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A Study on the Effect of Ice Impact Forces on an Ice-Strengthened Polar Class Ship After a Collision with an Iceberg

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빙산과의 충돌 시 충격 하중이 극지운항선박의 내빙 구조에 미치는 영향에 관한 연구

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Abstract : *Shipping activities have become possible in the Arctic Ocean due to melting ice by global warming. An increasing number of vessels are passing through the Arctic Ocean consequently bringing concerns of ship-iceberg collisions. Thus, most classification societies have implemented regulations to determine requirements for ice strengthening in ship structures. This paper presents the simulation results of an ice-strengthened polar class ship after an iceberg collision. The ice-strengthened polar class ship was created in accordance with the Unified Requirements for a Polar-Ship (IACS URI). An elastic-perfect plastic ice model was adopted for this simulation with a spherical shape. A Tsai-Wu yield surface was also used for the ice model. Collision simulations were conducted under the commercial code LS-DYNA 971. Hull deformations on the ice-strengthened foreship structure and collision interaction forces have been analysed in this paper. A normal-strength ship structure in an iceberg collision was also simulated to present comparison results. Distinct differences in structural strength against ice impact forces were shown between the ice-strengthened and normal-strength ship structures in the simulation results. About 1.8 m depth of hull deformation was found on the normal ship, whereas 1.0 m depth of hull deformation was left on the ice-strengthened polar class ship.*

Key Words : *Ice strengthened ship, Iceberg, Ice impact force, Collision, Polar class ship*

요 약 : 본 연구는 LS-DYNA 971 을 이용하여 내빙 구조 선박과 빙산 모형 간의 충돌 시험을 수행 후 북극해 운항 선박의 내빙 능력을 분석하였다. 국제선급연합회(IACS)의 Unified Requirements for Polar ship(URI) 규정을 바탕으로 FEM 선박 모형에 내빙 구조를 적용하였으며, 빙산 모형에는 Elastic-perfect plastic 물성과 Tsai-Wu 항복 곡면을 적용하였다. 또한 실험 결과 비교를 위하여 내빙 구조를 갖추지 않은 일반 선박 모형과의 충돌 시험도 수행하였다. 실험 결과 일반 구조 선박의 구형 선수에 빙산 모형에 의해 움푹 들어간 약 1.8 미터 깊이의 선체 손상이 발생하였으나, 내빙 구조 선박의 충돌에서는 약 1.0 미터 깊이의 선체 손상만이 발생하였다. 또한 일반 구조 선박과 충돌한 빙산 모형은 원형의 상태를 거의 유지한 반면, 내빙 구조 선박과 충돌한 빙산 모형은 내빙 구조의 구형 선수에 의해 빙산이 일부 파괴되는 현상이 발견되었다.

핵심용어 : 내빙 구조, 빙산, 빙산 충격하중, 충돌, 극지 운항 선박

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1. Introduction

The Arctic Ocean is now opened for merchant vessels to pass through its area as the ice cap is melting away by global climate change. As an increasing number of the ship navigates Arctic area, the possibility of a collision of the ship against an ice is consequently emerging. For example, navigating ice-infested water inevitably faces the danger of the collision against a floating small iceberg which could not be detected easily by ship radar. An iceberg-ship collision in the Arctic Ocean undoubtedly could trigger more harmful damages than in the other seas because the Arctic Ocean not only preserves precious natural resources but also is remote area to rescue people in due time. Thus, there is a strong need to research the effect of the ice impact forces on an ice-strengthened ship.

Determining ice impact forces posed on a ship structure is one of the main factor to analyse iceberg-ship collision interaction. Popov et al. (1967) firstly proposed energy method to determine ice collision forces, then this method has been developed by using a pressure-area model of ice indentation by Daley (1999). Daley therein presented eight collision geometry cases for applying to both ice-ship and ice-structure collisions problem. This developed energy method was adopted in Unified Requirements for Polar ship (URI) implemented by International Association of Classification Societies (IACS, 2006). However this rule has vaguely stated ice models for the requirements as determining appropriate ice material models is not well established yet. Nevertheless, some researcher has proposed few ice models so far. Gagnon (2007) simulated growler impact to a ship bow using crushable foam material model. However, this model did not consider ice crack and damage in the experiment. An elastic-perfect plastic material model was proposed for a ship - iceberg impacts experiment by Liu et al. (2011a). He defined an ice model as pressure-dependent and strain rate-independent in the experiment. Besides internal properties of ice materials, there are also various geometric ice shapes have been researched. Storheim et al. (2012) introduced five representative ice shapes, then analysed local shape dependency of iceberg interaction by using forementioned crushable foam and plasticity-based material model.

In this paper, Polar Class rule (IACS URI) was used to create an ice-strengthened foreship structure model of Finite Element Method (FEM). An elastic-perfect plastic ice model was selected for the simulation. This model is represented when ice has a brittle failure mode caused by its high strain rate (>10-3/s) which be arisen at relatively high collision speed (Schulson, 2001). The Tsai-Wu yield surfaces model proposed by Derradji (2000) was adopted. This yield surface was obtained from triaxial experiments on an iceberg by Gagnon and Gammon (1995). This simulation was conducted with commercial code LS-DYNA 971 and the ice models was created by a user-defined subroutine.

This paper analysed interaction forces of the ice-strengthened Polar Class ship after an iceberg collision and focuses on comparison of structural strength between ice-strengthened and normal strength ship hull structure.

2. Application Polar Class rule on the model ship

2.1 Overview of IACS Polar Class rule

IACS Polar Class rule applies to steel ships intended for navigating in ice-infested polar water, except ice breakers. This rule regulates structural and machinery requirements of the ship navigating polar waters. The Polar Class is divided into eight categories according to transit season and ice description (Table 1). The ice description is based on WMO (World Meteorological Organisation) sea ice nomenclature.

Table 1. Polar Class Description

Polar Class	Ice Description (based on WMO Sea Ice Nomenclature)
PC 1	Year-round operation in all Polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year round operation in second-year ice which may include multi-year ice inclusions
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

To determine ice impact loads on the ship, Polar Class rule provides related formulae and factors based on energy methods. Further details are not mentioned in this paper.

2.2 Application of Ice strengthened structure

Modelling a whole ship structure for collision simulation to analyse local deformation on a foreship structure is not only time-consuming but also low efficiency. In this reason, only a foreship structure model was constructed for the simulation. The actual main dimensions of the foreship structure model is listed in Table 2.

Table 2. Main Dimensions of Model ship

Item	Value	Unit
LOA	276	m
Breadth	45.8	m
Depth	26.5	m
Load Displacement	122,671	ton
Load Draft	11.72	M

To apply ice-strengthened structure to a FEM foreship structure model, physical properties of shell plate were calculated in accordance with Polar Class rule. Shell plate thickness and steel material of the FEM foreship structure model were defined as equivalent to PC 7. The Shell plate thickness can be obtained using following equation of IACS Polar Class rule;

$$t_{net} = 500 \cdot s \cdot ((AF \cdot PPF_p \cdot P_{avg}) / \sigma_y)^{0.5} / (1 + s / (2 \cdot b)) \quad (1)$$

where, s : Transverse frame spacing,

AF : Hull Area Factor,

PPF_P : Peak Pressure Factor,

P_{avg} : Average pressure within a design load patch,

σ_y : Minimum upper yield stress of the steel material

b : Height of design load patch.

It is seen that shell plate thickness is dependent upon ship frame structure, P_{avg} and class factors (AF, PPF_p). For calculating P_{avg}, it is required to calculate the following ice load characteristics of the ship bow area; shape coefficient (fa), total glancing impact force (F), line load (Q) and pressure (P). These ice load characteristics are to be calculated at the mid-length position of four sub-regions of ship's bow area which is divided equally along its waterline length. Hull angles are also to be measured at the forementioned four mid-length positions to obtain the ice characteristics. The hull angle definitions and measured values of the model ship are shown Fig. 1 and Table 3 respectively.

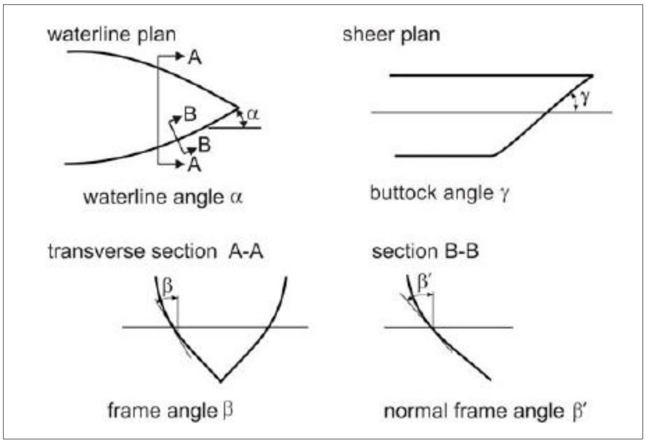

Fig. 1. Definition of hull angles.

where, β' : Normal frame angle at upper ice waterline (deg),

α : Upper ice waterline angle (deg),

ɣ : Buttock angle at upper ice waterline (angle of buttock line measured from horizontal, deg),

tan(β) : tan(α)/tan(ɣ), tan(β') is tan(β) · cos(α).

Table 3. Hull angles values at each position

Position	α	β	β'	γ
1	21.2	19	18	53.8
2	22.6	20.7	19.4	49.4
3	27.7	34.8	32.3	37.5
4	28.2	32.9	30.3	40.3

Table 4. Values for ice strengthened shell plate

Item	Value	Unit
Fa	0.233	
F	15.766	MN
Q	4.456	MN/m
P	3.034	MPa
P_{avg}	3.034	MPa
t_{net}	37.66	mm

Table 4 shows the calculation result of these load characteristics, P_{avg} and shell plate thickness for the FEM ship model.

Polar Class rule considers corrosion and abrasion allowance for shell plate thickness, thus final shell plate thickness is to be 39.66 ㎜ considering 2.0 ㎜ corrosion/abrasions addition. AH40 grade high tensile steel (390 N/㎟) is applied for the foreship structure model according to the rule.

3. Iceberg Modelling

An elastic-perfect-plastic iceberg material model developed by Liu et al. (2011b) and improved by Gao et al. (2015) was adopted for the simulation. The iceberg model behaves elastically before reaching the yield surface, and then shows perfect plastic behavior in which the stress keeps constant and the plastic strain increases. Upon reaching failure criteria, the ice element is deleted to represent the ice failure process such as pressure melting and microcracks for the simulation time.

During a ship-iceberg collision, the ice located in contact area is being at triaxial stress state. Thus, the triaxial compressive experiment for an iceberg conducted by Gagnon and Gammon (1995) was used for iceberg modelling. The serial experimental data of ultimate strength of iceberg can be fitted by 'Tsai-Wu' yield surface.

which is formulated as below.

$$f = J_2 - (a_0 + a_1 p + a_2 p^2) = 0 \quad (2)$$

where, f : hydrostatic pressure,

J_2 : Second invariant of deviatoric stress tensor

$a_0/a_1/a_2$: Constant parameters.

The failure criteria depend on the accumulation of plastic deformation and hydrostatic pressure as shown in formula (3).

$$\epsilon^p_{eq} = \sqrt{\frac{2}{3}\epsilon^p_{ij} : \epsilon^p_{ij}}$$

$$\epsilon f = \epsilon_0 + (\frac{p}{10^8} - 0.6)^2 \quad (3)$$

$$p < p_{cut} - off$$

where, p_{cut}-off : Cut-off pressure,

ε^p_{eq} : Effective plastic strain,

ε_f : Failure strain and

ε_0 : Initial failure strain.

If the hydrostatic pressure is smaller than the cut-off pressure which corresponds to the tensile stress state, or the effective plastic strain is larger than the failure strain, the element is failed and deleted.

The elastic part of this model was calculated by Hook's law and the perfect plastic part was implemented using cutting plane algorithm. The whole model was implemented by Fortran language and incorporated in commercial software LS-DYNA through user-defined material. The ice model's properties are listed in Table 5.

Table 5. Properties of the ice model

Item	Value	Unit
Density	900	Kg/m^3
Poisson's ratio	0.3	
Young modulus	9500	MPa
Diameter	8	m

4. Simulation of a ship collision with an iceberg

Ice-strengthened and normal-structure ships were used for the simulation to compare structural strength against ice collision forces. The normal-structure ship model has identical properties with the ice-strengthened model ship other than yield strength (235 N/㎟) and thickness (20 ㎜) of shell plates.

4.1 Collision scenario

A head-on collision scenario on a ship's bulbous bow were given for the simulation (Fig. 2). The Ship was supposed to navigates at 2.9 knots (1.49 m/s) which is designated as safety speed in Polar waters when Polar Class rule was being established (IMO, 2014). Whereas, the iceberg was assumed to float at 1.9 knots (1.0 m/s). A collision duration was set for one second to save computational time.

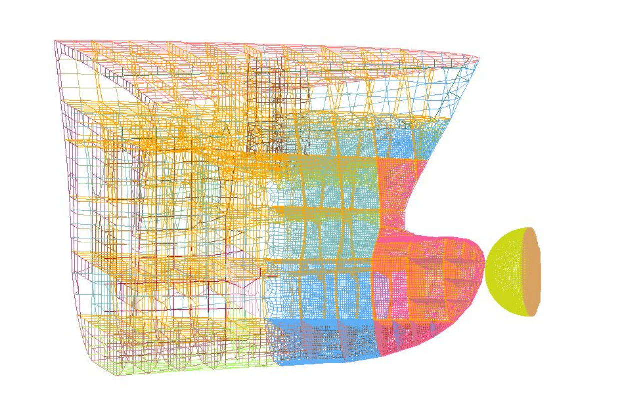

Fig. 2. Collision scenario.

4.2 Boundary Condition

The end of the bow structure was fixed and the iceberg is forced to impact on the ship structure at speed of 2.49 m/s. The main part of iceberg was also set as rigid part because only a small part of iceberg is crushed and contribute to the energy dissipation when an iceberg collides with a ship.

5. Simulation results

Considerable differences between ice-strengthened and normal-strength ship structure are seen in the simulation results. Fig. 3 and 4 depict hull deformations on the foreship structure models at the different time stages.

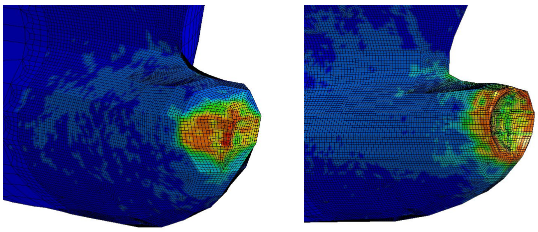

Fig. 3. Hull deformation on normal structure at 0.5s and 1s (Fringe levels).

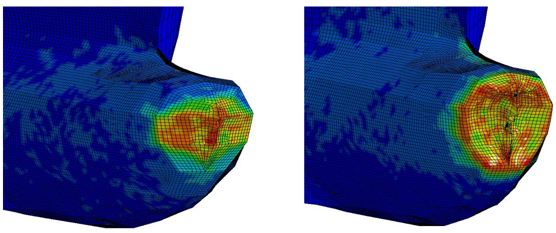

Fig. 4. Hull deformation on ice strengthened at 0.5s and 1s (Fringe levels).

As can be seen from a right picture of Fig. 3, there is a distinct crater remained on the center of bulbous, which means the normal-strength ship structure model could not sustain its shape against the ice collision. Whereas, the ice-strengthened bulbous structure (Fig. 4) is still remains at a functional shape compared to normal structure. Maximum Von Mises stresses of normal and ice strengthened structures were found as 404 MPa and 646 MPa, respectively.

Fig. 5 illustrates depth of hull deformations corresponding to contact forces. The depth of hull deformation were calculated by measuring the largest displacement of the node which is located on central contact area. The maximum depth of hull deformation (1.0 m) found on the ice-strengthened ship is significantly smaller than 1.8 m depth of deformation found on the normal-strength ship. Moreover, a notable factor is that deformation of the normal-strength ship kept consistently progressing during the simulation time. Whereas, deformation of the ice-strengthened ship very slowly underwent after suffering 0.1 meter deformation of the bulbous bow structure. Regarding the contact forces, only a half of the contact force was found in the normal-strength ship structure and iceberg collision case compared to the ice-strengthened ship collision. Also oscillation of the contact force in the lower graph of Fig. 5 is noticeable. It is owing to variation of contact area caused by considerable hull deformation on the normal-strength ship.

Dissipated energy of the two collision bodies are also worth being considered. Fig. 6 shows the internal energy dissipated by two collision bodies during the collision. From these two graphs, it is noted that the foreship structure dissipated considerable energy when compared to the iceberg. A drastic change of internal energy on the ice-strengthened structure was started at 0.5 s time stage when it is corresponding to 0.1 m deformation found in the upper graph of Fig. 5. It is assume that dissipated energy from the ice-strengthened ship was consumed for resisting its deformation. In the mean time, internal energy of the iceberg model against the ice-strengthened ship increases at a constant rate contributing to its erosion. Conversely, there is a very small amount of internal energy found on the iceberg model in the normal-strength ship and iceberg collision case. It could be a result of that the iceberg was nearly not affected by the ship's impact forces in this case.

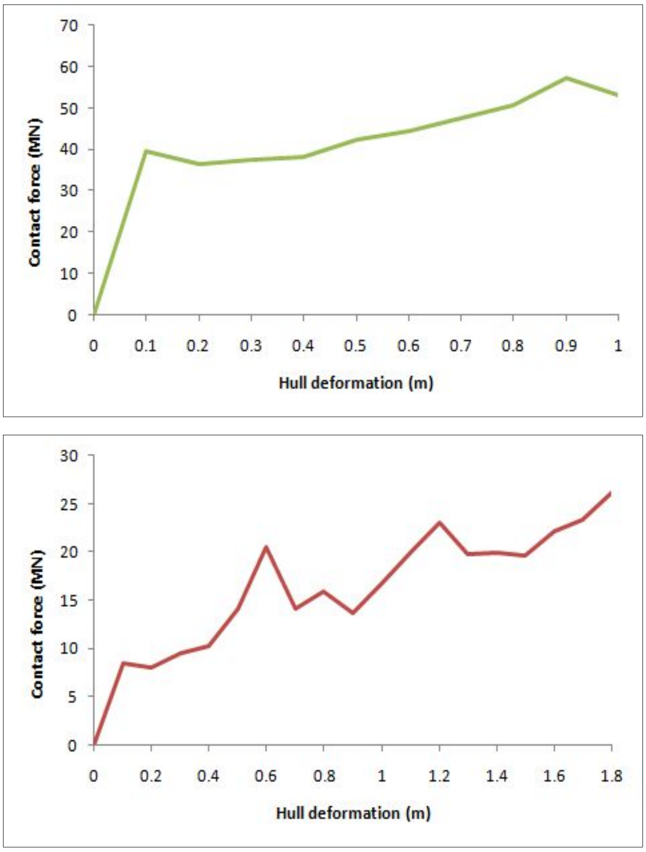

Fig. 5. Depth of Hull deformation of ice strengthened (upper) and normal strength (lower) structure by contact forces.

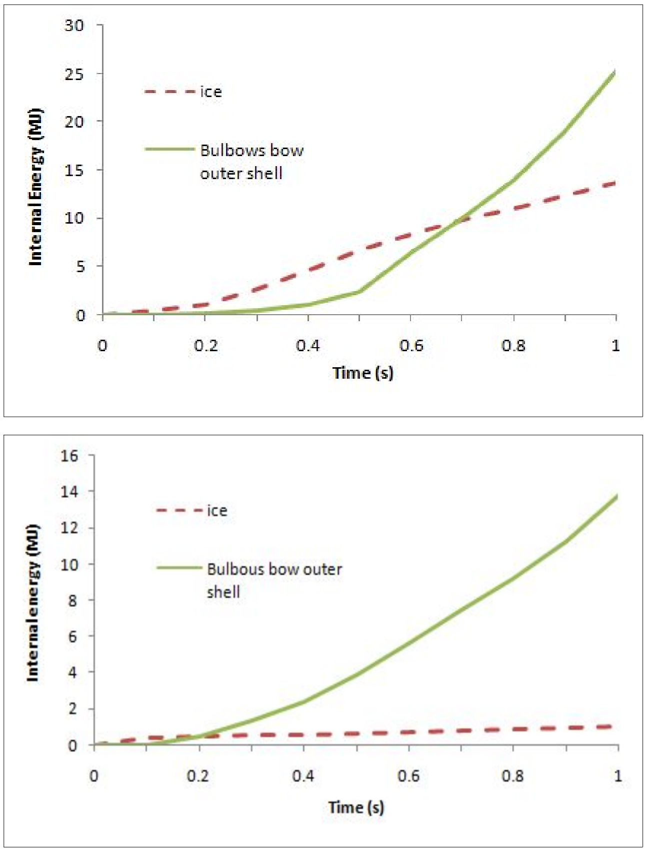

Fig. 6. Internal energy of ice strengthened (upper) and normal strength (lower) structure.

Ice deformations against the collisions are depicted in Fig. 7. It is seen that many elements of the contact area against ice-strengthened ship were scattered and failed during the simulation. On the other hand, the ice impacting on the normal-strength ship almost preserved its original shape having only few element failed and eroded. From this result, it is possible to suppose that the ice-strengthened bulbous structure could keep its functional shape even if collision interaction prolongs for a while. However, the normal-strength bulbous structure is supposed to lost its functionality as hull deformation is kept proceeding by the undamaged iceberg.

Noticeable different properties between the ice-strengthened and the normal-structure ship are listed in Table 6 to highlight the simulation result.

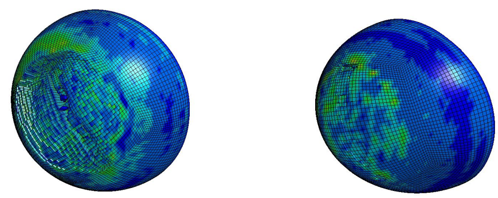

Fig. 7. Deformation of ice against ice strengthened (left) and normal structure (right) at 1s.

Table 6. Different properties of the two types of ship

Item	Ice strengthened ship	Normal structure ship
Shell plate thickness	39.66 ㎜	20.00 ㎜
Yield strengh of shell plate	390 N/㎟	235 N/㎟
Max. hull deformation	1.0 m	1.8 m
Max. Von Mises stresses	646 MPa	404 MPa

6. Conclusion

This paper presents the simulation results of ship - iceberg collisions. A main aim of this paper is to find out how an ice-strengthened Polar Class ship endures the ice impact forces against its collision. To present comparison result, a normal-strength ship and iceberg collision case was also simulated. Some notable results were found in the simulations.

1) The Polar Class ship needs thicker steel plates nearly twice normal ship steel plate to resist ice impact forces.

2) The Polar Class ship keeps its functional shape even though hull deformation is shown.

3) Most interaction energy is dissipated to crush iceberg other than damaging hull structure in the Polar Class ship - iceberg collision case, unlikely the normal strength ship - iceberg collision case.

4) The ice model keeps showing failure and erosion behaviors in case of the collision against Polar Class ship. Whereas the ice model remains almost intact in the normal strength ship - iceberg collision case.

This paper analyses the head-on collision simulation result. An oblique collision case also will be dealt with in ongoing work adding other ice models and at different collision speed in the future.

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