ABSTRACT

As LNG carriers become larger and new operating conditions are being designed, it is essential to develop a new procedure for the strength evaluation of a membrane-type LNG containment system under sloshing loads. The conventional comparative method based on existing service experiences and previous damage cases is currently used in most cases, but this method is only valid for designing new LNG carriers with similar size and type of existing ones. In this study, an analytical solution of acoustic-solid interaction has been derived and a simple 2D coupled acoustic-solid model has been simulated to investigate hydro-elastic effects for the verification purpose. After validation of FE modeling, a coupled model considering the fluid-structure interaction between LNG and containment system has been developed for structural analysis of LNG Mark III containment system. For LNG Mark III containment system, nonlinear dynamic FE analysis under sloshing impact pressure has been conducted using the fluid-structure coupling model. In FE simulations, the hydro-elastic effect in structural response has been studied through considering LNG as an acoustic medium, foam as a visco-elastic material, plywood as an orthotropic material, and mastic as an isotropic material. Parametric study has also been done to investigate the effects of material properties and loading patterns on hydro-elastic response in the coupled fluid-structure model. Based on FE results and experimental data, the strength of LNG Mark III containment system has been evaluated in terms of acceptance criteria. Finally, the new procedure has been developed for the strength evaluation of membrane-type LNG containment systems.

INTRODUCTION

The tank inner skin in the LNG tank is covered by insulation system that consists of thin metal membranes for the containment of liquid cargo and insulation material to maintain the temperature of the cargo in the cryogenic condition. Besides the steel hull structure, all other members of containment system are flexible and made of softer materials such as plywood and polymer foams. As a result, more active fluid-structure interaction is expected during the sloshing impact in LNG tanks compared to the ordinary tankers without insulation system. The failure mode of the containment system is also quite different from the hull structures. Therefore, it is very important to investigate the strength of LNG containment systems under sloshing loads. In the recently published ABS guidance notes (ABS [4]), the idealization of sloshing impact load has been introduced, and the three levels of strength assessment have been developed in structural analysis of LNG containment system based on previous work (Lee et al. [5], Shin, et al. [6], Lee, et al. [7], and ABS [8]). The strength evaluation...
of LNG NO 96 containment system has been conducted based on FE analyses (Wang et al. [9]).

In this study, an analytical solution to obtain the generalized added-mass force is derived for a simple 2D coupled acoustic-solid model after simplifying free-surface shape by a straight line. For compressible liquid model, finite-difference methods are used to solve the interaction problem numerically. A benchmark problem, in which analytical and numerical solutions are available, is presented such that those solutions can be utilized to validate hydro-elastic analysis results from FE simulation. After the validation of numerical modeling, a coupled acoustic-structure model is developed to simulate Mark III containment system. Stress and displacement fields in the structure are obtained from the finite element modeling. Based on the acceptance criteria, the strength evaluation of Mark III containment system in LNG carriers is done in terms of numerical results and material properties.

THEORETICAL BACKGROUND

Fluid-Structure Interaction in Coupling Model

In LNG containment system, LNG is assumed to be an acoustic medium. The equilibrium equation for small motions of acoustic medium is

\[ \frac{\partial p}{\partial t} + \rho_f \ddot{u}_f = 0 \]  

(1)

where \( p \) is the excess pressure, \( \mathbf{x} \) is the spatial position, \( \ddot{u}_f \) is the acceleration, and \( \rho_f \) is the density of the acoustic medium.

The constitutive behavior of the fluid is assumed to be inviscid, linear, and compressible, so

\[ p = -K_f (\mathbf{x}, \theta_f) \frac{\partial}{\partial \mathbf{x}} \cdot \mathbf{u}_f \]  

(2)

where \( K_f \) is the bulk modulus of the fluid.

The impedance boundary condition along the acoustic medium surface is governed by

\[ \dot{u}_{\text{out}} = \frac{1}{c_1} p \]  

(3)

where \( \dot{u}_{\text{out}} \) is the particle velocity in the outward normal direction of the acoustic medium surface, \( p \) is the pressure, and \( 1/c_1 \) is the proportionality coefficient.

The equation of motion for a structure is written as

\[ \mathbf{F} - \mathbf{I} = \mathbf{M} \cdot \ddot{\mathbf{u}} \]  

(4)

where \( \mathbf{M} \) is the diagonal lumped mass matrix, \( \mathbf{F} \) is the applied load vector, and \( \mathbf{I} \) is the internal force vector, and \( \ddot{\mathbf{u}} \) is the acceleration. The above equations are integrated using the explicit central difference integration rule

\[ \ddot{\mathbf{u}}^{(i+1/2)} = \ddot{\mathbf{u}}^{(i-1/2)} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2} \ddot{\mathbf{u}}^{(i)} \]

\[ \ddot{\mathbf{u}}^{(i+1)} = \ddot{\mathbf{u}}^{(i)} + \Delta t^{(i+1)} \ddot{\mathbf{u}}^{(i+1/2)} \]  

(5)

where \( \ddot{\mathbf{u}} \) is velocity and \( \dddot{\mathbf{u}} \) is acceleration. The superscript \( (i) \) refers to the increment number and \( i-1/2 \) and \( i+1/2 \) refer to midincrement values. The central difference integration operator is explicit in that the kinematic state can be advanced using known values of \( \dddot{\mathbf{u}}^{(i-1/2)} \) and \( \dddot{\mathbf{u}}^{(i)} \) from the previous increment.

The continuity conditions of displacement as well as stress and pressure in the normal direction at the interface between the acoustic medium and the structure are

\[ (u_{2z})_{\text{solid}} = (u_{2z})_{\text{acoustic}} \]

\[ (\sigma_{2z})_{\text{solid}} = p_f + p_{\text{forcing}} \]  

(6)

where \( u_{2z} \) and \( \sigma_{2z} \) are normal displacement and stress components, respectively. \( p_f \) is the pressure in the acoustic medium and \( p_{\text{forcing}} \) is an applied pressure at the interface.

In coupled acoustic-structure FE simulations, it requires the use of acoustic elements and either acoustic interface elements or a surface-based interaction. The pressure field modeled with acoustic elements creates a normal surface traction on the structure, and the acceleration field modeled with structural elements creates the natural forcing term at the fluid boundary. There are two methods to enforce this physical coupling condition in FE analysis. If the structural and acoustic meshes share nodes at the boundary, lining this boundary with acoustic-structural interface elements will enforce the required condition. Alternatively, a surface-based procedure can be used to enforce the coupling. Surfaces on the structural and fluid meshes, and the interaction between the two meshes are defined, and separate nodes at two sides of the interface between the acoustic medium and the structure are bonded together.

Analytical Solution of Acoustic-Solid Interaction

In case of compressible liquid model such as acoustic medium, a numerical solution is obtained by solving the wave equation using the finite difference method. A rectangular liquid domain with length, \( L \), and height, \( h \), is contacting with solid, shown in Fig. 1.

Governing equation is given by
\[ \nabla^2 \phi = \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2}, \quad 0 < y < h_x \]

(7)

Kinematic boundary condition at liquid-solid interface is

\[ \frac{\partial \phi}{\partial y}(x,0,t) = \frac{\partial \psi}{\partial t}(x,0,t) \]

(8)

Dynamic boundary condition at liquid-solid interface is

\[ \sigma_{yy} = -p(x,t) - p_{HE}, \quad \sigma_{yy} = 0, \quad y = 0 \]

where \( p(x,t) \) is the hydroelastic pressure, \( p_{HE} \), is given by \( p_{HE} = -\rho \frac{\partial \phi}{\partial t} \).

On the other boundaries, C1, C2 and C3, three different boundary conditions are imposed depending of the characteristics of the problem:

Symmetric condition (Rigid Wall):

\( C1: \phi(0,y,t) = 0, \quad C2: \phi(x,h_x,t) = 0, \quad C3: \phi(L,y,t) = 0; \)

Asymmetric condition (Free Surface):

\( C1: \phi(0,y,t) = 0, \quad C2: \phi(x,h_x,t) = 0, \quad C3: \phi(L,y,t) = 0; \)

Radiation condition (Impedance):

\( C1: \frac{\partial \phi}{\partial t} + c \frac{\partial \phi}{\partial x} = 0, \quad C2: \frac{\partial \phi}{\partial t} + c \frac{\partial \phi}{\partial x} = 0, \quad C3: \frac{\partial \phi}{\partial t} + c \frac{\partial \phi}{\partial x} = 0; \)

Second-order central difference is used to discretize the governing and boundary conditions.

DYNAMIC FE ANALYSIS ON COUPLED ACOUSTIC-SOLID MODEL

Sloshing Loads

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 an LNG carrier need to be evaluated for the structural assessment of the LNG containment system. ABS recommends the sloshing model test be performed to estimate the extreme sloshing load. Because of the sensitivity of the sloshing impact load in location and area, panel pressure averaged over a specified area is preferred to the local pressure measured by individual pressure sensors. The measured panel pressures are statistically processed to estimate the design load. It should be noted that not only the magnitude but also the time footprint of the sloshing load is important for the dynamic response of the LNG CS.

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, rise time and duration.

\[
\begin{align*}
\frac{p(t)}{p_{max}} & = \begin{cases} 
1, & 0 < t < T_{rise}; \\
\frac{T_{duration} - t}{T_{duration} - T_{rise}}, & T_{rise} < t < T_{duration}; \\
0, & \text{otherwise}
\end{cases}
\end{align*}
\]

Fig. 2 shows the definition sketch of a triangular pulse. Skewness parameter, \( S = 2T_{rise} / T_{duration} \), is introduced to define the loading pattern. 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 3.

![Fig. 2 Triangular pulse for uniform pressure](image)

Fig. 3 Idealization pressure by a triangular pulse

The skewness parameter varies from 0 to 2, depending on the shape of the impulse in such loading case. Based on the sloshing loads, the strength
assessment of LNG containment system can be implemented.

**Coupled Simulation of 2D Simple FE Model**

The acoustic medium and the solid structure are coupled together through the interface in a 2D simple FE model. The geometry and dimensions of the coupled acoustic-solid model in plane strain state are shown in Fig. 4. Linear elastic constitutive model is used for solid material. Material parameters are $\rho = 120$ kg/m$^3$, $E = 100$ MPa, and $\nu = 0.2$. The inviscid, linear, and compressible constitutive model is employed for acoustic medium. For LNG, $\rho = 474$ kg/m$^3$ and $C_d = 1,700$ m/s.

Two sides of solid structure and acoustic medium are constrained along the normal direction. The bottom of the solid structure is constrained along all directions. In numerical simulations, three boundary conditions are used on the top surface of acoustic medium, which are rigid wall, free surface, and radiation (impedance) boundary conditions, respectively. A uniform triangular pulse pressure, shown in Fig. 2, is applied to the top surface of solid structure along the interface, in which $p_{\text{max}} = 3.5$ MPa, $T_{\text{rise}} = 0.001$ s, and $T_{\text{duration}} = 0.01$ s.

FE model consists of 4,141 nodes and 4,000 elements for the acoustic medium, as well as 2,121 nodes and 2,000 elements for the solid, respectively. The adaptive mesh technique is employed to avoid the distortion of elements, due to the large ratio of deformation speed to wave speed for the material in this simulation. The plane strain element, CPE4R (4-node bilinear, reduced integration with hourglass control), is used in solid part, and 2D elements, AC2D4R (4-node linear 2D acoustic quadrilateral, reduced integration with hourglass control), are used in acoustic medium.

For coupled acoustic-solid simulations, the continuity conditions of displacement and stress along the normal direction in the interface are as the following: $u_x^{\text{solid}} = u_x^{\text{acoustic}}$ and $(\sigma_{22})^{\text{solid}} = p_f + p_{\text{forcing}}$.

The hydro-elastic effect on the stress and pressure in the coupled acoustic-solid model is investigated under three different boundary conditions on the top surface of acoustic medium, which are rigid wall, free surface, and radiation (impedance) boundary conditions, respectively. Fig. 5a shows the effect of hydro-elasticity on the stress is negligible under the radiation (impedance) boundary condition. However, there exists oscillation for the free boundary condition in Fig. 5b. Under the rigid wall boundary condition, the effect of hydro-elasticity on the stress is very obvious and cannot be ignored, shown in Fig. 5c. In Fig. 5, all the comparisons between analytical and numerical results under three boundary conditions show that they are very consistent. Thus, both analytical and FE results are verified each other through this simple 2D coupled acoustic-solid model under the uniform triangular impulse pressure.

**Coupled Simulation of Mark III Containment System**

The Mark III containment system in LNG carrier is a layered structure composed of polyurethane (PU) foam, plywood, and mastic [See Fig. 6(a)], and it can be simplified as a 2D plane strain problem [See Fig. 6(b)]. 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. Coupled acoustic-structure model for LNG Mark III insulation system is shown in Fig. 6(b). In FE mesh, the plane strain element, CPE4R (4-node bilinear, reduced integration with hourglass control), is used in structure part, and 2D elements, AC2D4R (4-node linear 2D acoustic quadrilateral, reduced integration with hourglass control), are used in acoustic medium.

The layered structure consists of LNG, plywood, foam, and mastic materials. Linear elastic model and visco-elastic constitutive model [Standard Linear Solid (SLS) model] are used for PU foam, respectively. The stress and strain relation in visco-elasticity is 

\[ \sigma_{ij} = \int_{-\infty}^{\infty} 2\mu(t-\xi) \frac{\partial e_{ij}}{\partial \xi} + \delta_{ij} \int K(t-\xi) \frac{\partial e_{ii}}{\partial \xi} \, d\xi, \]

where \( e_{ii} \) is the volumetric strain, \( e_{ij} = \epsilon_{ij} - \frac{1}{3} \epsilon_{kk} \delta_{ij} \) is deviatoric strain, \( \epsilon_{ij} \) and \( \epsilon_{kk} \) are stresses, and \( \mu \) and \( K \) are the shear and bulk relaxation moduli, respectively.

In SLS model, \( E(t) = E_\infty + \sum_{i=1}^{\infty} \mu_i \exp(-t/\tau_i^\infty) \) and \( K(t) = K_\infty + \sum_{i=1}^{\infty} K_i \exp(-t/\tau_i^\infty) \). In SLS model, \( E_\infty \) is instantaneous elastic modulus, \( E_\infty \) is long time modulus, and \( \tau \) is relaxation time. Plywood is assumed as an orthotropic elastic material. Herein, it is further simplified as transverse isotropy, which is characterized by a plane of isotropy at every point in the material. Assuming the 1-2 plane to be the plane of isotropy at every point, transverse isotropy requires that 

\[ E_{11} = E_{22}, \quad E_{12} = E_{21}, \quad \nu_{12} = \nu_{21}, \quad \nu_{13} = \nu_{23} = \nu_{33}, \]

where \( p \) and \( t \) stand for “in-plane” and “transverse,” respectively. Mastic is assumed as an isotropic elastic material.

Loading and boundary conditions are shown in Fig. 6(b). The bottom of mastic in the insulation structure is constrained along all directions. Due to the symmetry of the structure, two sides of solid structure and acoustic medium are constrained along the normal direction. In acoustic medium, the radiation (impedance) boundary condition is used for the top surface to simulate an infinite acoustic medium. In the interface between acoustic medium and structure, separate nodes at two sides of the interface are bonded together to satisfy the continuity conditions using the *TIE option. For other interfaces of two different materials such as plywood and foam, foam and plywood, as well as plywood and mastic, at each interface meshes for both materials share nodes at the boundary to enforce the deformation compatibility.

Based on sloshing load analysis, a uniform impulse triangle pressure is employed as the applied load in the interface between acoustic medium and composite structure, shown in Fig. 2, in which \( p = 0.8 \) MPa, \( T_{\text{rise}} = 0.001 \) s, and \( T_{\text{duration}} = 0.01 \) s. The material properties of polyurethane foam are time-dependent (or rate-dependent) and exhibit in dynamic behavior. Therefore, due to highly transient and dynamic loading on the insulation system during cargo sloshing events, dynamic effects to dominate the mechanical response of PU foam material need to be considered in structural analysis.

RESULTS AND DISCUSSION

Nonlinear dynamic finite element analysis has been conducted on the coupled acoustic-structure model using ABAQUS (HKS Inc. [10]). Stress, displacement and strain distributions in each layer are obtained from numerical results. Thus, the strength and deformation of the insulation system can be evaluated based on appropriate criteria.

Stress - von Mises stress, normal stress and shear stress contours in the insulation structure are obtained from FE results, respectively. The shear and bulk relaxation moduli are expressed in Prony series as

\[ \mu(t) = \mu_\infty + \sum_{i=1}^{\infty} \mu_i \exp(-t/\tau_i^\infty) \]

and

\[ K(t) = K_\infty + \sum_{i=1}^{\infty} K_i \exp(-t/\tau_i^\infty) \].
the corner of lower plywood layer and mastic. Detailed three stress components in foam layer and plywood layer are also obtained from FE analysis. Maximum normal and shear stresses in each layer are found out to evaluate the strength of foam layer and plywood layer. Maximum von stress in mastic is also found out to evaluate the strength of mastics.

Since the stress concentration takes place near the corner of lower plywood layer and mastics, the stresses near the above interfaces are relatively high. Thus, the interfacial delamination most likely occurs caused by either normal or shear stress. Such kind of failure is associated with bonding material properties at the interface.

Ultimate strengths of foam, plywood, and mastic along different orientations are measured from material property testing. The safety factor in stress analysis is defined as

\[
\text{Safety Factor} = \frac{\text{Strength}}{\text{Maximum Stress}}
\]

The major concerns about the strength capability of the 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. Nonlinear dynamic FE analysis indicates that the Mark III insulation system is safe in strength under the uniform impulse pressure with the maximum value of 0.8 MPa. FE results also give maximum normal tensile/compressive stress and shear stress under the uniform impulse pressure with the maximum value of 3.5 MPa. Results show that there is a linear relation between the applied load and the stress for the same loading history.

Deformation - The displacement along the vertical direction, which is the same as the loading direction, in the insulation structure is obtained from FE results. Since the visco-elastic behavior is considered for the foam material, the maximum strain rate needs to be checked in the foam layer. The maximum strain rate in the foam layer is about 5 s⁻¹.

The effect of material properties on the hydro-elastic/hydro-visco-elastic response has been also investigated under the uniform impulse pressure with the maximum value of 3.5 MPa using elastic and visco-elastic constitutive models, shown in Fig. 8. Referring to the only insulation structure without considering LNG, stress response in the coupled acoustic-structure model reduced 31% due to the hydro-elastic effect, and stress response in the coupled model reduced 43%-66% due to the hydro-visco-elastic effect.

Recently, more detailed tests on foam material properties have been conducted and experimental data indicate that the Young’s modulus of PU foam does not change very much at low strain rates from \(10^3\) – \(10^1\) s⁻¹. This means that the foam material may be simplified as a linear elasticity in numerical modeling in this case, which is also shown in Fig. 8.

The impact-loading pattern is given in terms of skewness parameter of the impact pressure, which is defined by \(S = \frac{2T}{T_{\text{rise}}}\). The effect of impact duration and shape on the hydro-visco-elastic response of the coupled model is investigated by varying duration and skewness. To show the load reduction due to hydro-elastic/hydro-visco-elastic and dynamic effect more clearly, hydro-elastic load factor and hydro-visco-elastic load factor are defined as

\[
\text{Hydro-elastic Load Factor} = \frac{\max p_{\text{elas}}(t)}{\max p_{\text{nal}}(t)}
\]

\[
\text{Hydro-visco-elastic Load Factor} = \frac{\max p_{\text{visc}}(t)}{\max p_{\text{nal}}(t)}
\]

The applied pressure at the interface without considering hydro-visco-elastic effects is \(p_{\text{nal}} = 3.5\) MPa. \(p_{\text{elas}}\) stands for the stress response in the coupled model considering hydro-visco-elastic effects. The hydro-elastic effects at different skewness and durations are investigated and the hydro-elastic load factors for different skewness and durations are shown in Fig. 9(a). 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. 9(b). These two figures indicate that with increasing duration, the hydro-elastic/hydro-visco-elastic...
effects decrease. For long durations, the effect on hydro-elastic/hydro-visco-elastic response at large skewness is more than that at small skewness; but for short durations, the effect on hydro-elastic/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-elastic/hydro-visco-elastic effect cannot be neglected, especially in case of short duration. Lower the skewness is, more effect on hydro-elastic/hydro-visco-elastic response there will be.

![Hydro-elastic/hydro-visco-elastic load factor for different skewness and durations](image)

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.

**CONCLUSIONS**

A coupled acoustic-structure model has been developed to investigate the hydro-elastic/hydro-visco-elastic effects in Mark III containment system. The nonlinear dynamic finite element analysis has been conducted on the containment system using finite element commercial code. The coupling technique to satisfy continuity conditions in the interface has been implemented using TIE option. Two FEM models, a 2D simple coupled model and a coupled layered structure model in terms of Mark III containment system, have been investigated in coupling simulations. An analytical solution for the coupled acoustic-solid model has been derived and can be solved using the finite difference method. For the simple model, the comparison of numerical and theoretical results shows to be consistent so as to validate the dynamic finite element analysis on the coupled acoustic-structure model. Dynamic stress analysis on LNG Mark III insulation system has been performed to evaluate the strength of the insulation structure and FE results indicate that all maximum normal and shearing stresses along different orientations are less than the ultimate strength of materials. Therefore, the Mark III insulation system is safe in strength under the uniform impulse pressure with the maximum value of 0.8 MPa. Under the uniform impulse pressure, the effect of material properties on the hydro-elastic/hydro-visco-elastic response has been investigated using elastic and visco-elastic constitutive models. Referring to the pure insulation structure, stress response in the coupled acoustic-structure model reduced 31% due to the hydro-elastic effect, and stress response in the coupled model reduced 43%-66% due to the hydro-visco-elastic effect. Hydro-elastic and hydro-visco-elastic effects at different loading patterns with different skewness and durations have been compared for the 2D simple coupling model and the Mark III insulation system. It can be concluded that hydro-visco-elastic effect cannot be neglected, especially in case of short duration. Lower the skewness is, more effect on hydro-visco-elastic response there will be. With increasing duration, the hydro-visco-elastic effect decreases in the coupled acoustic-structure model.

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Strength Evaluation of LNG Containment System Considering Fluid-Structure Interaction under Sloshing Impact Pressure


