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Analysis of Ship Structural Response due to Ice Collision

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ABSTRACT

The ice impact load is considered as the most significant factor in the structural design of ships and offshore structures operating in arctic sea. It results from the mutual interactions during the ice-structure collision process and which is closely related to mechanical characteristics of ice. The strength and failure properties of ice, however, show very complicated aspect varying with temperature, volume fraction of brine, grain size, strain rate and so on. So it is nearly impossible to establish a perfect unified material model of ice satisfying all the mechanical characteristics completely. Therefore, in general, ice collision analysis was carried out by relatively simple material models considering only specific aspects of mechanical characteristics of ice and it would be the major cause of inevitable errors in the analysis. Especially, it is well-known that the most distinctive mechanical property of ice is high dependency on strain rate. Ice shows brittle attribute in higher strain rate while it becomes relatively ductile in lower strain rate range. In this study, the simulation method of ice collision to ship hull using the nonlinear dynamic FE analysis was dealt with. To consider the strain rate effects of ice during ice-structural interaction, strain rate dependent constitutive model in which yield stress and hardening behaviors vary with strain rate was adopted. To reduce the huge amount of computing time, the modeling range of ice and ship structure were restricted to the confined region of interest. Under the various scenario of ice-ship hull collision, the structural behavior of hull panels and failure modes of ice were examined by nonlinear FE analysis technique.

KEY WORDS : Ice collision simulation; Fresh water ice; Sea ice; Material property; Strain rate dependency; Nonlinear FE analysis; LS-DYNA

INTRODUCTION

Along with the development of oil and natural gas resources in the arctic region, recently many shipping companies and shipbuilders have interest in the construction of various types of ships with ice grades as an attempt to reduce the transportation cost through exploiting the arctic sea route. However, since the arctic sea is always covered with thick ice except during the short summer season, there is a growing need for arctic engineering to overcome the cold ice sea in order for ships to operate in the area.

Ice loads, which are considered to be the most important in the structural design of vessels and offshore plants operating in the arctic sea, take place as interactions due to collision of ice and structures. However, the collision phenomenon between ice and structures can be varied very diversely, and the analysis method of ice load can be changed according to occasions. In addition, since magnitude and duration time of the ice loads show various aspects depending on the strength of the structure and the material characteristics of the ice during the collision, there are still many difficulties in accurate estimation of the ice collision loads. In order to secure the safety of ships operating in the arctic region, therefore, it is essential to establish reasonable estimation methods of ice load, and apply them to the structural analysis and design process.

As mentioned above, ice loads due to ice-structure interaction are very sensitive to the collision conditions and material properties of ice. The mechanical property of ice is, however, so diverse and complicated depending on the various environmental conditions different from common structural materials. Therefore, it is very difficult to propose an unified material model for ice strength that can be applied to the all cases of ice-structure interaction. Moreover, since the ice-hull collision condition is also very diverse, the design of arctic structures should be carried out considering the rational ice collision conditions. The ice colliding scenarios proposed by DNV(2006) and ABS(2009) are typical examples of them.

Recently, studies for the ice collision problem by numerical approach have been attempted (Kujala, et al, 2007). Han et al(2008) and Lee et al(2009) carried out the ice collision analysis using nonlinear finite element analysis codes in order to evaluate the structural safety of LNG carriers operating in the arctic region.

In the numerical analysis, however, the obtained ice collision loads are also very irregular due to the diversity of material characteristics of ice and the collision conditions and they are the main source of inevitable uncertainty in ice load estimation. Therefore, it would be necessary to set up a rational procedure for the numerical simulation to evaluate ice collision loads.

This study dealt with the simulation method of ice-hull collision using the nonlinear dynamic FE analysis. In order to show the standard structural safety evaluation procedure for the ice-hull collision in the arctic region, 2 simple ice collision scenarios for the level ice and ice bergy bits colliding a ship’s hull were simulated and results were considered. The structural modeling range were restricted to minimum level to reduce the simulation time within reliable accuracy for evaluating the hull structural response. In addition, the constitutive model considering strain rate effect, which is the most typical characteristic of ice was adopted.

MATERIAL PROPERTIES OF ICE

The mechanical properties of ice are complicatedly varying with many factors such as temperature, brine volume, size of crystalline, strain rate and so on. In particular, as shown in Figure 1, the deformation behavior of ice tends to be brittle at high strain rate while it becomes relatively ductile at low strain rate. And the overall shape of the stress-strain curves varies sensitively according to the strain rates.

Such complexity of ice deformation behavior is caused by microstructural changes in the crystalline structure of ice including micro crack growth and propagation. For the reasonable estimation of the ice-structure interaction and ice load due to ice collision by applying the theoretical and numerical approach, it is necessary to set up the rational constitutive equation, which can represent the actual stress-strain relationship of ice deformation. Although it is not easy to model the complex strength characteristics of ice closely, the basic mathematical form of the constitutive equation is assumed considering the physical behavior of the ice in various mechanical aspects related to the purpose of analysis. And the related coefficients of constitutive equation can be determined by experiments or field measurement.

Ice generally shows typical brittle material characteristics, it is much stronger for compressive stress than tensile stress with high strain rate dependency. In this study, ice was basically regarded as an elasto-plastic material. Considering the limitations of the material library included in the nonlinear structural analysis code (LS-DYNA), an piecewise linear plasticity material model with the von-Mises yield condition was adopted, which can define arbitrary stress versus strain curves according to the strain rates considering the strain rate dependency of the hardening curves. Also, the failure condition of ice was defined as failure strain expressed by cumulative equivalent plastic strain.

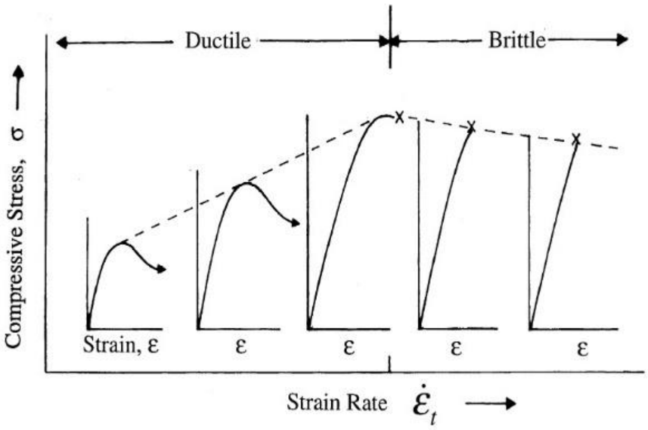
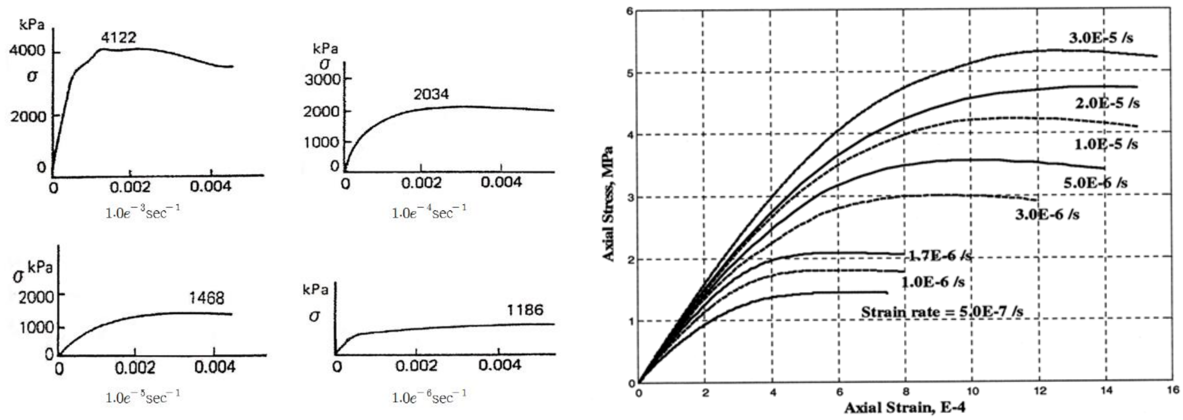


Figure 1. Compressive failure modes in ice as a function of strain rate (Carney, 2006)

Characteristics of Sea Ice

A lot of research has been carried out about the properties of sea ice in various aspects and viewpoints. Wang(1982) showed the different shapes of stress-strain curves of sea ice depending on the strain rates as shown in Figure 2(a). The present study also used this experimental results for the level ice collision problem.



a) sea ice(Wang,1982) b) fresh water ice(Derradji-Aouat, 2000)

Figure 2. Stress-strain curves of ice depending on strain rates obtained by experiments

Characteristics of Iceberg

Iceberg generally falls out of land glaciers, so it is basically similar to fresh water ice. Johns(2006) showed that the strength of iceberg is slightly weaker than freshwater ice in high strain rate range, but the difference is not significant.

Therefore, in the present study, the stress-strain curves for fresh water ice, as shown in Figure 2(b) (Derradji-Aouat, 2000) was adopted for the collision analysis of iceberg. The shapes of the hardening curve vary considerably depending on the strain rates.

ICE SHIP COLLISION SCENARIO

There can be so many different situations of ice collision to ship's hull. In this study, the collisions of level ice sheet and iceberg was dealt with.

Considering the hydrodynamic and buoyancy forces of a mass of ice drifting in water, it could be a more accurate way to include the surrounding fluid region in the analysis modeling range for the collision simulation.

Even present day, however, it is not easy to provide a quantitatively reliable results for the FSI problems based on the CFD technique in spite of a great computation time. Therefore, a simplified practical method proposed by Kolari et al (2009) was applied, in which the added mass of drifting ice in water was calculated roughly (Bishop & Price, 1979) and modified the overall density of ice considering it.

Collision of Level Ice

The collisions of level ice sheet should be considered when ships are directly breaking the ice covered sea or pass through the ice channels provided by ice breakers. When passing through the ice channels, the ice sheets or the ice floes may collide the bow or shoulder of the hull. The collision speed can be determined by considering the velocity and turning speed of ship.

Level ice is generally composed of 1-year-old sea ice. The speed of the ship in this situation is usually about 3 ~ 5 knots, and thickness of the level ice was assumed to be about 0.8m ~ 1.0m.

Collision of Iceberg

Han et al(2008) mentioned that icebergs of 2m high above water line could be easily detected by deployed ice monitoring systems of ships and avoided easily by change of ship speed and course. Hence, the icebergs with sail heights less than 2m can be bigger threat to the safety of ships and should be fully investigated with possibility of collision to ships voyaging in their full speed. So it would be better to call them ice bergy bits from now on.

Therefore, it is rational to consider situations in which ice bergy bits may collide with bow, shoulder, or side of ships. DNV (2006) proposed some typical ice collision scenarios and shapes of ice bergy bits. For the iceberg collision analysis, not only the relative speed of the ship and ice but also the collision angle should be considered to simulate the actual phenomena accurately, However, this study aimed to establish a standard interpretation procedure, it was assumed that the spherical ice bergy bit collides to the side structure of a membrane type LNG carrier in vertical direction with a speed of 2 m/s as a typical example.

ICE COLLISION ANALYSIS AND CONSIDERATIONS

As shown in Figure 3 and 6, the colliding process of iceberg and level ice to ship's hull were simulated precisely using a commercial nonlinear structural dynamic FEA code LS-DYNA.

Material Properties

Even though nonlinear FE structure analysis codes, including LS-DYNA, provide hundreds of material models, it is not easy to find an adequate material model to implement the complicated mechanical properties of ice as described above. In this study, MAT_ PLASTIC_KINEMATIC model of LS-DYNA which can consider the strain rate dependency of ice was adopted. In this material model, elastic modulus is thought to be constant during deformation and yield stress and hardening curve can be defined differently according to the strain rate by piecewise linear curves. The isotropic strain hardening model was used neglecting the Bauschinger effect. The mild steel used for hull structure was regarded as an elastic-perfect plastic material for simplicity.

Table 1 summarizes the mechanical properties of freshwater ice, sea ice, and mild steel for ship structure. The failure condition of ice was defined by failure strain given by a representative constant value regardless of the strain rate because of the limitation of material model.

Table 1. Mechanical characteristics of materials

	Mild steel	Sea ice	Fresh water ice
Elastic modulus, GPa	210	7.3	7.8
Density, kg/m^3	7850	920	920
Poisson's ratio	0.3	0.34	0.34
Yield strength, MPa	285	Figure 2(a)	Figure 2(b)
Hardening curves	Elastic- perfect plastic material		

Collision Analysis of Level Ice

As an example of level ice collision analysis, a side structure of arctic cargo ship with a longitudinally framed system was selected. The target ship structure was assumed to collide to an 1 m thick ice sheet located in an ice channel with relative speed of 5 kts(2.572 m/sec) vertically.

Considering the geometrical symmetry of the target structure, the only 1/4 part was modeled and analyzed. In order to reproduce a realistic situation, the colliding ice was modeled as an arc shaped sheet for gradual contact and failure. The FE modeling of collision scenario and boundary condition was described in Figure 3. As shown in the figure, the mesh of ice contact part of the panel was divided more precisely to enhance the analysis accuracy. The material properties of level ice are shown in Figure 2(a).

In Figure 4, the equivalent stress distribution and time histories are shown at the 3 positions of panel around the collision point including the midpoints of long and short side(position A, B) and the corner position C of the plating, in which the stress levels are expected to be high.

The stress level of point A was relatively higher than other positions, however, the possibility of plastic deformation on the shell panel seems to be low since the average stress level was not so high and the duration times of peak value are very short.

The time series of the stresses are very randomly distributed because the failure of ice sheet takes place very irregularly during collision. In general, the actual ice load data obtained from onboard measurement shows typical regularly periodic triangular shaped response during ice collision process and random high frequency behaviors are overlapped on it. The high frequency behavior may take place due to the impact load generated during the partial corruption and removal process of contacting ice.

The periodic triangular shape response is caused by the bending failure at a distance from the loading point of ice, untill now, however, the phenomenon is not easy to implement by FE simulation technique and it is thought to be a challenging field of the future.

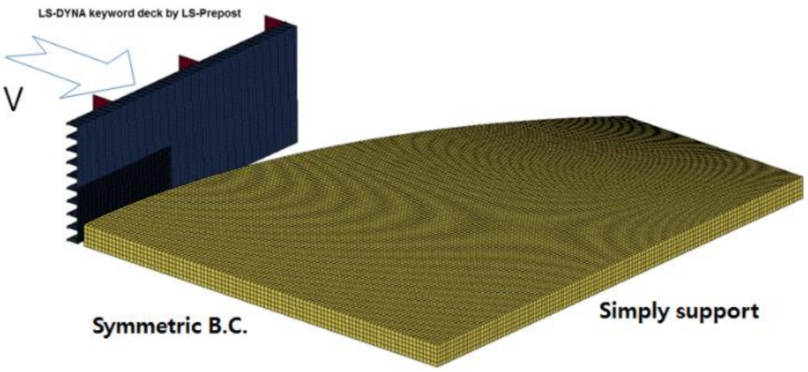


Figure 3. Modeling of ship structure, level ice and boundary conditions

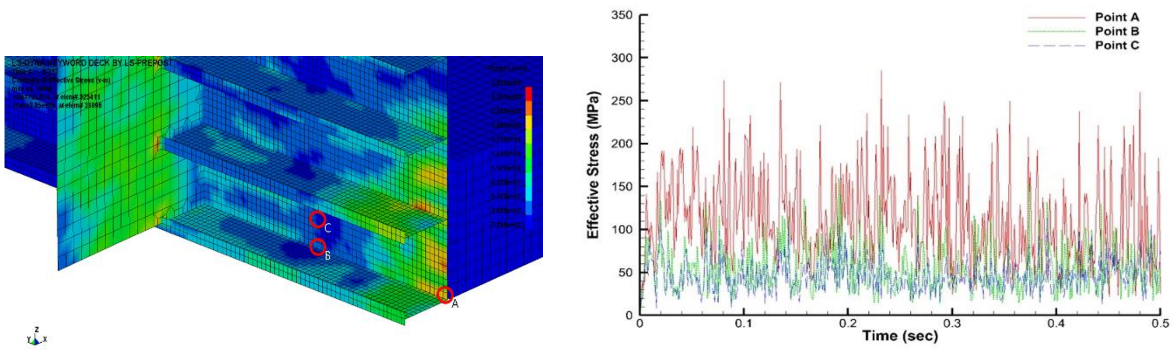


Figure 4. Distribution and time histories of effective stresses in ship structure

Collision Analysis of Ice Bergy bit

The side structure of the Mark III membrane type LNG carrier was analyzes under the situation that an ice bergy bit is colliding at the speed of 1, 2 and 3 m/sec to it as a scenario shown in Figure 5. 4 different ice bergy bits with sphere, bell or cubic types represented in Figure 6 were considered as recommended by DNV(2006).

The ice bergy bits were considered to collide at the center of the side structure and an insulation panel located at the collision position was included in the structural analysis model (Nho et al, 2014). As shown in Figure 7, the R-PUF, mastic and plywood in the insulation panel were modeled precisely to investigate the structural integrity of CCS. The side hull of LNG carrier was modeled by 2-D shell elements and the ice bergy bits and insulation panel were modeled by 3-D solid elements. For the material properties of the ice bergy bits, the characteristics of fresh water ice by Derradji-Aouat(2000) shown in Figure 2(b) was applied and ABS(2006) data were used for those of insulation panel.

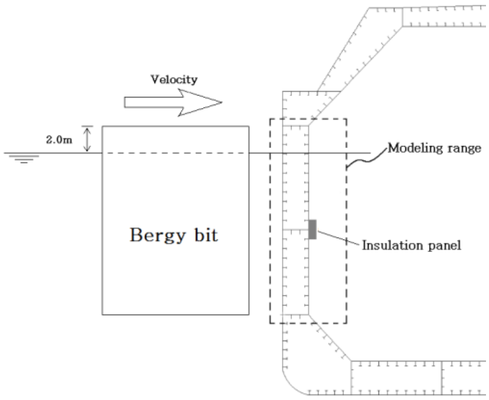
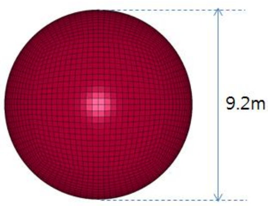
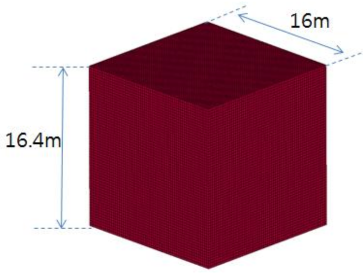


Figure 5. Ice bergy bit colliding scenario and modeling range of side structure



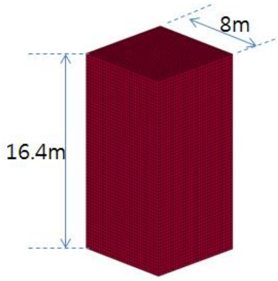
- Radius : 5.1 m
- Volume : 555 m^3
- Mass: 500 ton

a) Spherical type



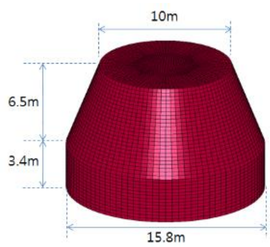
- Height : 16.4 m
- Edge length : 16 m
- Volume : 4,200 m^3
- Mass : 3,780 ton

b) Cubic type 1



- Height ; 16.4 m
- Edge length ; 8 m
- Volume: 1050 m^3
- Mass: 944 ton

c) Cubic type 2



- Height ; 9.9 m
- Volume ; 1,500 m^3
- Mass : 1,370 ton

d) Bell type

Figure 6. Modeling details of ice bergy bits

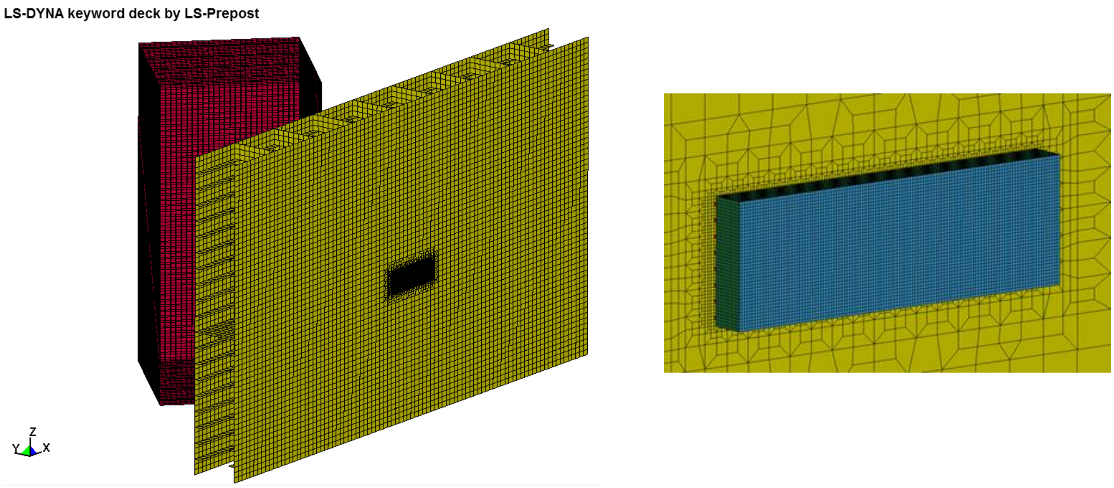


Figure 7. Structural modeling of side hull structure and insulation panel

The maximum collision loads according to the collision velocities and shapes of ice bergy bits were compared in Figure 8 respectively. It was obvious that the iceberg collision load was depends on the weight of iceberg. So, the analysis results for the cuvic 1 which is the heaviest model are dealt with from here.

The obtained equivalent stresses time histories of the side hull and insulation panel according to the variation of collision velocity were shown in Figure 9. And maximum von Mises equivalent stress distributions in hull structure and R-PUB were presented in Figure 10.

In the side hull structure of LNG carrier, the collision position suffered relatively high stress level and slight plastic deformations were taken place, however, most of the rest parts including the insulation panel showed low stress level within elastic limit. Therefore, it was concluded that the structural integrity of the CCS of this membrane type LNG ship against iceberg collision can be validated.

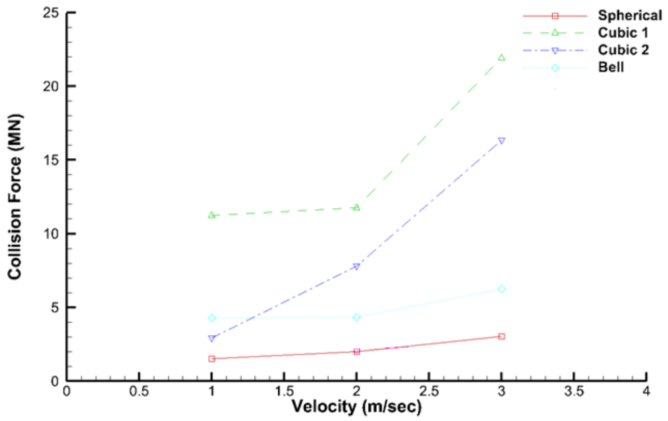
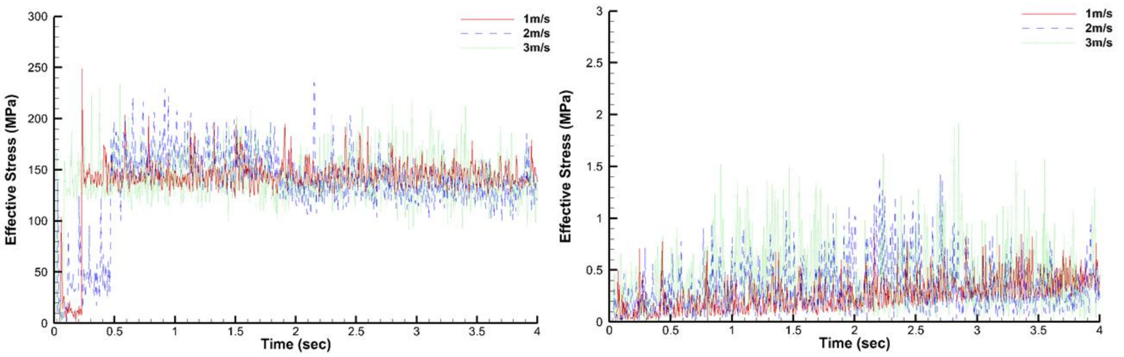
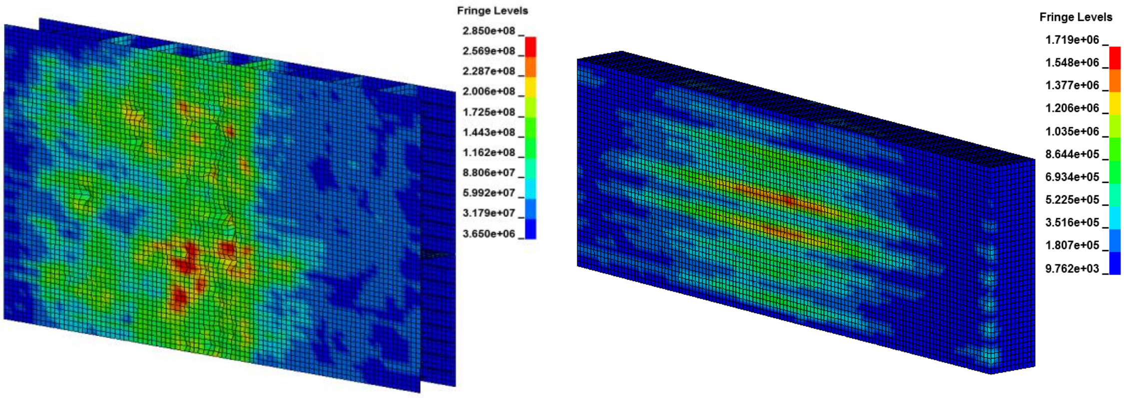


Figure 8. Maximum collision forces according to collision velocity



a) in ship's side structure b) in R-PUF

Figure 9. Time history of effective stress



a) in ship's side structure b) in R-PUF

Figure 10. Distribution of effective stress

CONCLUSIONS

In this study, the simulation method of ice-hull collision process using the nonlinear finite element method (LS-DYNA) was dealt with to evaluate the structural safety of the hull. The estimation of material properties of ice is also a challenging field to be studied in the future, however, the strain rate dependency of material properties of ice was considered. And material test data for sea ice(Wang, 1982) and fresh water ice(Derradji-Aouat, 2000) were adopted.

Though the conditions of ice-hull collision are very diverse, in this study, a few relatively simple scenarios were assumed for the example analysis to verify the suggested simulation methods. Based on the consideration for the example analyses, the suggested simulation method of ice collision was considered to be a selectable means to evaluate the ice load and structural safety of ship's hull.

In future, it would be necessary to develop more accurate ice collision simulation technology for the rational structural design of arctic ships and more precise interpretation would be possible if the detailed basic researches on material characteristics and failure mechanism of ice are supported.

ACKNOWLEDGEMENTS

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REFERENCES

ABS, 2006. *Guidance note on Strength Assesment of Membrane-Type LNG Containment Systems under Sloshing Loads*.

Bishop, R., and Price, W., 1979. *Hydroelasticity of ships*, Cambridge University Press.

Carney, Kelly S., Benson, David J., DuBois, Paul and Lee, Ryan, 2006. "A phenomenological high strain rate model with failure for ice," *International Journal of Solids and Structures*, Vol. 43, pp.7820-7839.

Derradji-Aouat, A., Sinha, N.K. and Evgin, E., 2000. "Mathematical Modelling of Monotonic and Behaviour of Fresh Water Columnar Grained S-2 ice", *Cold Regions Science and Technology*, 31, pp.59-81.

DNV, 2006. "Iceberg Collision Scenario," *DNV Report No. 2006-0672*, pp.8-14.

Han, S.K., Park, Y.I., and Che, J.S., 2008. "Structure Risk Analysis of a GTT NO96 Membrane Type LNG Carrier in Baltic Ice Operations", *Proceedings of IMechE 2008*, Vol. 222, Part M, pp.179.

Jones, S., 2006. "Comparison of the Strength of Iceberg and Other Freshwater Ice and the Effect of Temperature," *PERD/CHC Report 20-83 TR-2006-07*, NRC Canada.

Kolari, K., Kuutti, J. and Kurkela, J., 2009. "FE-simulation of Continuous Ice Failure based on Model Update Technique," *Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 9-12, 2009, Luleå, Sweden.

Kujala, P., Suominen, M. and Jalonen, R., 2007a. "Increasing The Safety of Icebound Shipping," *Final Scientific Report: Volume 1&2*, Helsinki University of Technology, Ship Laboratory.

Lee, S.G., Lee, J.S., Baek, Y.H., Paik, J.K., 2009. "Structural Safety Assessment in Cargo Containment System in Membrane Type LNGC under Iceberg Collisions," *Proceeding of the Annual Autumn Meeting, the Society of Naval Architecture of Korea*, Mungueong, pp.29-30, October.

LSTC, 2007. *LS-DYNA keyword user's manual, Volume 1*, Version 971.

Nho, I.S., Yun, Y.-M., Park, M.-J., Oh, Y.-T. and Kim, S.-C., 2014. "Structural Safety Assessment of Mark III Membrane type LNG CCS under Ice Collision," *Journal of Ocean Engineering and Technology*, 28(2), pp.126-132.

Wang, Y.S., 1982. "A Rate-Dependent Stress-Strain Relationship for Sea Ice," *Proceedings of The 1st International Offshore Mechanics And Arctic Engineering Symposium*, Vol. Ⅱ.