Ice Collision Analysis and Alternative Full Scale Impact Test for ARC 7 LNG Carrier

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ABSTRACT

The structural strength of ARC7 LNG carrier was guaranteed in consideration of reinforcement according to class rule. But more detailed strength estimation based on directly calculated ice loads followed by FEA was requested to secure the structural strength under the unexpected ice conditions. For ice conditions from ARC7 requirement, detailed ice collision analysis was carried out to verify hull strength as well as safety of CCS (Cargo Containment System). Based on ice load from direct calculation, the nonlinear static analysis was carried out according to ice collision scenarios defined by ship speed and ice thickness.

The unexpected thick ice may cause high stress in local ice belt zone even though Arctic class vessel has strongly reinforced structure against ice loads. Therefore, the full scale impact test was also performed to check the soundness of hull structure and weld strength against dropping steel object. The high local strain was measured by means of strain gauges. The measured structural response was compared to FE analysis result.

KEY WORDS: Ice Collision, Arctic LNG, Ice Load, Plasticity

INTRODUCTION

An arctic LNG carrier was newly constructed according to ARC 7 class of RMRS(Russian Maritime Register of Shipping). Even though she is designed in accordance with RMRS rule to have enough strength against ice loads, detailed strength assessment based on directly calculated ice loads was requested to check structural capacity of hull as well as cargo containment system against ice loads.

For ice loads from level ice, the ARC7 requirement for ice conditions (ice thickness and ship speed combination) was considered. First ice condition is based on ARC7 requirement of RMRS, which defines structural capacity considering local plastic deformation of hull structure. All of ice pressures were calculated using 'Ice Load+' developed by KSRC(Krylov State Research Center). Hull form angles, ship speeds and ice thicknesses related to requirements were used as the input data of 'Ice Load+'. According to ice collision analysis, it was verified that no additional reinforcement is required and hull design has enough strength against ice load.

The full scale impact test was performed to check the soundness of hull structure and weld strength against impact load. The dropping steel of 7 ton with controlled dropping height was used to realize impact load equivalent to encountered ice load. The drop height was determined based on the iterative drop object analysis result which is similar with the nonlinear analysis result for ARC 7.

The high local strain induced from impact load was measured by means of strain gauges. From the measured strain data, the plasticity could be founded. However, due to absence of available dynamic material property of high tensile steel in the FE analysis, it was founded that the stress response during the impact test was not identical to that from dropped object simulation.

ICE LOAD CALCULATION FOR HULL STRENGTH EVALUATION

Ice loads were calculated for the NO.1 cargo hold region described in Figure 1. Inclined angles (α and β) of each location were measured and used as input data for ice load calculation. To determine the ice thicknesses and ship speeds inducing ice loads, the BDSC curve was introduced and ARC 7 curve among BDSC curves described in Figure 2 was selected to calculate ice pressure and related patch size. Ice pressure and its patch sizes (width and length) were obtained from 'Ice Load+' program. 'Ice Load+' calculates ice loads for ten points specified in BDSC curve, i.e., ten combination of ship speed and ice thickness. Among calculated ice loads, the maximum values were used in ice collision analysis.

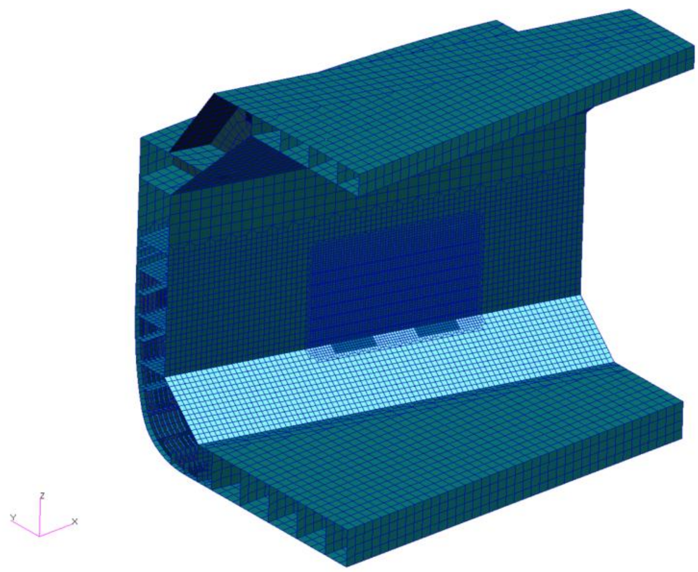


Figure 1.NO.1 Cargo Hold Region Model

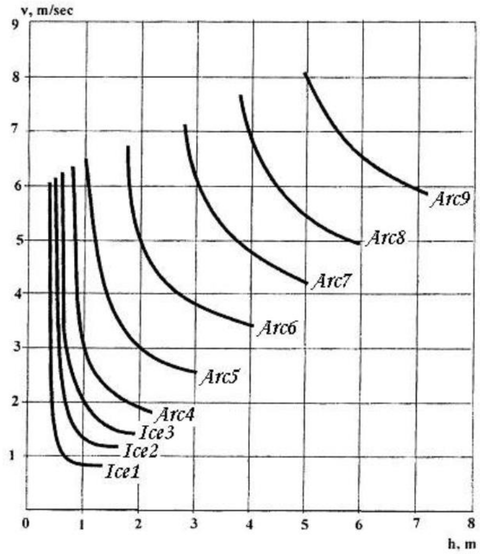


Figure 2.Recommended format for paragraphs

CONSIDERED ADDITIONAL SCENARIOS AND CALCULATED ICE LOADS

When a ship is escorted by an icebreaker of less width, the canal width is increased through interaction of its edges with the large ship hull. This interaction in the form of periodic impacts resulting in bending failure of canal edge portions is called as the finish breaking. From increased impact number and edge failure, the ice force is to be increased by 1.16 times in A1I area specified in RMRS rule. The relationship between original and increased ice pressure is as follows;

$$p_{A_1 I}^{KT} = p_{A_1 I} \cdot k_2; \qquad (1)$$

Where, $p_{A_1 I}$ = original ice pressure in A_1I area ignoring large ship features;

$p_{A_1 I}^{KT}$ = increase ice pressure for large ship;

k_2 = enlargement coefficient that could be taken equal to k_2 = 1.16.

Based on additional scenarios, the ice load were calculated using ‘Ice Load +’. Calculated pressure is summarized in Table 1. For strength verification, the trapezoidal ice load pattern described in Figure 3 was applied in the direct strength evaluation.

Table 1.The Ice Load Calculated for Strength Evaluation

BDSC 10 Condition		Ice Pressure	Ice Pressure Patch Size	
Ship Speed [m/s]	Ice Thickness [m]	P [MPa]	b [m]	l^H [m]
4.22	5	9.78	1.17	5.97

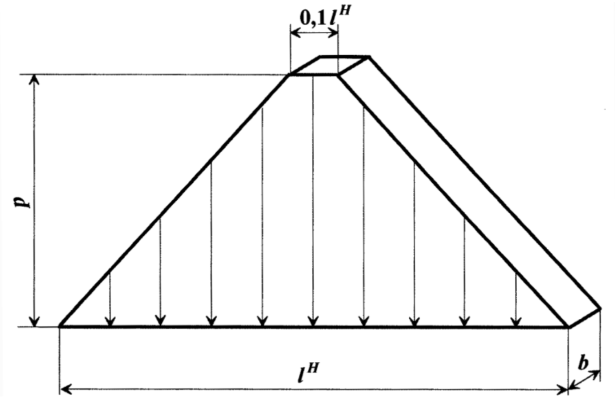


Figure 3.Ice Load Pattern

ALLOWABLE CRITERIA

The several design rules for Arctic vessels including RMRS rule adopt plastic design concept against ice load. For loads corresponding to ARC7 class, the structural capacity was calculated considering slight plastic deformation. To confirm the hull safety against ice load, the strength capacity should be calculated. Using the relation between load and deflection, strength capacity can be evaluated. Strength capacity, i.e., limit load calculation method is shown in Figure 4. Ultimate strength (limit load P_{ult}) can be defined as the intersection point of the tangent line at 5 times of the yield point and tangent line in the elastic region.

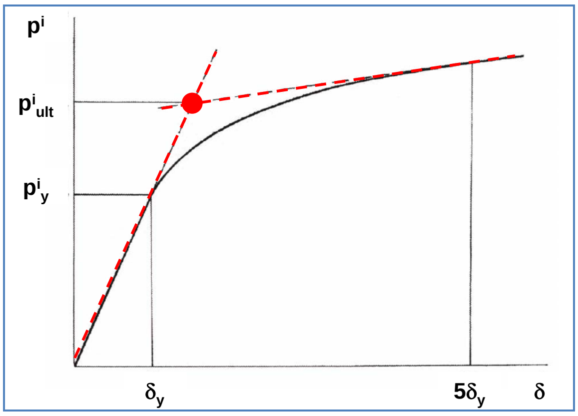


Figure 4.Limit Load Calculation Method

In case of GTT NO.96 containment system, the coupler provides the insulation boxes with coercing forces to remain in erection position and flexibility that can absorb any accidental deflection damages. According to GTT, the operating limit of coupler base with flexibility is 4.6mm/m which is a kind of relative deflection.

STRENGTH EVALUATION RESULT

FE analysis was carried out to verify hull strength according to ARC7. Nonlinear static analysis was adopted to check structural capacity and the inner hull deformation for operational limit of CCS(Cargo Containment System) strength. NASTRAN solution sequence 600 was used for nonlinear static analysis.

As shown in Table 2, it is concluded that structural capacities of reinforced structures exceed the demand which is defined as the ice load at concerned region. The load deflection curve and von-Mises stress contour were described in Figure 5.

The relative deflection for operational limit check was obtained from deflection per 1m distance based on length of plywood box. Figure 6 shows detailed description for relative deflection calculation methodology. As this result, 0.3 mm/m of maximum relative deflection, shown in Figure 7, was calculated for No.1 cargo hold. The resultant relative deflection is much smaller than operational limit of 4.6 mm/meter.

Table 2.Strength Evaluation Result

Hull Strength Evaluation		CCS Strength Check	
Demand [MPa]	Capacity [MPa]	Relative Deflection [mm/m]	Operational Limit [mm/m]
9.78	10.06	0.3	4.6

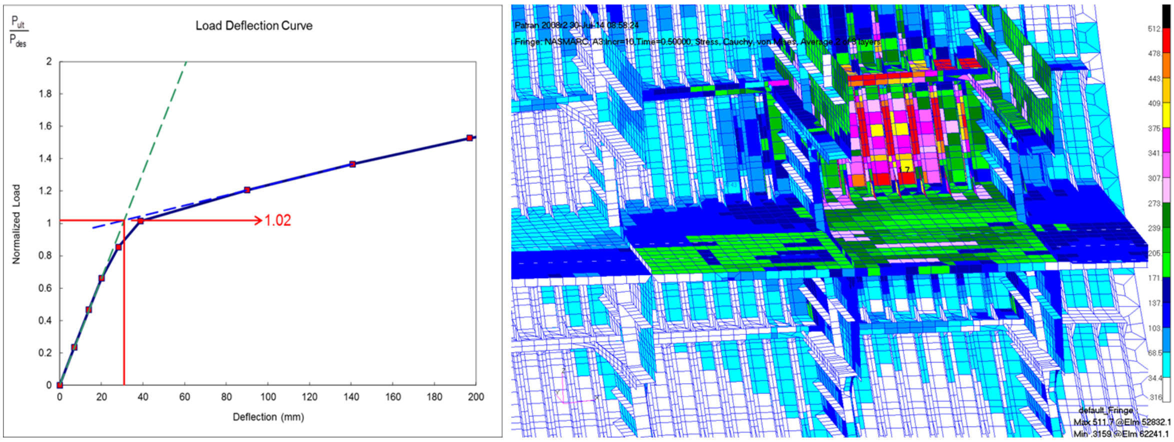


Figure 5.Normalized Load Deflection Curve and von-Mises Stress Contour

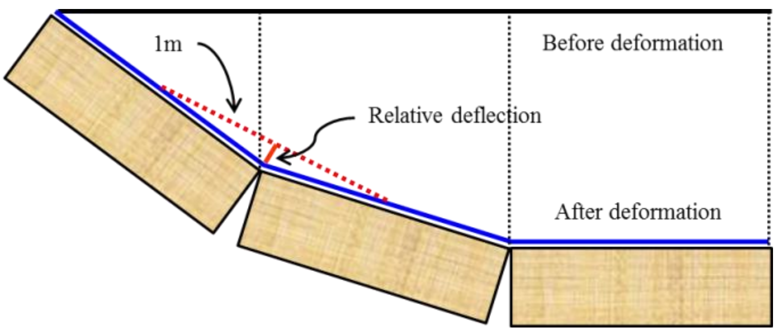


Figure 6.Relative deflection calculation methodology

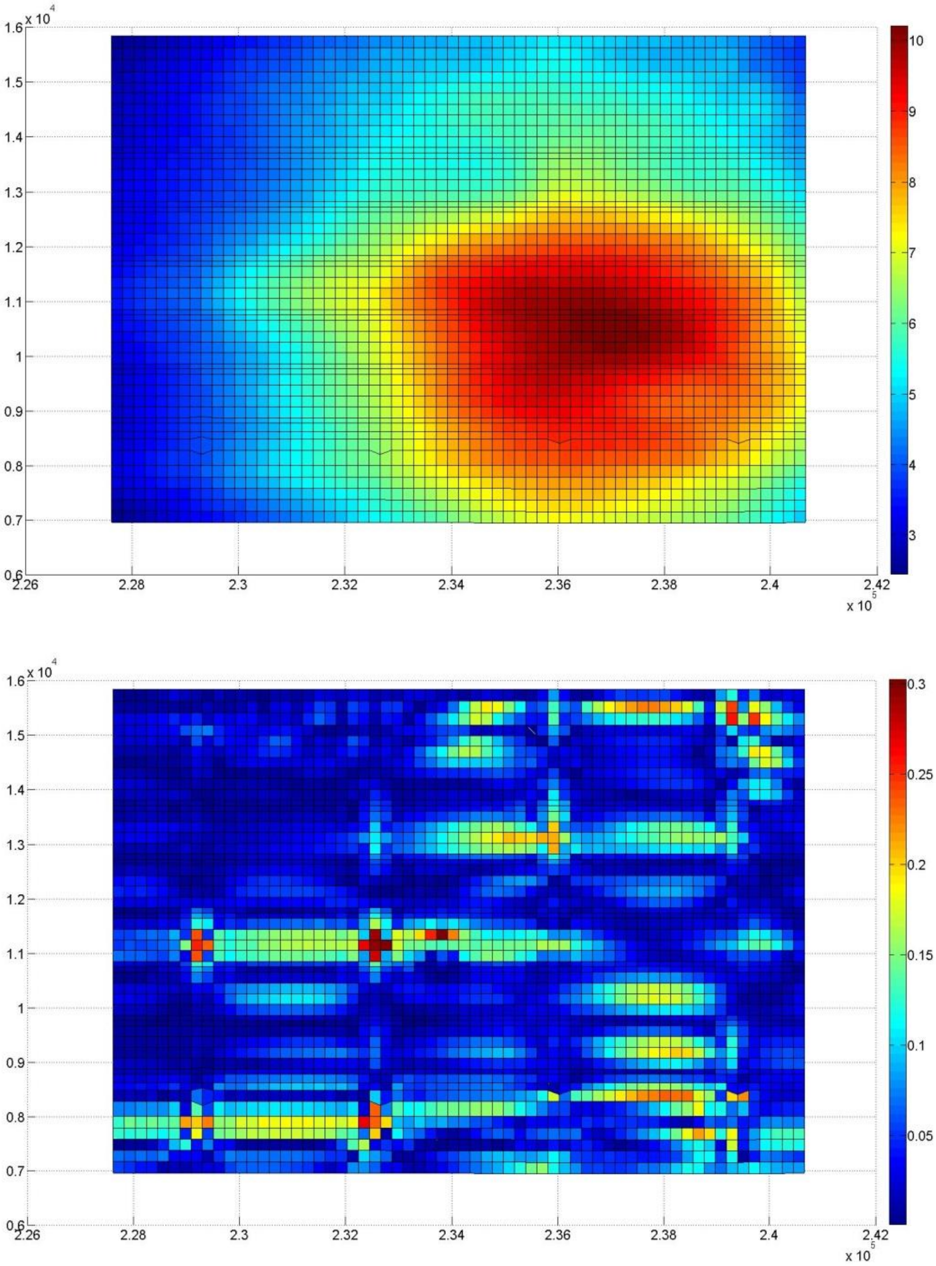


Figure 7.Absolute (Upper) and Relative (Lower) Deflection of NO.1 Hold L.BHD

FULL SCALE IMPACT TEST

The local high stresses against the ice load would occur at the ice strengthened structures. Even though the reinforcement for ARC class ship was regulated in RMRS rule, it is necessary to verify the soundness of hull structure and weld strength. Therefore, without the scale down, the full scale impact test was performed in the real block of A_1I region.

The weight bar of 7 ton with controlled dropping height was used to realize impact load equivalent to encountered ice load. The drop height was determined based on the iterative drop object analysis result which is similar with the nonlinear analysis result for ARC 7.

Figure 8 shows the test setting and weight bar of 7 ton. In order to drop on the exact location, the casing, such as guiding structure for weight bar, was installed on the concerned location of block. Firstly the weight bar was inserted into the casing by the crane. After adjusting drop height of 2m, the weight bar was dropped freely through the casing.

Figure 8.Test Setting (Left) and Weight Bar (Right)

The 3-axial and 1-axial strain gauges were installed at the each impact location in order to record the behavior of the impacted structure against impact load. For each impact point, four 3-axial gauges and one axial gauge were used as shown in Figure 9.

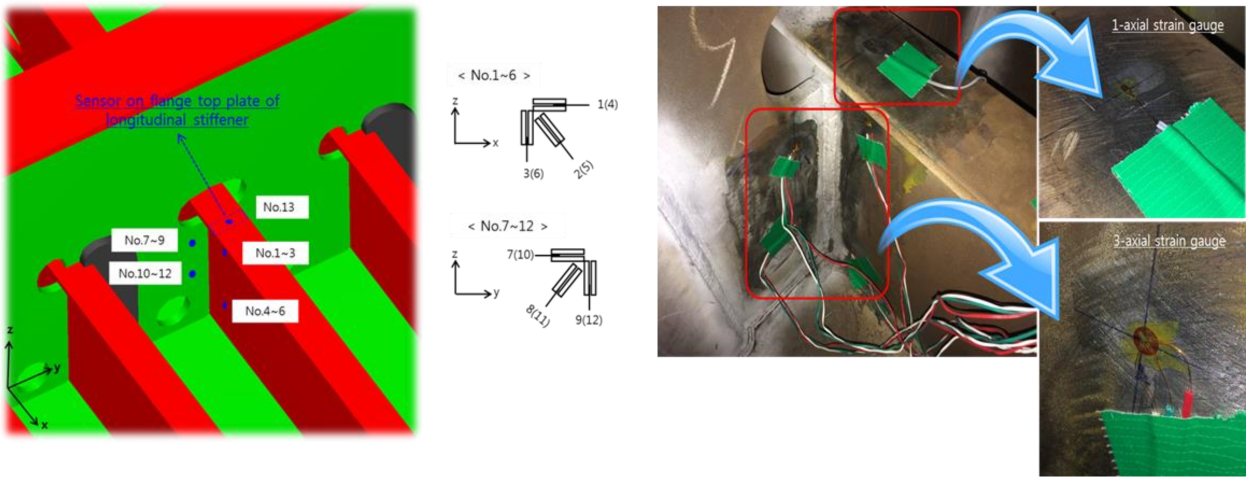


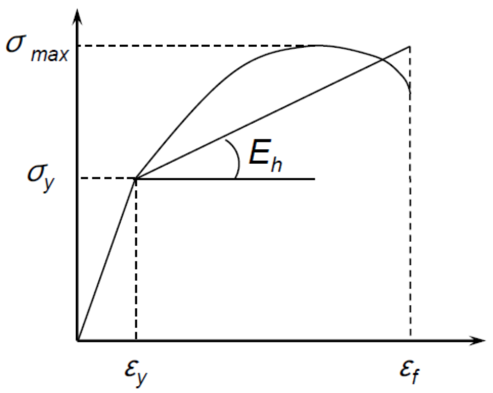
Figure 9.Strain Gage Installation at Joint between Intermediate Frame and Longi. Stiffener

STRAIN HARDENING EFFECT

In the dropped object simulation and the post processing of impact test data, the large deformation of structures and elasto-plastic material property were adopted to consider strain hardening effect. The strain hardening effect as well as ultimate stress was considered as a bi-linear strain-stress curve according to material grades as shown in Figure 10. The fracture was determined on the basis of the critical plastic strain of the steel material used as per the NORSOK document. In case of steel material, the critical strain for rupture was determined from data of mild steel and HT 32 only according to NORSOK standard. For material not shown in NORSOK standard, critical strain was calculated through linear extrapolation based on known data such as material data of HT 32. The concerned locations were designed by S500 steel.

Figure 11 shows material properties used in nonlinear simulation. The Cowper-Symonds rate enhancement formula was used to consider the effect of strain rate on material properties as shown in Figure 12.

To realize strain hardening effect in FE analysis, the commercial software LS-Dyna was used. As a material card, in flexible body, *MAT_PIECEWISE_LINEAR_PLASTICITY was used to simulate rupture and strain hardening of hull structure.



$$\sigma_p = \sigma_y + \frac{EE_h}{E - E_h}\varepsilon_p$$

$$E_h = \frac{\sigma_{max} - \sigma_y}{\varepsilon_f - \varepsilon_y}$$

σ_y = Yield stress

E_h = Young's modulus

E_h = Hardening modulus

σ_p, ε_p = Plastic stress & Plastic strain

Figure 10.Stress-strain Curve for Bi-linear Material

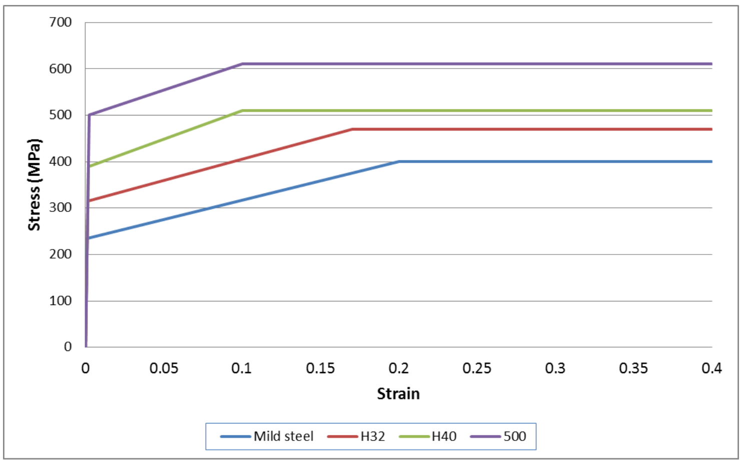
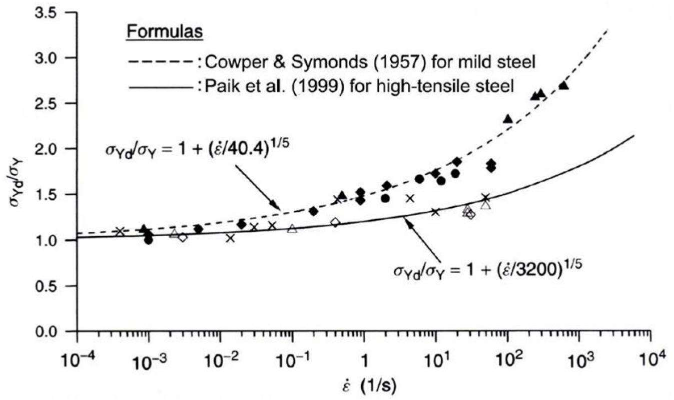


Figure 11.Stress and Strain Curves for FE Analysis



$$\frac{\sigma_{yd}}{\sigma_y} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}$$

Mild Steel: C= 40.4, p=5
HT Steel: C=3200, p=5

Figure 12.Strain Rate Effect of Steel

COMPARISON OF IMPACT TEST AND FE ANALYSIS RESULT

The total equivalent strains at concerned locations same in impact test were obtained from dropped object simulation. The plasticity was not founded at concerned locations. Total equivalent strains were smaller than the equivalent yield strain and the value at intermediate frame, location3 and 4, is bigger than at longi. stiffener. However, in full scale impact test, plasticity was clearly identified as shown in Table 3 and Figure 13 which represent total strain value at concerned locations for comparison.

As the result shown in this difference, it is necessary to verify the contact condition and the strain hardening effect in the FE analysis. The mesh shape of slave and mister part should be adjusted until the plastic strain at intermediate frame is identified. Moreover, the parameters for stain hardening effect, such as in Cowper Symonds, should be iterated to decrease gap with impact test result.

Table 3.Maximum Total Strain

		Max. Equivalent Strain (mm/mm)	
	Strain Gage No.	FE analysis	Impact Test
Location01	No.01~03	1.79E-03	2.27E-03
Location02	No.04~06	1.50E-03	1.59E-03
Location03	No.07~09	2.10E-03	1.17E-02
Location04	No.10~12	1.87E-03	7.61E-03

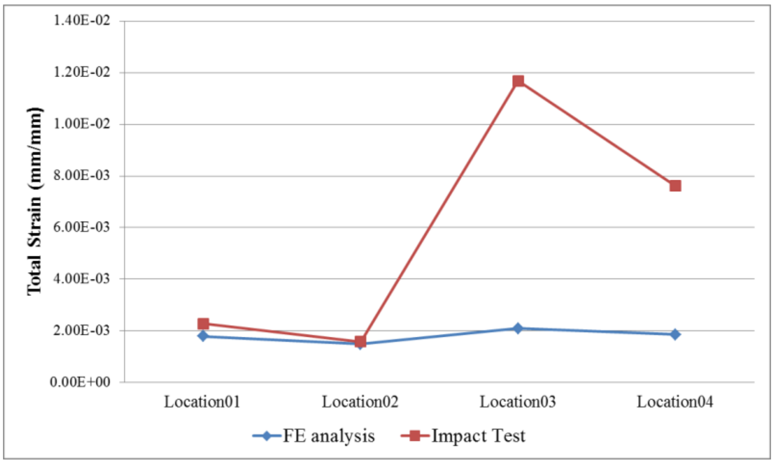


Figure 13.Maximum Total Strain

The weld crack against impact load was not identified according to NDT (Non-destructive testing), after impact test. The plasticity was not founded in Location 1 and 2. In measured effective plastic strain and total strain for von-Mises criteria as shown in Figure 14, the soundness of hull structure and weld strength was identified because measured values were below than the critical strain of concerned material (S500 steel: 0.1).

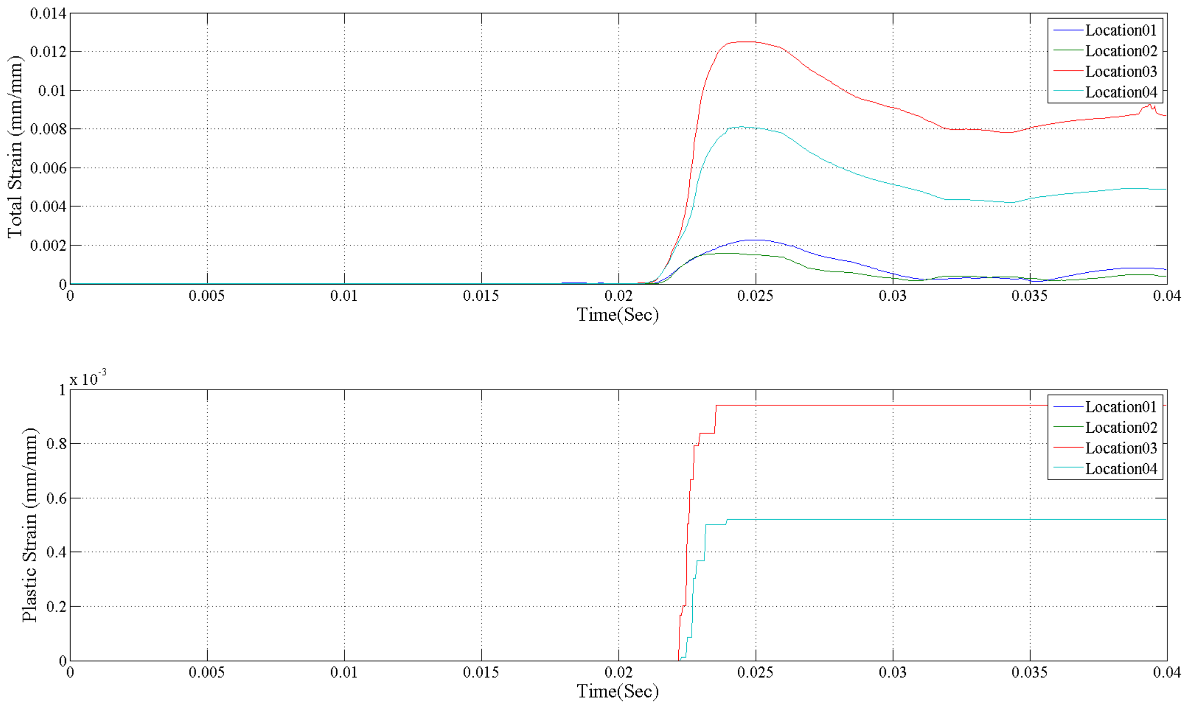


Figure 14.Effective Plastic Strain and Total Strain for von-Mises Criteria

CONCLUSIONS

According to direct ice load calculation introducing the finishing breaking scenario, the ice load for ARC 7 requirement was calculated based on real LNGC design. The nonlinear analysis was performed to guarantee the hull and CCS strength against ice load. The requirement was satisfied as the FE analysis result. Especially, the enough margin of CCS strength was identified in relative deflection check.

From the full scale impact test, the designed structure has enough impact strength, even though the high local strain induced from impact load was measured. However, it was founded that the impact response in FE analysis was not matched with in impact test. In future study, the contact option and the parameters for stain hardening effect in FE analysis will be deeply investigated to simulate realistic impact phenomenon.

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