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AXIOMATIC DESIGN OF AN IMPACT RESISTANCE SYSTEM FOR LNG CONTAINMENT SHIPS

Ki-Hyun Kim
kimkyun@kaist.ac.kr
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
373-1 Guseong-dong Yuseong-gu
305-701, Daejeon, South Korea

Byung Chul Kim
zagato00@kaist.ac.kr
ACCIS, Aerospace Engineering, University of Bristol,
Queen's Building, University Walk, Bristol BS8 1TR,
UK

Bu Gi Kim
willy4@kaist.ac.kr
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
373-1 Guseong-dong Yuseong-gu
305-701, Daejeon, South Korea

Dai Gil Lee
dglee@kaist.ac.kr
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
373-1 Guseong-dong Yuseong-gu
305-701, Daejeon, South Korea

ABSTRACT

Liquefied nitrogen gas (LNG) containment ships must provide cryogenic reliability and safety for at least 40 years of operation. The LNG containment system on these ships is composed of metal membrane as a barrier and insulation panels. Recently, it has been found that the barrier systems can be damaged by impact pressure of LNG due to the generation of cavitation in containment. The impact pressure, which is higher than 1 MPa, with a duration less than a few μs, can induce deformation of the metal membrane as well as damage the insulation panels. However, in conventional designs of LNG containment systems, this problem was hard to overcome due to the coupled nature of system. Therefore, in this study, the axiomatic design approach was employed to develop a new impact resistance system for LNG containment ships.

Keywords: LNG ship, cryogenic, impact, fatigue, cavitation

1 INTRODUCTION

The cryogenic containment system for LNG (liquefied natural gas) ships consists of a dual barrier system and insulation panels as shown in Figure 1.

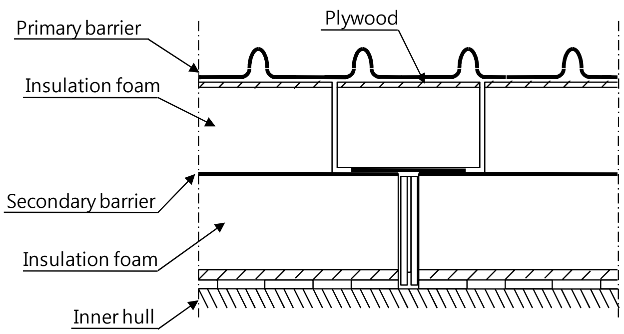

Figure 1. Schematic diagram of configuration of membrane type LNG carrier.

Each containment system has an octagonal pillar and the total storage volume (with 3-4 containers in a LNG ship) is over 150,000 m^3 [Kim and Lee, 2008]. The primary barrier is composed of welded thin stainless steels. The secondary barrier is composed of bonded metal sheets with epoxy adhesive for high gas tightness [Kim and Lee, 2008]. When the primary barrier fails, the role of the secondary barrier is to maintain a leak-tight seal for the LNG during the 15 days that it may take to arrive at the nearest harbor for repairs. The insulation panel is made of glass reinforced polyurethane foam which has low thermal conductivity and plywood which has high stiffness and low density. The polyurethane foam and plywood are adhesively bonded to create a light weight structure with high bending stiffness.

Recently, it has reported that the primary barrier was deformed and insulation panels were damaged due to the high impact pressure of the gas during operation. In conventional approaches, the impact pressure was estimated with a sloshing pressure by the LNG flow in the LNG containment unit due to the movement of the LNG ship. However, from numerical analysis, it was found that the impact pressure by sloshing under certain conditions could not induce the damages experienced by the containment system. Also, conventional test methods could not be used to investigate the damages by high impact pressure due to the differences between the test conditions and the real conditions in LNG containment ships. Therefore, another approach was needed to verify the high impact pressure. Many ship building industries have tried to overcome these problems to guarantee the reliability and safety of LNG containment systems. However, in the conventional design of LNG containment, reliability and safety are hard to achieved due to the coupled design of LNG containment.

In this study, the high impact pressure was investigated with a focus on cavitation phenomena. Cavitation is the formation of gas bubbles of LNG, where the local pressure drops below the vapour pressure. After the formation of these gas bubbles, the bubbles rapidly collapse and produce shock waves with a impact pressure higher than 100 MPa [Franc and Michel, 2005]. Since the LNG inside the containment unit could evaporate easily due to the low pressure inside, cavitation could be occurred easily with high impact pressure. Therefore, the cavitation theory should be considered to explain the high pressure in the containment system. In this study, a pressure resistance system with pressure resistance structure and a vibration isolation layer is developed to decrease the impact pressure applied to the containment structure using the axiomatic design approach.

2 AXIOMATIC DESIGN OF THE CRYOGENIC CONTAINMENT SYSTEM FOR LNG SHIP

For efficient and safe transportation of LNG, leak-tightness and high thermal insulation performance should be guaranteed. Therefore, the functional requirements of LNG containment could be written as follows:

FR_1 = Prevent LNG leakage.

FR_2 = Increase insulation performance.

While the tightness of the containment system is largely dependent on the structure of the barrier systems, the thermal insulation performance is largely dependent on the thermal properties of the insulation panels. Therefore, the design parameters of LNG containment could be written as follows,

DP_1 = Barrier system

DP_2 = Insulation panels

The design equation for the LNG containment could be depicted with FRs and DPs above as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \qquad (1)$$

2.1 DECOMPOSITION OF FR AND DP BRANCH OF THE BARRIER SYSTEM

The barrier system (primary barrier) with a thin SUS foil with a thickness of 1.2 mm has direct contact with low temperature LNG (-163^{o}C). The primary barrier had corrugation low plane stiffness for low thermal stress at cryogenic temperature and it is welded for high tightness. Also, the primary barrier should have high pressure resistance against impact pressure. Therefore, the functional requirements of primary barrier could be written as follows,

FR_{11} = Keep gas tightness.

FR_{12} = Have low surface stiffness.

FR_{13} = Have high pressure resistance.

In conventional barrier system design, two DPs for satisfying the three FRs could be written as follows:

DP_{11} = Welding structure of SUS foil

DP_{12} = Corrugation

The design equation for the conventional barrier system may be written as follows:

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \\ x & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \end{Bmatrix} \qquad (2)$$

The construction process of the primary barrier is largely dependent on the shape of the corrugation. The shape of the corrugation should be maintained for constructability. Therefore, the constraint for the barrier system design may be dictated as follows:

C = Maintain formability of corrugations of SUS foil.

Since the design matrix does not satisfy the half triangular condition, a new barrier system of LNG ship is needed [Lee and Suh, 2006]. In conventional research, the shape of corrugation was changed to decrease the plane stiffness as well as to increase the pressure resistance. However, these two requirements could not be satisfied simultaneously through the optimization of the shape of the corrugation due to the coupled design as shown in equation (2). When the plane stiffness is low, the primary barrier could be deformed easily under impact pressure. Moreover, there is a constraint of the thickness of SUS foil for satisfying bending formability during the fabrication process of corrugated SUS foil. Therefore, in this study, the pressure resistance structure as an independent component was developed to increase the pressure resistance without increasing the plane stiffness as shown Figure 2.

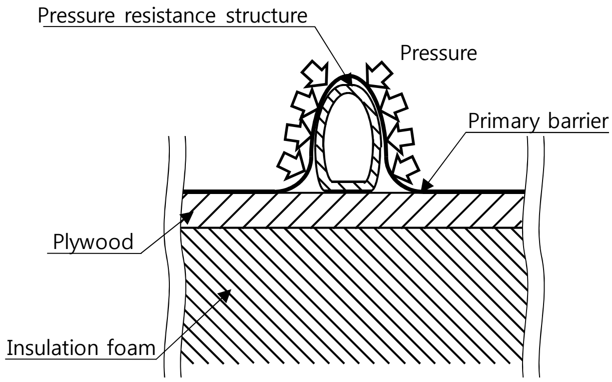

Figure 2. The schematic diagram of configuration of pressure resistance structure.

The pressure resistance structure is not joined with the primary barrier to prevent a change in the plane stiffness of the primary barrier. However, under impact pressure to primary barrier, the pressure resistance structure could support the corrugation of the primary barrier as shown in Figure 2. Then the design equation with the new DP (DP_{13} = Pressure resistance structure inside the corrugation) could be written as follows:

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ x & X & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix} \qquad (3)$$

Since the design matrix becomes half triangular, the primary barrier with a pressure resistance structure could be designed with independent parameters for plane stiffness and pressure resistance.

2.2 DECOMPOSITION OF FR AND DP BRANCH OF INSULATION PANEL

The insulation panel is composed of glass fiber reinforced polyurethane foam with low thermal conductivity for high thermal insulation performance. The coefficient of thermal expansion (CTE) of foam should be low for low thermal stress of the structure. Also, the top surface of the insulation panel should be flat for construction of the primary barrier and its pressure resistance should be high enough to avoid damages by impact pressure. Therefore, the functional requirements could be written as follows:

FR_{21} = Have low thermal conductivity.
FR_{22} = Have low CTE.
FR_{23} = Support barrier uniformly.
FR_{24} = Have high impact resistance.

For the conventional insulation panel design, three DPs for satisfying four FRs stated as follows:

DP_{21} = Polyurethane foam
DP_{22} = Glass fiber reinforcement
DP_{23} = Plywood panel

The design equation for the conventional insulation panel may be written as:

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{Bmatrix} = \begin{bmatrix} X & X & 0 \\ 0 & X & X \\ 0 & 0 & X \\ X & x & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \end{Bmatrix} \qquad (4)$$

Since the design matrix does not satisfy the half triangular condition, a new insulation panel of LNG ship needs to be designed [Lee and Suh, 2006]. Although the pressure resistance of insulation panel could be improved with high density foam, the thermal conductivity could be increased, which lowers the thermal insulation performance.

In this study, for the decoupled design of the structure, a vibration isolation layer (VIL) with low stiffness was employed as a bumper, which was placed on the top surface of insulation panels as shown Figure 3.

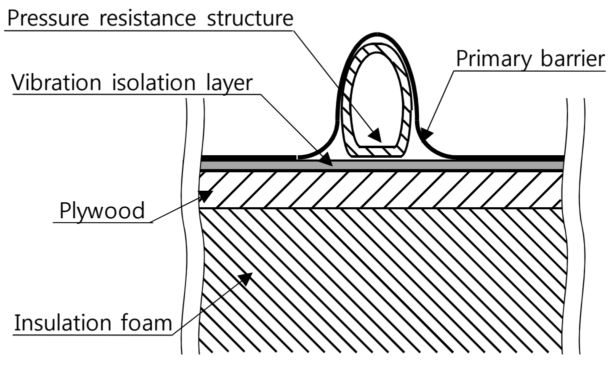

Figure 3. The schematic diagram of configuration of the vibration isolation layer.

An additional layer of VIL could decrease the transferred pressure to the polyurethane foam for high impact resistance of the overall structure. Therefore, design equation (4) with a new DP (DP_{24} = Vibration isolation layer) could be re-written as follows:

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 \\ 0 & X & X & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{Bmatrix} \qquad (5)$$

Since the design matrix becomes half triangular, the new insulation panel could be designed with low thermal conductivity and high impact pressure.

3 AXIOMATIC DESIGN OF IMPACT RESISTANCE SYSTEM OF LNG CONTAINMENT SHIPS

According to the design matrix of the barrier system, the new design is a decoupled design, so it can be realized by designing from DP_{11} sequentially. DP_{11} and DP_{12} are now conventionally satisfying FR_{11} and FR_{12}. Therefore DP_{13} has to be designed to satisfy FR_{13} [Suh, 2001]. Figure 4 shows the configuration of a specimen for a pressure resistance test of the primary barrier and Figure 5 shows the shape of the corrugations of the primary barrier with respect to the pressure. When the applied pressure was higher than 1 MPa, the corrugation collapsed. The collapsed corrugation could increase the plane stiffness of primary barrier.

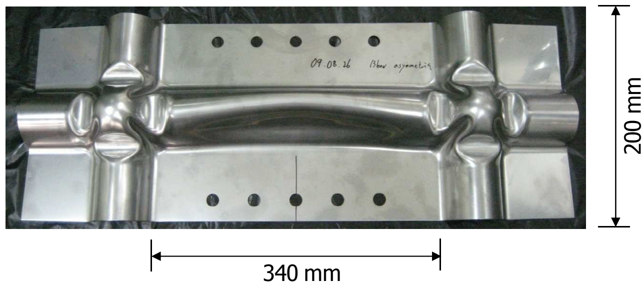

Figure 4. Specimen for pressure resistance test.

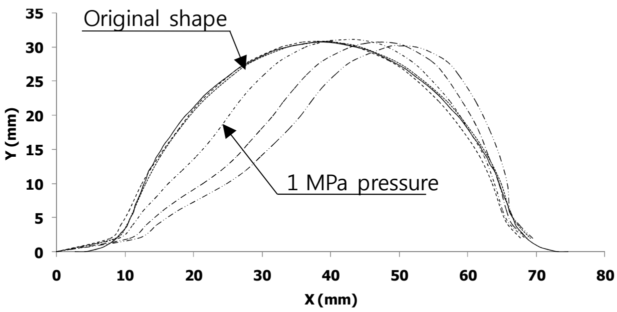

Figure 5. Experimental result of the corrugation shape after pressure is applied.

However, from the experiments, the primary barrier with a pressure resistance structure was not deformed under 3 MPa. Therefore, it was found that the pressure resistance structure could increase the pressure resistance of the primary barrier.

3.1 AXIOMATIC DESIGN OF VIBRATION ISOLATION LAYER

The VIL should have low stiffness at -163°C to isolate impact from the insulation panels. Also, the VIL should be durable at cryogenic temperatures for 40 years which is the service life of LNG ships. Therefore, the functional requirements are as follows:

FR_{241} = Reduce impact transfer from the primary barrier to insulation panel.

FR_{242} = Have ductility at cryogenic temperature.

Two DPs for satisfying two FRs stated as follows:

DP_{241} = Low stiffness at -163°C

DP_{242} = Material without low temperature brittleness

The constraint of the VIL is the cost for application to the LNG ships as follows, because the total amount of VIL could be 24000 m^2:

C = Minimize the manufacturing cost of the VIL.

The design equation for the VIL may be written as follows:

$$\begin{Bmatrix} FR_{241} \\ FR_{242} \end{Bmatrix} = \begin{bmatrix} X & X \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{241} \\ DP_{242} \end{Bmatrix}$$

A feasibility test was conducted to satisfy the functional requirements. The brittleness was investigated with a compaction test with a pressure of 1.5 MPa (estimated impact pressure in containment) for 10 ms at cryogenic temperatures. After the weight drop, the compressive stiffness of the materials was measured by a compressive test to investigate the change of properties due to the damage from brittleness (Table 1.).

Table 1. Results of feasibility test about low temperature brittleness of several materials.

Material	Brittleness at -163oC
Nylon mat	Brittle
PU foam	Brittle
PE foam	Brittle
EVA foam	Brittle
Melamine foam	Brittle
PE mat	Brittle
Glass wool mat	Ductile
Cotton	Ductile

According the test result, a glass wool mat and cotton could be used for VIL materials. However, since the cost of cotton is much higher than glass wool mats, the glass wool mat was employed for the VIL material.

A fatigue test of VIL was conducted to investigate the durability of VIL with a test device as shown in Figure 6. The pressure was 3.0 MPa. Because it is much larger than the strength of the corrugations (1.0 MPa), this test will guarantee the reliability.

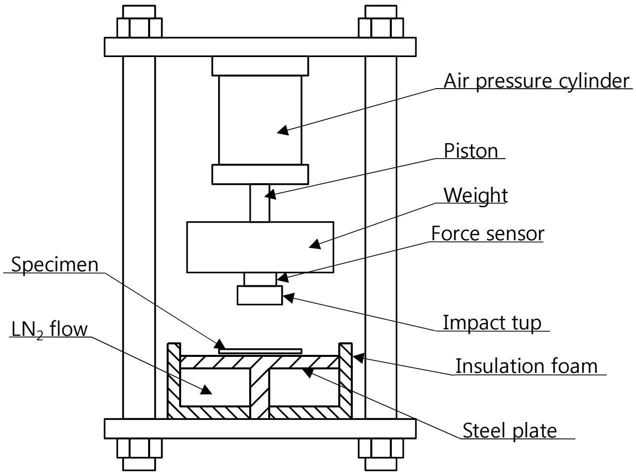

Figure 6. A schematic diagram of low temperature impact fatigue test equipment.

The compressive stiffness of materials was measured with respect to the number of impacts applied to verify the durability.

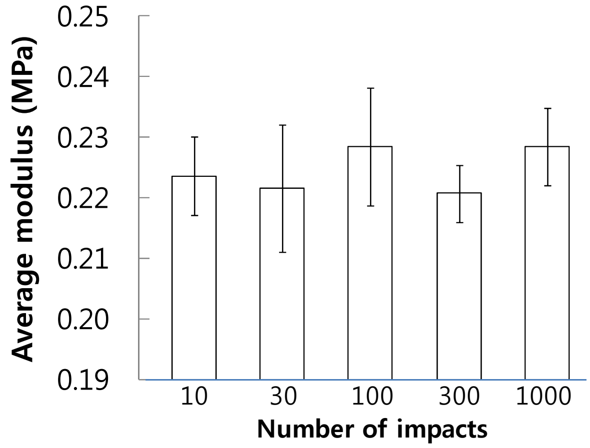

Figure 7. The test result of impact fatigue test for glass wool mat.

Figure 7 shows the result of the impact fatigue test for a glass wool mat. From the results, it was found that the glass wool mat could have durability during 1000 cycles of impacts. Therefore, the glass wool mat could be a feasible materialfor the VIL for LNG ships.

4 FABRICATION OF VIBRATION ISOLATION LAYER AND TEST

In this study, a test device was developed to investigate the effect of the vibration isolation layer (VIL) on the decrease of impact pressure as shown in Fig. 8.

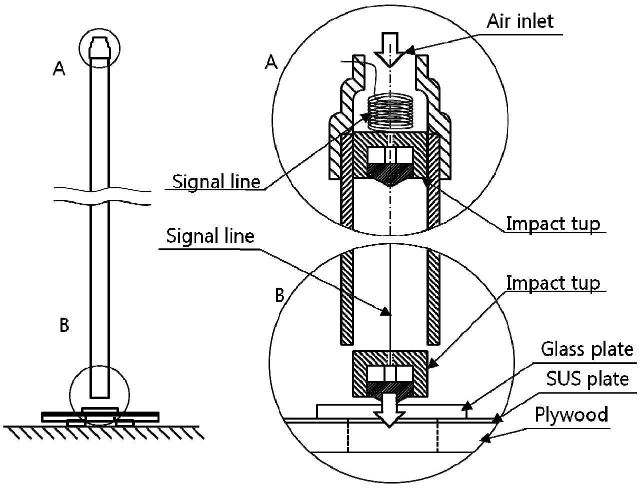

Figure 8. Schematic diagram of short duration impact test equipment.

The test device equipment was designed to give impacts with short duration, which could induce similar conditions as cavitaion. The impact tup was accelerated with high air pressure of about 0.6 MPa to give a short duration of impact with high pressure. While the glass plate was broken by the tup, the pressure could be transferred to the top side of the SUS foil (primary barrier) with short duration. The velocity of the tup was measured with a velocity sensor to investigate the impact speed. Figure 9 shows a schematic drawing of the specimens. The thickness of VIL was 3 mm.

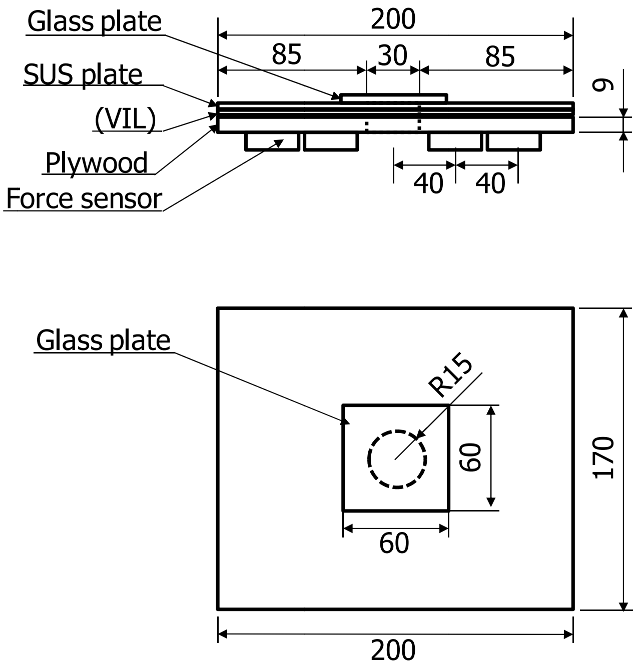

Figure 9. Schematic diagram of the specimen for the short duration impact test (unit : mm).

An accelerometer was used to measure the impact duration. The measured duration of impact was about 30 μs. Also, force sensors were placed under the plywood of the insulation panel to measure the transferred impact pressure to the insulation panel. From the results as shown Figure 10, with the VIL, the pressure transferred to the insulation panels could be decreased by 60%, which could improve the impact resistance of insulation panels.

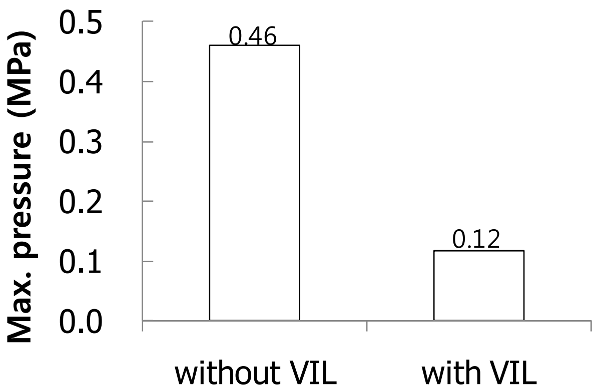

Figure 10. The impact test result with and without the vibration isolation layer (VIL).

5 CONCLUSION

In this research, impact resistance systems for membrane type LNG ships were designed by the axiomatic design approach. The pressure resistance structure (PRS) and the vibration isolation layer (VIL) concepts can make the coupled design matrix of the conventional LNG ship system decoupled. The PRS can increase the strength of the corrugation of the primary barrier by a factor of 3. The glass wool mat for the VIL was suggested due to its ductility at cryogenic temperature. Also, it was tested by the method of low temperature impact fatigue test, and there was no decrease of material properties of the glass wool mat after impact. The VIL composed of the glass wool mat decreased transfer impact load from the primary barrier to the insulation panel by 60%. Therefore the membrane type LNG ship system could be improved by the axiomatic deign theory.

6 ACKNOWLEDGEMENTS

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