysis is performed to determine the design sloshing load in terms of the damage index of the load. Statistical properties may be obtained by first ordering the pressure peaks in decreasing order. The ordering of pressure
peaks should be based on the damage index. Histograms of the damage index may be established by dividing the damage index range into a number of bins. Standard probability distributions are fitted to the data to provide a continuous probability density function. Weibull distributions are preferred for the statistical analysis of the sloshing impact load. Weibull probability density distribution is given by

\[
f(D) = \frac{\gamma}{\beta} \left( \frac{D - \delta}{\beta} \right)^{\gamma - 1} \exp \left[ - \left( \frac{D - \delta}{\beta} \right)^{\gamma} \right], \quad \delta \leq D < \infty
\]

where \( \delta \) is the location parameter, \( \beta \) is the scale parameter and \( \gamma \) is the shape parameter. Standard method of moments is recommended for the estimation of the Weibull parameters.

Design sloshing loads for the structural FE analysis are selected from the measured impact loads represented by damage indices. The damage index of extreme sloshing load of probability level 10^{-3} is given by

\[
D_{1/1000} = \delta + \beta (\ln 1000)^{1/\gamma}
\]

The impact loads that have a damage index between 90% and 110% of the extreme damage index, \( D_{1/1000} \), are selected first. Then the magnitude of the selected impact loads are adjusted to make their damage indices normalized to \( D_{1/1000} \). Fig 7 shows an illustration of the selection process. Each data points represent the impact load measured from the model test. For simplicity, skewness of the impact load is not indicated in the figure, which is found to be unimportant (See Fig 13). The circled data points are the selected impact load to be used as a design sloshing load after normalizing the magnitude. In this paper, the maximum value in this figure will be taken as the design sloshing load \( p = 6 \text{MPa} \) as an example in the later section.
STRUCTURE RESPONSE OF CONTAINMENT SYSTEMS BY FEM

Modeling and Assumptions of Containment Systems

Configurations of LNG containment systems are shown in Fig 8. For the consideration of hydroelasticity, the real containment systems with LNG are simplified as acoustic-structure models. This method was validated in references [1, 2, 12, 13]. In the strength assessment of LNG containment systems, the coupled acoustic-structure FE model is constructed including the fluid-structure interaction to investigate the hydro-elastic/hydro-visco-elastic effects. The layered foam type containment system such as Mark III consists of layer solid plates and can be simplified as a 2D plane strain problem. Its cross-section is to be considered as a 2D representative. Thus, a 2D FE model with LNG representing the layered foam type containment system is to be used to evaluate the strength of the layered foam type insulation structure. The box type containment system such as NO 96 consists of primary and secondary boxes and 3D effect must be considered. Therefore, a 3D FE model with LNG representing the box type containment system is to be used to evaluate the strength and stability of the box type insulation structure.

Fig 8 a) Configuration and Loading/Boundary Conditions for Mark III Containment Systems

For material properties of the insulation structure, mastic is an isotropic material, plywood is a transversely isotropic material, and foam is a visco-elastic material. LNG is assumed as an acoustic medium. The uniform impulse pressure is applied as the loading condition at the interface between LNG and the insulation structure. Loading and boundary conditions are shown in Fig 8.
Solution Procedures for Structural Analysis

1) Procedures for Layered Foam Type Containment System

For the layered foam type containment system such as Mark III, nonlinear dynamic stress FE analysis has been conducted on the coupled acoustic-structure model using commercial codes. In the structural analysis procedure, the following steps are executed: Step 1 FE model is constructed in terms of all material properties of plywood, foam and mastic under the design sloshing load; Step 2 Based on FE results, stress distribution in each component of the insulation structure is evaluated with the ultimate strength of material. For instance, all stress components are required in plywood and foam layers, and von Mises stress is required in mastics; Step 3 Based on FE results, displacement distribution in each component of the insulation structure is evaluated with the allowable deformation of the containment system. Furthermore, parametric study of material properties and loading patterns is conducted for hydro-elastic/hydro-visco-elastic effects on stress response in the structure.

2) Procedures for Box Type Containment System

For the box type insulation system such as NO 96, nonlinear dynamic stress FE analysis has been conducted on the coupled acoustic-structure model using commercial codes. Nonlinear dynamic post-buckling FE analysis and eigenvalue buckling FE analysis are conducted on the simplified model without LNG using commercial codes. In the structural analysis procedure, the following steps are to be executed: Step 1 FE model is constructed in terms of all material properties under the design sloshing load; Step 2 Based on FE results, stress and displacement distributions in each component of the insulation structure are evaluated with the ultimate strength of materials and the allowable deformation of the containment system; Step 3 Eigenvalue buckling analysis is conducted to determine static critical buckling loads and corresponding buckling modes; In most cases, the minimum static critical buckling load is taken as the critical buckling load for the conservative design. Otherwise, Steps 4 and 5 are continued. The first buckling mode is employed in the following step analysis. Step 4 An imperfection is introduced by adding the first buckling mode to the ‘perfect’ geometry of the box type insulation structure for nonlinear dynamic post-buckling analysis. The scale factor of the lowest buckling mode is recommended to be 5% of plate thickness; Step 5 Nonlinear dynamic post-buckling FE analysis is conducted to determine the load-deflection curve under the impact loading. Thus, the critical buckling load of the insulation structure is determined in terms of the buckling criterion described in Section 4. Furthermore, parametric study of loading patterns is conducted for the effect of loading patterns with different skewness and durations on stress response in the insulation structure.
Example Analysis on Mark III Containment System

As an example, following procedures in the above section, structural analysis on Mark III containment system has been conducted. FE mesh for Mark III containment system is shown in Fig 9. 2D plane strain elements and 2D acoustic elements are used in the layered structure and the acoustic medium, respectively. A uniform impulse triangle pressure as a critical design sloshing load from last chapter (See Fig 7) is applied on the top surface of the insulation structure, shown in Fig 10. From FE results, von Mises stress contours in the insulation structure are shown in Fig 11 as an example.

In the strength assessment, all maximum stresses are obtained from FE analysis under the design sloshing load, which is determined from screening procedure described in the last chapter. The safety factor in stress analysis is defined as the ratio of strength to maximum stress. Strength evaluation of foam, plywood, and mastic can be conducted using maximum stress from FE results and ultimate strength from experimental data. The major concerns about the strength capability of Mark III containment system are related to the maximum allowable stress along different orientations in each layer. The plywood in a composite material has the weakest strength at bonding across layers leading to the delamination of the material. Either normal stress or shear stress in the plywood is very important at bonding locations.

Fig 9 FE Mesh of Mark III Containment System

Fig 10 Uniform Impulse Triangle Pressure

Fig 11 Snapshot of von Mises Stress Contour in Layer Structure
Parametric study has also been done to investigate the effect of different loading patterns on the hydro-visco-elastic response of the coupled model by varying impact duration and skewness. To show the load reduction due to hydro-visco-elastic effects more clearly, hydro-visco-elastic load factor is introduced as

$$\text{Hydro-visco-elastic Load Factor} = \frac{p_{\text{flex}}(t)}{p_{\text{rigid}}(t)}$$

where $p_{\text{rigid}}$ is the applied pressure on the rigid structure without considering hydro-visco-elastic effects and $p_{\text{flex}}$ is the resultant pressure which is the stress response at the interface in the coupled model, considering hydro-visco-elastic effects. FE results indicate that the hydro-elastic effects on the containment system, considering the fluid-structure interaction, is very obvious compared to the insulation system structure without considering LNG, shown in Fig 12. The hydro-visco-elastic effects at different skewness and durations are investigated and the hydro-visco-elastic load factors for different skewness and durations are shown in Fig 13. This figure indicates that with increasing duration, the hydro-visco-elastic effects decrease. For long durations, the effect on hydro-visco-elastic response at large skewness is more than that at small skewness; but for short durations, the effect on hydro-visco-elastic response at large skewness is less than that at small skewness. It can be explained that the short durations are not long enough for hydro-visco-elastic response at large skewness. It can be concluded that hydro-visco-elastic effect cannot be neglected, especially in the case of a short duration. The lower the skewness is, the more effect on hydro-visco-elastic response that there will be. Numerical results also show that the skewness is not sensitive to the hydro-visco-elastic load factor.

![Fig 12 Hydro-elastic Effects in Structure](image)

![Fig 13 Hydro-Visco-Elastic Load Factor](image)

**Failure Modes and Acceptance Criteria**

Failure modes in LNG containment systems are categorized as yield/rupture, buckling, and serviceability limit. Corresponding to failure modes, there are acceptance criteria. All these criteria are employed in the strength evaluation of LNG containment systems. In the box type containment system, primary and secondary boxes are subjected to the compressive loading so as to possibly lead to the buckling failure of structure. However, in the layered foam type containment system, no buckling failure issue exists due to the layered solid plate structure. Failure modes are also associated with material properties such as stress-strain relation, ultimate strength, and fracture toughness. The layered foam type containment system is made of different materials including polyurethane foam (PUF), plywood, and mastic, while the box type containment system is made of two kinds of plywood materials. In general, plywood and PUF are anisotropic materials, in which ultimate strengths are different along different orientations, even if transversely isotropic elastic and isotropic elastic/visco-elastic constitutive models are assumed in FE analyses, respectively. Mastic is an isotropic material. Thus, maximum normal tensile/compressive stress and shear stress in RUF and plywood are evaluated with corresponding strengths in each orientation. Maximum von Mises stress in mastic is evaluated with ultimate strength of material.
Yield/Rupture Criterion
Nonlinear dynamic FE analysis on the insulation structure is performed to obtain stress fields under the design sloshing load. For the layered foam type containment system, maximum normal tensile/compressive stress and shear stress are evaluated with the ultimate strength of material in each orientation for foam and plywood layers, and maximum von Mises stress is evaluated with the ultimate strength of material for mastics. For the box type containment system, maximum von Mises stress is evaluated with the ultimate strength of material for plywood boxes and mastics.

Buckling Criterion
The maximum compressive pressure from the design sloshing load applied to the top surface of the primary box in the box type containment system is evaluated with the critical buckling load. The critical buckling load is determined through the following two step analyses, including eigenvalue buckling FE analysis and nonlinear dynamic post-buckling FE analysis.

Serviceability Limit Criterion
Maximum displacement in each component is evaluated with the allowable deformation.

CONCLUSIONS
A proposed procedure with analysis procedures has been developed for the strength evaluation of containment systems in the membrane-type LNG carrier. The analysis procedure consists of seakeeping, sloshing analysis, and model test measurement to find the maximum sloshing load on the rigid wall during the LNG carrier’s lifetime operation in the design environmental condition, and a hydro-elastic/hydro-visco-elastic analyses of containment systems considering the fluid-structure interaction. In this study, a method to determine the design sloshing load has been developed and a coupled fluid-structure model has also been developed to simulate the hydro-elastic/hydro-visco-elastic effects in LNG containment systems under the design sloshing load. FE solution procedures in structural analysis have been developed in the strength assessment of LNG containment systems. As an example, dynamic stress FE analysis on Mark III insulation system has been performed to investigate hydro-visco-elastic effects using the elastic/visco-elastic constitutive models in the structural part and an acoustic medium in LNG part. The strength of containment system has been evaluated based on maximum stresses in the structure from FE results and the ultimate strength of materials from experimental data. FE results have also shown the hydro-elastic effects on stress response in the structure under the impact loading as well as the hydro-visco-elastic effects under different loading patterns with different impact skewness and durations. For the strength evaluation, failure modes and acceptance criteria have also been proposed in the procedure.

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REFERENCES


