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< Evaluating Structural Safety of Inner Hull Structure Affected by Cryogenic Temperature >

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ABSTRACT

The market of LNG (Liquefied Natural Gas) carrier is continuously in a prosperous condition, and a lot of LNG vessels are being built in many shipyards. Membrane-type MARK-III LNG CCS (Cargo Containment System) is used more and more in the construction of LNG carrier, and it has already taken considerable market share among the various LNG CCS products.

This paper deals with a study on structural safety of LNG carrier whose inner hull structure is affected by cryogenic temperature of LNG. If the primary and secondary barriers are failed simultaneously, the inner hull structure comes to be in direct contact with LNG. It is well known that the cryogenic temperature exposes the inner hull structure to fatal risk of structural failure due to brittle fracture, but nevertheless it is quite difficult to find a precedent research which explains the degree of risk and severity with due consideration of the consequence caused by structural failure of inner hull.

The heat transfer test has been performed using the specimen appropriate to realize test scenario while considering cryogenic liquid flow from primary and secondary barrier into inner hull structure, and at the same time, the specimen has been tested by applying proper deformation so as to examine the structural behavior of inner hull structure under cryogenic condition. The heat transfer analysis has been performed to simulate and verify the heat transfer test, and consequently it is possible to obtain actual distribution of temperature in the inner hull structure exposed to cryogenic temperature. The structural analysis has been performed to evaluate the damage of inner hull structure and as a result to assess overall decrease of hull girder strength of LNG carrier. Finally, consequence of the decrease of global strength has been discussed.

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BODY OF PAPER

1. INTRODUCTION

There is an increasing concern regarding the quality of secondary barrier in membrane type LNG cargo containment system recently. It is defined that secondary barrier should be liquid tightened not to be gas tight in IGC code and it is supposed that whenever cryogenic liquid is contacted to steel structure it may make a big accident and ship operation. In case of Mark III type LNG cargo containment system, the accident in primary barrier is never reported because of the existence of corrugation and the thickness of membrane after the first delivery of Mark I system from 1972.

Even though the accident of primary barrier never is reported, it is recommended to start the research and test to confirm the effect of leakage of cryogenic liquid in structural point of view and operational points of view.

Before starting the main research, some research items are checked which have been researched previously. Many research activities have been found for the former (e.g. Rhee [3]), while the latter has received relatively less attention. There have been other relevant studies found in the literature, such as the review of spreading and vaporization of cryogenic liquid spills by Thyer [5], analysis of temperature and pressure changes in LNG tanks by Chen et al. [1], the effect of the foam dispersed onto leaked LNG on the diffusion of vaporized gas by Takeno et al. [4], and the numerical modeling of gas leakage through a structure by Kumazawa and Whitcomb [2].

The main research items are as follows, where all the tests and analyses are carefully designed to simulate real situation.

(1) Test for temperature distribution with specimen by means of the artificial defect on secondary barrier using cryogenic fluid.

(2) Theoretical confirmation for the specimen test results and development of vaporization model in CFD calculation.

(3) Specimen experiment to extract structural response of inner hull which is subjected to hull deformation under cryogenic temperature due to leakage of LNG.

(4) Material test to examine material properties of normal mild steel under cryogenic temperature.

(5) Evaluation of hull girder strength when the inner hull is damaged by cryogenic temperature of which distribution is obtained from the former CFD calculation.

2. EXPERIMENTAL APPROACH FOR TEMPERATURE DISTRIBUTION

- **Preliminary Tests for Ballast Water Effect**

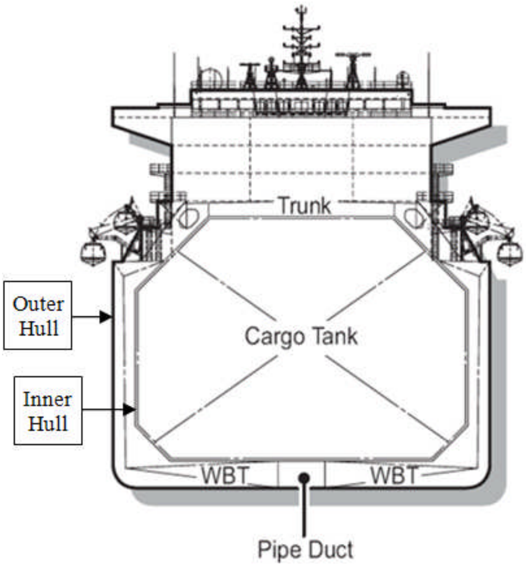


Fig.1 Typical section of LNG Carrier

LNG carrier consists of double hull structure and those areas are used ballast tank to contain ballast water. Fig. 1 shows the typical section of LNG carrier.

If the cryogenic fluid makes damage at the inner hull and there is no water inside ballast tank, it may damage the outer hull also. On the contrary, if the cryogenic fluid makes damage at the inner hull and there is water inside ballast tank the damaged area could be blocked due to icing effect with heat transfer between cryogenic liquid and water. To confirm this effect, it is tested using specimen and confirmed. The test specimen and results are presented in Fig. 2 and Table 1.

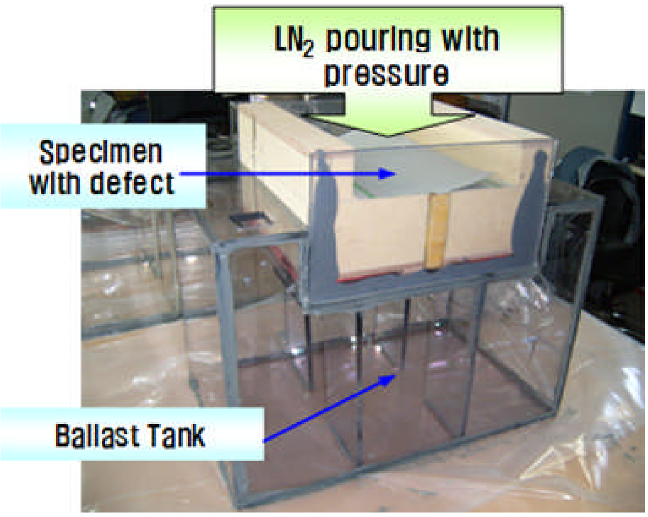


Fig.2 Test specimen for ballast water effect

Diameter of defect	**Ballast with pressure (3bars)**	**Ballast without pressure**
1mm	Less than 1 min.	Less than 1 min.
3mm	8.8 min.	3.0 min.
5mm	9.4 min.	6.5 min.
10mm	17.3 min.	7.8 min.
30mm	More than 1 hr.	19.2 min.

Table 1 Test results of ballast water effect

- **Experimental Setup**

Typical section of Mark III cargo containment system is shown in Fig. 3. As shown in Fig. 3, two spaces in insulation system are divided by secondary barrier.

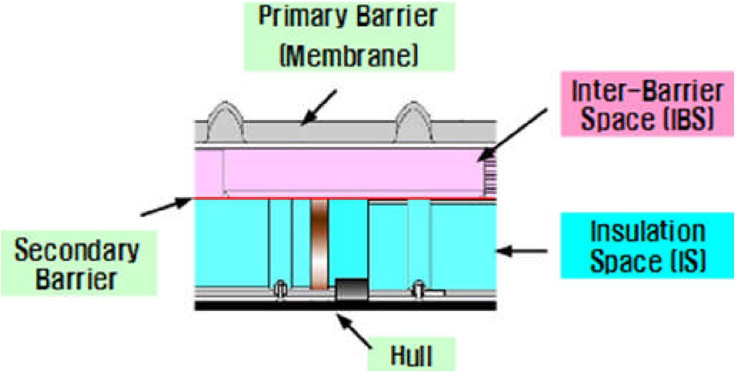


Fig.3 Typical section of MARK-III CCS

A piece of the cargo containment system is fabricated for the model tests (Fig. 4).

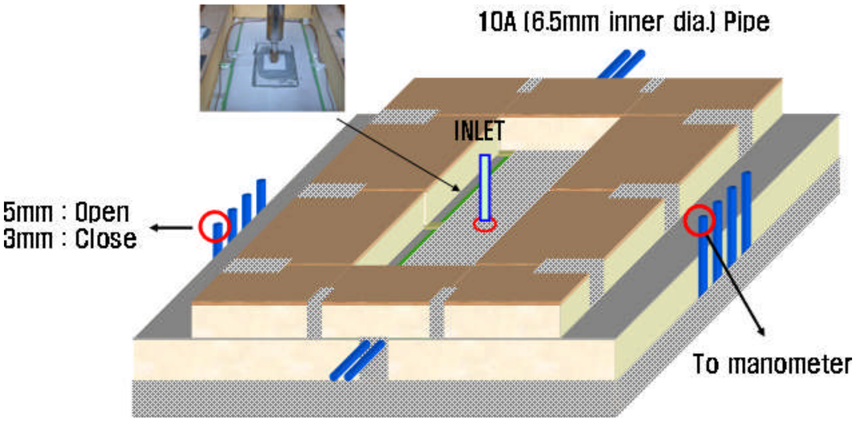


Fig.4 Test model

Since it was assumed that the primary barrier had been already damaged, only a partial structure was built above the secondary barrier. On the top of the secondary barrier, a hole was made to let the LNG flows in at the fully loaded pressure condition, i.e., 1.5 bar. On the sides of the secondary insulation layer, a series of holes were made and served as exits for the mixture of NG and N2. The overall size of the model was 1400 mm wide (x-direction), 1000 mm long (y-direction), and 196.5 mm high (z-direction). Two different sizes, 3 mm and 5 mm diameter, were considered for the inlet hole as the typical damage size on the secondary barrier. Totally, of 25 thermocouples were distributed on the inner hull surface as shown in Fig. 5. Note that the No. 13 thermocouple was located directly below the inlet. Fig. 6 shows the status of the typical experiment.

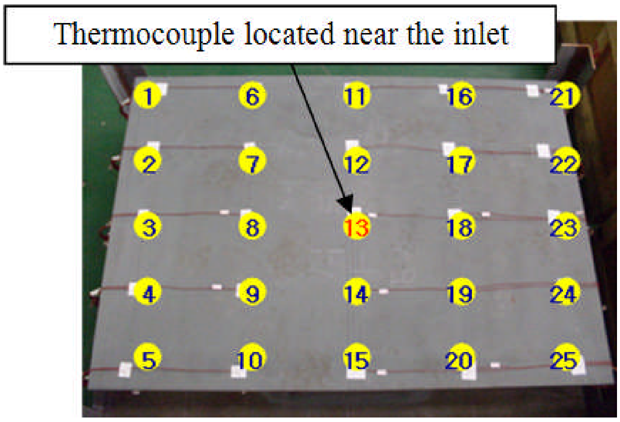


Fig.5 Arrangement of thermocouples

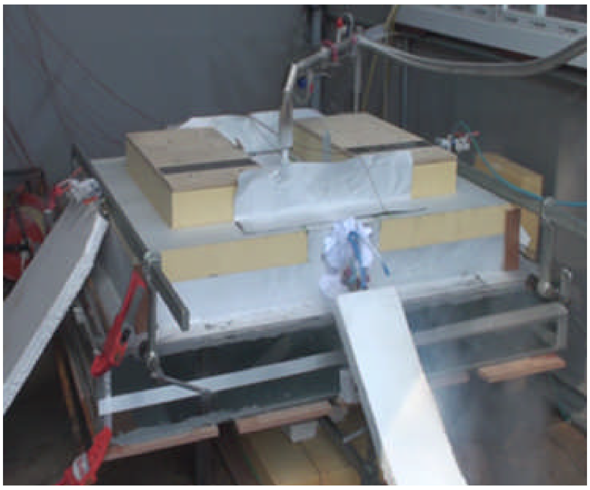


Fig.6 Typical scene of experiment

- **Test Cases**

Test cases for cryogenic fluid are summarized in Table 2.

	Diameter of defect	**Ballast effect**
Case 1	3mm	Off
Case 2	3mm	On
Case 3	5mm	Off
Case 4	5mm	On

Table 2 Test cases for cryogenic fluid

Totally, 4 cases of test were done and the temperature data were collected for each case. Fig. 7 shows the typical pattern of temperature history measured at every thermocouple.

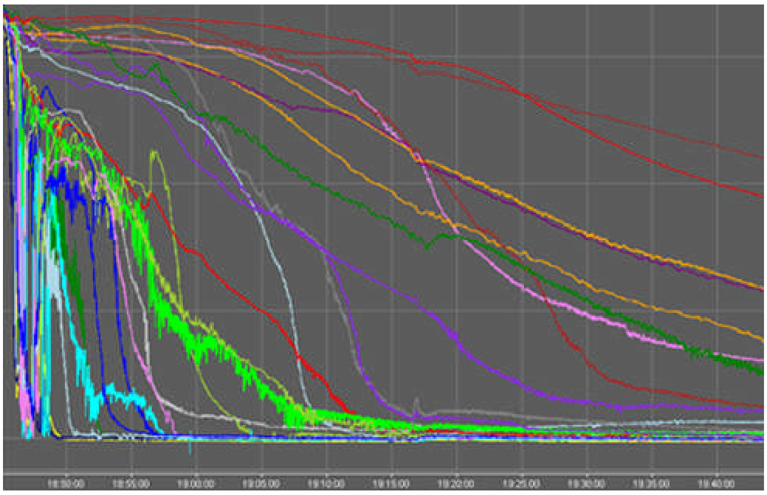


Fig.7 Temperature history of each thermocouple (example)

3. THEORETICAL APPROACH FOR TEMPERATURE DISTRIBUTION

- **Model Problem**

It is assumed that the primary barrier is already damaged, and the LNG fills the primary insulation layer and leaks through the secondary barrier. A small hole represents the damage in the secondary barrier. The LNG at -163℃ flows through this small hole and the flat joint made of a porous material, i.e., a material similar to glass wool. Note that the flat joint is located in the gap between the pieces of the secondary insulation layer. Since the temperature in the insulation wall is maintained at the normal temperature, most of the leaked LNG quickly evaporates while it flows through the flat joint and void area between the secondary layer and the inner hull. There are lines of mastic support in the void space area, which is filled with nitrogen(N2) at a certain pressure level, approximately 2% higher than the atmospheric pressure, i.e., 1.02 bar. Therefore, the flow of interest is a complicated multi-phase (liquid & gas) and multi-species (NG+N2) one.

- **Computational Method**

The commercial CFD code, FLUENT 6.3, was selected as the platform solver. As described in the model problem section, the computational method needs to be able to handle the multi-phase (liquid and gas)flow, multi-species gas flow, evaporation, liquid and gas flow in the a porous medium, and conjugate heat transfer in both fluid and solid areas. A series of specially designed codes were developed for the present study and hooked up with the platform solver to take care of the material properties of LNG and NG, the additional resistance in the porous medium, and the evaporation mechanism, i.e., phase change and mass transfer.

The flat joint is made of a porous material and requires a special treatment. In the present study, the resistance on the flow in the flat joint was taken care of by additional source term in the momentum equation. By solving conservation equations for gas species in multiphase flows, the mixing and transport of gas species can be modeled.

- **Result**

After thorough grid dependency tests, a structured grid with 146,000 cells was generated for the flow domain that corresponds the secondary insulation layer including the flat joint porous medium region and the solid regions of the mastic support and the inner hull steel plate. Fig. 8 shows the base grid for the present study.

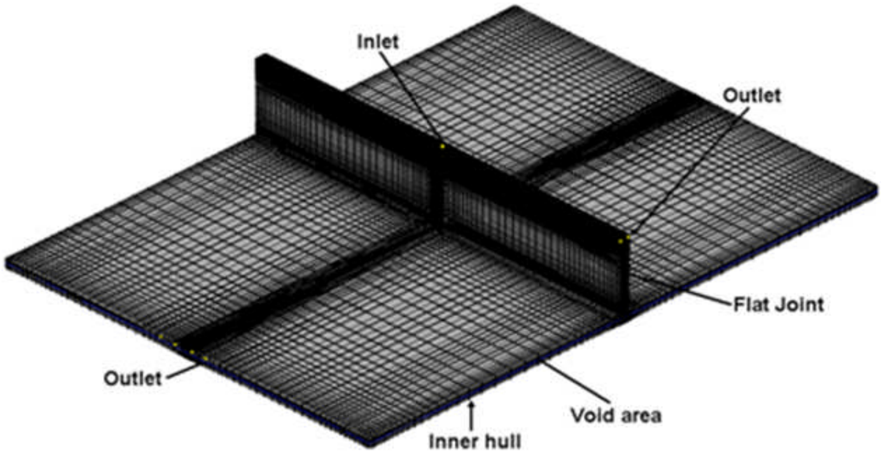
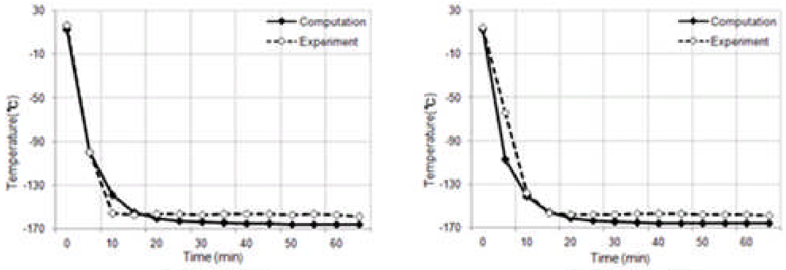
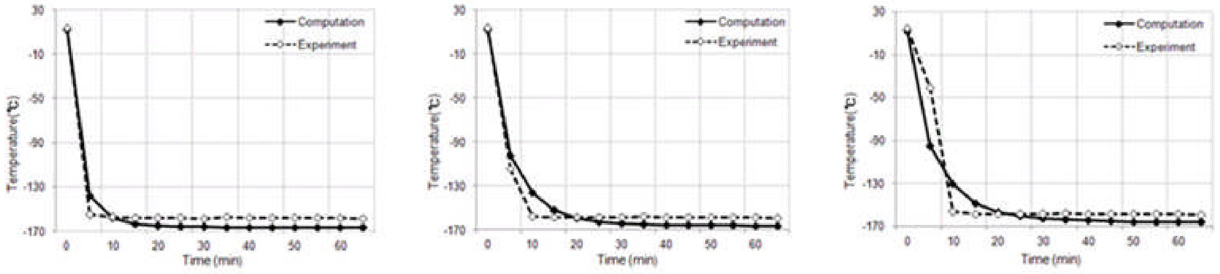


Fig.8 Computational grid system

In order to see how closely the developed procedure predicts experimental measurement at specific locations, say thermocouple NO. 8, 12, 13, 14 and 18, the time history of the temperature is compared in Fig. 9. Although there is a slightly discrepancy, the agreement is quite good, confirming that the computational procedure can be used reliably for the transient behavior.



(a) NO.8 (b) NO.12



(c) NO.13 (d) NO.14 (e) NO.18

Fig.9 Time history of hull plate temperature for 5mm leak size

In order to further extend to the actual hull size, the calculation procedure is applied to the hull domain of 20m × 20m size. This is to evaluate the time history of the cold spot diameter at hull steel plate due to LNG contact on the hull. The calculation was carried out for the leak size of 5 mm and the same calculation procedures were applied. Based on the results, even the LNG leakage happens, the cold spot diameter does not increase continuously. This is attributed to the fact that the heat transfer happens between external environment and hull plate and reaches at equilibrium state.

4. SPECIMEN EXPERIMENT

Specimen experiment is carried out to extract the structural response of inner hull which is subjected to hull deformation under cryogenic temperature due to direct contact with LNG. The specimen is prepared as shown in Fig. 10. The hull deformation acts on the specimen by applying a displacement of jack-up. The amount of jack-up displacement is carefully calculated and equivalent to the hull deformation of actual LNG vessel.

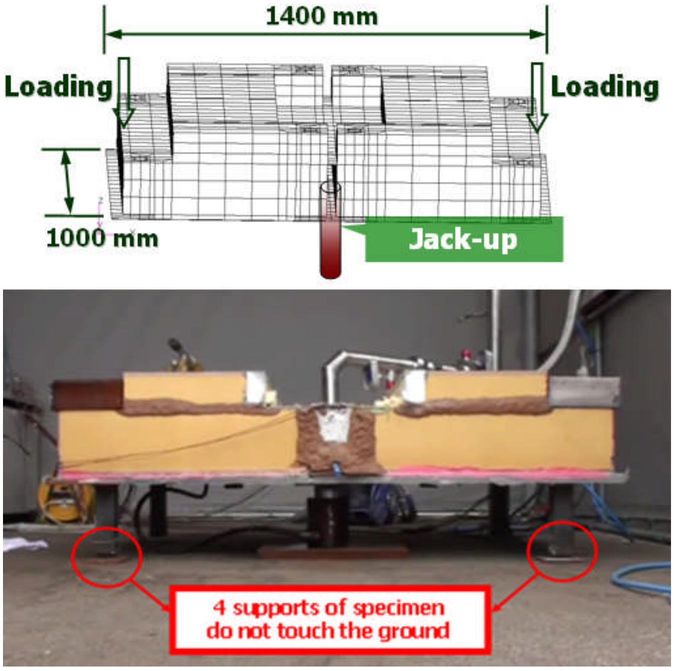


Fig.10 Test setup for specimen experiment

Cryogenic liquid is given to the specimen, and moreover, repetitive loading and unloading of hull deformations are acted on the specimen. Fig. 11 shows the situation.

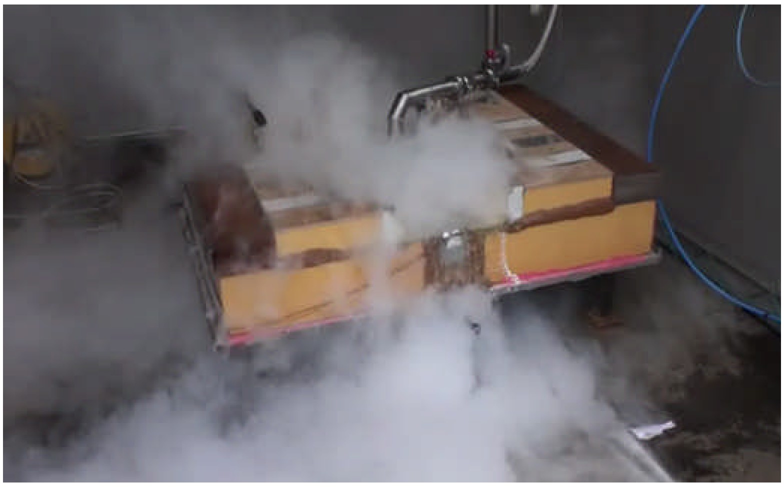


Fig.11 Specimen subjected to hull deformation under cryogenic temperature

The result of close visual inspection shows that there is no damage in mild steel plate of specimen after the experiment, therefore it is expected that cryogenic temperature does not cause severe damage of brittle fracture to mild steel plate even under repeated loadings, if there is no initial defect.

5. MATERIAL EXPERIMENT

Material experiment is performed to investigate material properties of normal mild steel under cryogenic temperature. Normal mild steel is the lowest grade material for inner hull structure.

- **Strength Test**

Static loading test is performed under a variety of temperatures in order to examine the effect of temperature on the strength of mild steel. Fig. 12 shows the test setup.

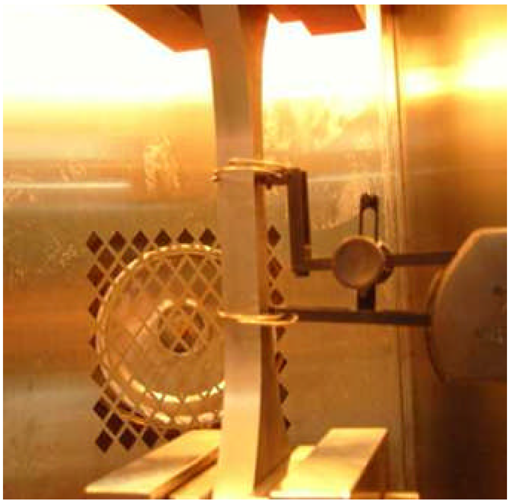


Fig.12 Setup for strength test

The strength test is carried out in cryogenic chamber and the load and displacement is measured with appropriate device.

The result of strength test is shown in Fig. 13. The higher strengths of mild steel are found at lower temperatures.

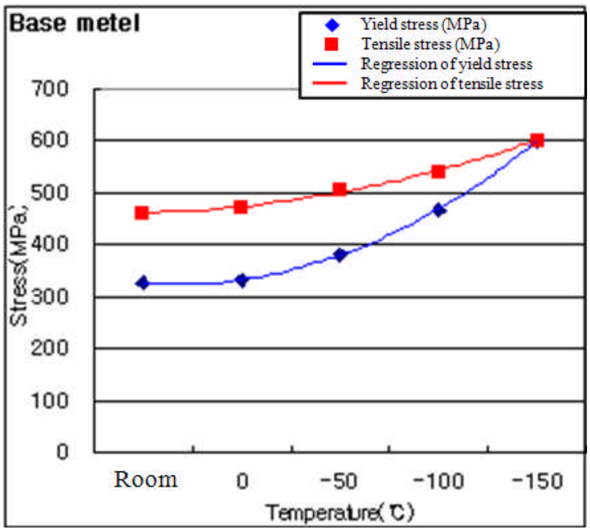


Fig.13 Result of strength test

- **Fatigue Test**

Dynamic loading test is performed under a variety of temperatures in order to examine the effect of temperature on the fatigue strength of mild steel.

The fatigue test is also performed in cryogenic chamber and structural response is measured with strain gauge for cryogenic temperature. Fig. 14 shows the test setup.

Fig.14 Setup for fatigue test

The result of fatigue test is summarized in Table 3.

Temp. (℃)	**Fracture cycle**	**Fracture type**
-163	1,524,110	Brittle
-50	695,694	Intermediate
0	124,621	Ductile
20	123,567	Ductile

Table 3 Result of fatigue test

As shown in Table 3, the fatigue strength is increased as temperature is decreased. However in the cryogenic temperature, there is almost no crack growth after initiation. Brittle fracture takes place immediately after crack initiation.

- **The Other Test for Examining Brittleness of Mild Steel under Cryogenic Temperature**

Considering the results of strength and fatigue tests, it is supposed that the mild steel has less ductility at lower temperature and shows brittle behavior in the cryogenic environment. Therefore, it is necessary to investigate the effect of low temperature on the brittleness of mild steel.

Charpy v-notch test has been carried out to examine capability of impact energy absorption under a variety of temperatures and accordingly to find out critical temperature of ductile-brittle transition. As a result, the transition phenomenon of ductile-brittle property is clearly founded at not much low temperature, and therefore, it is likely that the possibility of brittle fracture under cryogenic temperature is not negligible.

The crack propagation test has been also carried out to examine the relationship between loading cycle and crack length, i.e. the speed of crack growth. The effect of temperature on crack propagation property of mild steel is investigated by carrying out the test under a variety of temperatures including cryogenic temperature. As a result, relationships between loading cycle and crack length could be obtained at higher temperature than -50℃, but regarding cryogenic temperature, brittle fracture occurs too early to give meaningful result of crack propagation.

Consequently, it is noticed that the structural failure of mild steel due to brittle fracture under cryogenic temperature is not negligible, although severe damage of mild steel plate due to brittle fracture was not found in the specimen test shown in Fig. 11. Because there always exists an inherent defect in every kind of material, brittle fracture can take place at the defect area, soon after the cyclic loading acts on the material under cryogenic temperature.

Therefore, it is strongly recommended to evaluate the strength of hull structure, assuming that inner hull under cryogenic temperature is completely failed due to brittle fracture.

6. EVALUATING STRUCTURAL SAFETY OF LNG CARRIER

As explained before, the strength of hull structure of which inner hull is affected by cryogenic temperature is verified. It is assumed that inner hull under cryogenic temperature is completely failed and removed from the hull structure relevant to strength evaluation.

Ultimate strength analysis is carried out to investigate the overall decrease of hull girder strength of LNG vessel and to assess its structural safety by comparing the remainder of hull girder strength with strength criteria i.e. design hull girder strength.

Fig. 15 shows the cases of damage strength evaluation. The blue circle indicates damaged area. The damaged length is obtained from the temperature distribution which is formerly calculated by CFD.

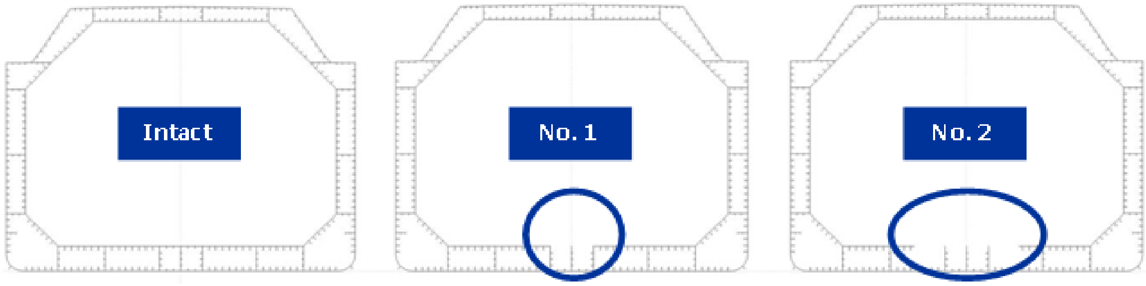


Fig.15 Cases for strength evaluation

The result of ultimate strength evaluation is illustrated in Fig. 16.

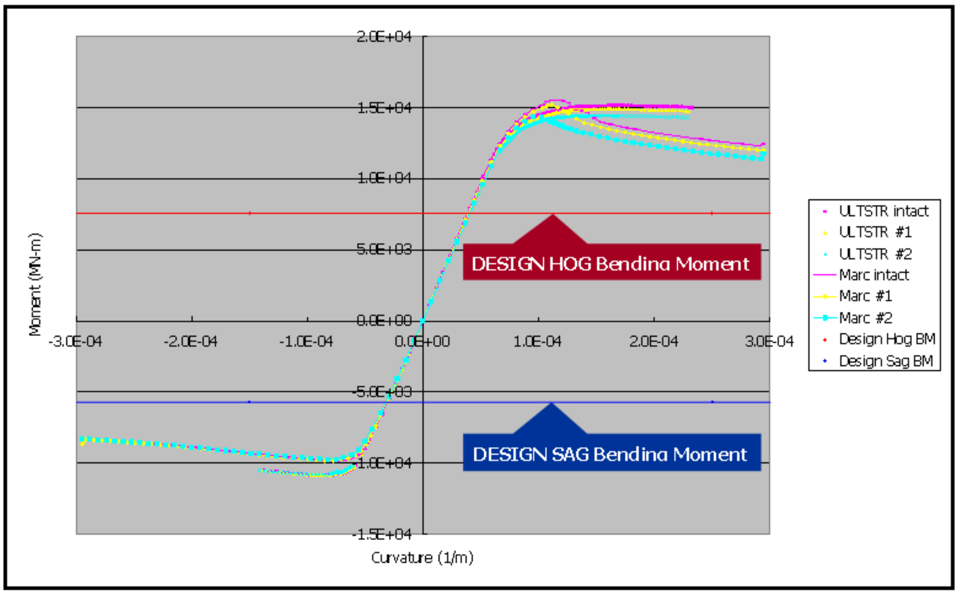


Fig.16 Result of strength evaluation

As shown in Fig. 16, simplified method and nonlinear FE analysis give similar results of ultimate strength for each analysis case. Though strength is reduced by damage application, the amount of strength reduction due to damage is quite small even if compared with intact case. The residual hull girder strength for each case still has a considerable margin, compared with design strength.

7. CONCLUSION

Based on the results of safety assessment of inner hull structure affected by cryogenic temperature, it could be concluded that:

- Numerical model including vaporization effect has been developed and validated using experimental results with real LNG.
- The experimental and computational results suggest that, unless there is a massive leak, the LNG mostly evaporates in the insulation layer and cold spot area at inner hull due to remaining LNG is very limited even though there is a massive leak.
- The structural failure of mild steel due to brittle fracture under cryogenic temperature is not negligible, although severe damage of mild steel plate due to brittle fracture was not found in the specimen test.
- The amount of strength reduction due to damage is quite small even if compared with intact case, and therefore, the residual hull girder strength after damage still has a considerable margin, compared with design strength.

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