Study on Strength of LNG Carrier against Ice Impact

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Summary

This paper proposes the methods of structural assessment of Arctic and sub-Arctic LNG carrier with different extreme ice load scenarios. First, iceberg (bergy bit) collision at midship and shoulder part in forward region are investigated assuming a normal or lower ice class LNG carrier. The shoulder part collision case, which is considered more critical, is analyzed with estimated absorbed energy from an actual damage record. Second, global strength in ramming operation of an ice breaking LNG carrier is investigated using a whole ship FE Model combined with global shear force. Finally, numerical simulations with special types of elements are carried out to take into account the ice crushing behavior.

The authors conclude that, the proposed methods are very useful for strength assessment of ship in Arctic and sub-Arctic region, and spherical type LNG carriers are suitable to the concerned regions.

1. Introduction

Gas field developments in Arctic and sub-Arctic regions, such as Norway and northern Russia, are gathering great interest as new exporters of LNG, which is currently being sourced primarily from South East Asia, Australia, and the Middle East, as well as around the Atlantic Basin. LNG carriers operating in such cold climate zones (image is shown on Fig.1) require special considerations for the hull strength for ice-navigation, as well as equipment and outfitting for low temperature ¹⁾.

Especially, ice impact load against such LNG carriers is a concern, and recently some papers have been presented ⁸⁾. However, most of the previous studies regarding iceberg collision did not take into account the effect of ice crushing. On the other hand, scientific research to obtain characteristics of ice crushing has been carried out recently ¹⁴⁾.

Following the previous studies, this paper proposes methods of structural analysis of LNG carriers against ice impact, especially methods to take into account the effects of energy absorbed by ice crushing.

First, an analysis for collision by a small iceberg at midship is carried out by a rigid ice block model and several problems are pointed out. Then, an analysis for collision at a shoulder part in forward part is carried out by an improved method, which is proposed based on the observations from the midship analysis.

Second, global strength in ramming operation of ice breaking LNG carrier is investigated using a whole ship FE model in order to investigate feasibility of the ice breaking LNG carrier.

Third, numerical analyses are carried out to simulate the ice crushing behavior during iceberg collision to ship structure.

Finally, usefulness of the proposed analysis methods is discussed for conclusions.

Fig. 1 Image of icebreaking LNG carrier

2. Ice Impact Load Scenarios and Previous Studies

Strength against ice load is defined in so-called ice-class rule and a ship navigating in ice region is designed with the rule corresponding to a proper classification, for example Finnish-Swedish ice class 1A or 1C ⁴⁾. This requirement is mainly for local structures, for example, structure around side shell against local load from an ice belt.

Recently, following the development of gas fields in northern region, selection of cargo containment systems is an issue. Several ice impact load scenarios have been picked up for comparison of tank systems ^{5,6,7,8)}. With reference to these studies, the following ice impact load scenarios are investigated in this paper.

a) Iceberg collision case

- 1) Midship collision scenario: Chapter 3
- 2) Shoulder part collision scenario: Chapter 4

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b) Global strength in ramming operation of ice breaking LNGC: Chapter 5

Fig. 2 Different ice collision scenarios

The scenarios are illustrated in Fig.2

The above a) is considered as the scenario for an LNG carrier trading between Barents Sea and the East Coast of US/Canada against an iceberg from Greenland. Such accidental load cases are discussed by Aldwinckle⁵⁾ and DNV⁶⁾. In this paper, based on the study by DNV, it is assumed that iceberg with height of 2m or more above sea level may be detected by radar. Consequently, iceberg with height above sea level up to 2m is assumed in the study here. This assumption gives about 7300 ton in case of cube shape as shown in Fig.3. An iceberg of such size is called a bergy bit.

Fig.3 Definition of bergy bit (small iceberg)

b) is a scenario for an ice breaking LNG carrier in Arctic region, which is more relevant for future projects. For ice breaking ships, global strength in ramming operation may be considered, and this may require special considerations for a large ice breaking LNG carrier.

During these studies, some problems are noted in modeling of ice. In the previous studies, the small iceberg (berg bit) is modeled as a rigid object. However, it is preferred that the ice crushing and the energy absorbed by ice can be simulated by numerical methods. This is still a difficult problem, but some attempts are made in the last chapter.

3. Bergy Bit Collision at Midship

3.1 Analysis Model for Midship Collision

First, we carry out an analysis with a cube shaped rigid object having 20m length, based on the assumption in Chapter 2. A 147,000m³ spherical tank type LNG carrier (LxBxD= 274m x 49m x 26.8m) designed for Finnish-Swedish Ice Class 1A is analyzed. The structural model used for analysis is shown in Fig.4. Analysis conditions are summarized as follows.

- A rigid iceberg (size 20m x 20m x 20m, mass 7300 ton) is assumed based on the study by DNV as mentioned.
- Collision speed of 2.0 m/s is assumed considering maneuvering speed of the vessel and drifting speed of the iceberg.
- LS-DYNA (non-linear, elastic-plastic explicit method) is applied. Three holds are modeled. Shell element is applied. Mesh size of FE model generally follows the reference⁹⁾.
- Material properties are shown in Fig.5. Rupture of the side shell is modeled as element failure with failure strain of 20%. The strain rate effect is taken into account by adopting the Cowper-Symonds model⁹⁾.
- Starboard side of ship is fixed in order to prevent ship motion. Sea water is not modeled.

The effect of ship motion (including effect of sea water) is not considered in this analysis because the displacement of the iceberg is sufficiently small, compared to the displacement of the ship.

Fig.4 FE model of ship structure and ice (rigid cube model)

Fig.5 Applied stress-strain relationship of material

3.2 Results of Analysis for Midship Collision

Fig.6 and Fig.7 show residual plastic strain distribution obtained by the analysis. The time history of contact force is shown in Fig.8. The maximum load is 571MN and duration of the load is 0.002 sec. The maximum residual deformation of hull structure is about 20mm.

Fig.6 Residual plastic strain distribution in outer shell

Fig.7 Residual strain and deformation of internal structure (deformation exaggerated)

Fig.8 Time history of contact force

3.3 Remarks from Midship Collision Analysis

As shown in Fig.6 and Fig.7, residual strain after collision is limited, and there is no residual strain in the cargo containment system including in the skirt (the cylinder to support the spherical tank). The energy flow in the analysis is shown as follows.

- Initial kinetic energy (7300ton mass with 2 m/s): 15MJ
- Total energy after collision: 15MJ
 - Energy absorbed by hull: 10MJ
 - Remaining kinetic energy of iceberg: 5MJ

There is no clear criterion for energy absorbed by hull structure of an LNG carrier. However, the absorbed energy in this chapter (about 10MJ) is considered moderate, compared to the criteria for offshore structure¹⁰⁾. This is because the initial kinetic energy (contact speed) in the midship collision case is low. Therefore, it is expected the forward collision case (head to head collision) is more critical and is investigated in the next chapter.

Another concern is modeling of the bergy bit as a rigid cube. This simplified modeling gives results somewhat different from actual phenomena, in view of maximum value and duration of the contact load as follows.

- Due to the assumption of large flat contact area, multiple (four) transverse webs work at the same time, and stiffness of hull is very large. This causes a very large reaction force with very short duration time.
- The above overestimate of hull stiffness causes about one third of remaining kinetic energy of the bergy bit after the collision. The energy absorbed by the hull structure may be underestimated from this viewpoint.
- On the other hand, if the ice crushing (bergy bit) is considered, the energy absorbed by the hull structure may be reduced, because some part of kinetic energy can be absorbed by the ice crushing.

From the above consideration, it is concluded that the consideration of the energy absorbed by an iceberg and shape of an iceberg is very important to improve the accuracy of analysis. Improved methods are proposed in the following chapters.

4. Bergy Bit Collision at Shoulder Part

4.1 Introduction

In this chapter, No.1 hold (shoulder part) of normal or lower ice class LNG carrier is investigated with dynamic analysis program LS-DYNA. As mentioned in the previous chapter, No.1 hold collision is a head to head collision case, and considered more critical in view of kinetic energy before collision.

Based on a feedback from the previous chapter, the following two improvements are applied to the analysis.

- A sphere is adopted as shape of a bergy bit in this chapter. This is better to create the local deformation of hull structure.
- Analysis condition is defined by kinetic energy obtained by a reverse analysis of damage information. In this approach, the effect of absorbed energy by the ice crushing can be taken into account without numerical modeling of ice crushing.

4.2 Definition of Analysis Condition

There is reference for ice collision damage at bow structure of a ship sailing near Alaska¹¹⁾. According to the reference, the ship speed was about 5 knots at the collision. A damage photograph is shown in the reference. This is useful information, and the following procedure is proposed for definition of analysis conditions.

[Step-1]

Reverse analysis simulating the actual damage photograph is carried out, to define energy absorbed by the hull structure.

[Step-2]

Then, a collision analysis of the LNG carrier in shoulder part (No.1 hold) is carried out, with an iceberg having mass and initial speed equivalent to the defined energy.

In the proposed procedure, it is not necessary to consider the energy absorbed by the ice crushing, because it is already included in the analysis condition defined by the damage record (condition of photograph).

As shown in Fig.9, analysis for Step-1 is carried out for FE Model of an oil tanker, with similar displacement to the damaged ship (about 100000 ton) in the reference¹¹⁾. A spherical iceberg shape with radius of 10 m, (mass 4000 ton) is selected, because it creates similar shape of the bow damage. The model of the bergy bit has a constant speed of 5 m/s (initially assumed value), while the ship is in a fixed position. Modeling procedure and material properties are in accordance with the procedure of the midship analysis.

Fig.10 shows the relationship between displacement and the energy absorbed by the bow structure. According to the reference, the bow deformation is about 2m. This corresponds to 37MJ. Fig.11 shows deformation of bow, with 2m of deformation. This deformation plot is quite similar to the photograph of the actual damage in the reference¹¹⁾.

From the above result, the energy absorbed by the bow structure is estimated to be 37MJ. This is equivalent to a kinetic

energy of 4000 ton iceberg with an initial speed of 4.3 m/s (8.4 knots). The speed is lower than the reported speed in the reference (about 10 knots). This is considered due to assumption of mass of the bergy bit. Since the kinetic energy is maintained, it is considered that the slight differences of the speed and mass do not create problem.

Relative angle of contact speed significantly influences the result. In this paper, the relative angle is assumed to be normal to ship's side shell for conservative assumption.

Finally, the assumed analysis conditions are summarized as follows.

- Bergy bit: mass 4000 ton, spherical shape, radius 10m
- Initial speed 4.3m/s (kinetic energy 37MJ)
- Relative collision angle: Normal to ship's side shell angle.

Fig. 9 Reverse analysis for simulation of damage record

Fig. 10 Relation between deformation and absorbed energy

Fig. 11 Deformation corresponding to damage photo

4.3 Collision Analysis of Shoulder Part (No.1 hold)

Collision analysis is carried out with the conditions defined in the previous section, as follows.

- A 165,000m³ spherical tank type LNG carrier without ice class is analyzed. FE model and analysis condition are shown in Fig.12.
- The ship is fixed at the rigid modeling parts in Fig.12. No.1 hold is modeled as an elastic-plastic model, and other parts are modeled as rigid, as shown in Fig.12.
- Location of collision is shown in Fig.13.

Deformation plot is shown in Fig.14. It should be noted that the location of the foundation deck (the lower edge of the skirt) is higher in the No.1 hold than other holds (midship), due to structural arrangement considering hull form. The results of analysis are summarized as follows.

- There is no residual deformation (residual strain) in the cargo containment system including the skirt (cylindrical support of cargo tank system)
- Residual deformation in outer shell is about 900mm.
- Residual deformation in inner hull (longitudinal bulkhead) is about 100mm.

In this analysis, the remaining kinetic energy of the bergy bit after the collision is 1.7MJ. This is much smaller than the case of the midship analysis. The reason for the difference is considered to be that the round shaped bergy bit can create more local deformation, and therefore the hull structure absorbs more energy. Because the round shaped bergy bit can produce deformation similar to the actual damage photograph, the energy balance in this chapter is considered closer to reality.

From the analysis in this chapter, we confirm that the independent spherical cargo containment system remains intact after collision with 4000 ton bergy bit in nearly head to head hitting condition, with relative speed of about 8 knots.

Fig. 12 Analysis condition for shoulder part collision

Fig. 13 Location of collision

Fig. 14 Result of bergy bit collision analysis for No.1 hold (Residual deformation at middle of No.1 hold)

5. Global Strength Analysis

5.1 Global Load in Ice Breaking Operation

Design of an ice breaking large LNG carrier is still limited to concept level, however, it could be pointed out that one of the additional items in structural design might be longitudinal strength during ice breaking operation. In this chapter, a global FE analysis is carried out, to know the level of stress caused by ice breaking operation as a feasibility study.

Global loads by DNV rule¹²⁾ for a 147,000m³ a spherical tank type LNG carrier with "Polar 20" classification (LxBxD= 274m x 49m x 26.8m, continuous tank cover type) are calculated as follows.

- Global shear force during ramming operation
(Reaction force by ice stacking):
Maximum shear force about 130 MN near bow --- (1)
- Global bending moment by beaching
(Only ship's bow is supported by ice without buoyancy):
Maximum moment about 9000 MN-m at midship -- (2)

5.2 Assessment and Consideration

Fig.15 shows the result of analysis by load case (1). It is confirmed that the stress is allowable level in all location. This is also confirmed by hand calculations. If we assume 1.5 m² of effective shear area of the concerned section, it gives 87 MPa (=130/1.5) of nominal shear stress.

The above (2) is similar to grounding load, a mechanism studied by Pedersen¹³⁾. If we assume 45m³ of section modulus, it gives 200 MPa (=9000/45) and this is considered the level of

nominal stress is manageable by proper design considerations.

Based on the above investigations, it is considered that an ice breaking large LNG carrier is feasible, with proper design considerations. Dynamic effects are not considered in the discussion here and non-linear dynamic analysis remains for further study. It may be considered that, against shocking load, a spherical independent tank type would be preferable, as the tank systems are welded to the main hull, however, such a characteristic shall be investigated by dynamic analysis. The continuous tank cover type LNG carrier has advantage of providing necessary reinforcement against the ice breaking global loads.

Fig. 15 Global strength analysis in ramming operation
(Deformation exaggerated)

6. Additional Study on Modeling of Ice Pressure

6.1 Comparison of Rigid Ice Modeling with Measurement

In chapter 3, rigid modeling of ice with flat surface causes a problem that the area of deformation cannot be correctly represented. This is due to lack of consideration of ice crushing.

In the field of scientific research, Ritch¹⁴⁾ carried out a full scale measurement for bergy bit collision using a ship called Terry Fox (length 75m, displacement 6800 ton) near Newfoundland. Collision loads with various shape and size of bergy bits were measured. As shown in Table 1, according the measurements, the maximum load is 5MN and the duration of load is between 0.2 and 0.5 sec.

Table 1 Typical Ice collision load by actual measurement¹⁴⁾

Max. pressure	11.3 MPa
Total Force	5 MN
Duration	0.24 sec
Loaded area	2.4 m ²
Mass	1900 ton
Collision speed	1.3 - 3.3 m/s

Table 2 Comparison of rigid ice analysis and measurement

	FEM (rigid ice)	Measurement ¹⁴⁾
Mass of ice	7300 ton	1900 ton
Maximum Contact Force	571 MN	5 MN
Duration	0.002 sec	0.2 - 0.5 sec

As compared in Table 2, there is large difference in the order of maximum force and duration, between the measurements and the analysis with rigid cube in Chapter 3.

Reasons for difference are considered as follows.

- In reality, the bergy bit is not rigid. Due to the effect of the ice crushing, the maximum load is reduced, and the

duration of load is increased.

- The actual bergy bit does not have a perfect flat surface, but an irregular shape. In the analysis in Chapter 3, the whole area of flat surface contacted the side shell at the same instance, and this assumption causes direct load transfer to multiple transverse frames, which causes large impact load in very short time. On the other hand, in reality, sharp part of the bergy bit first contact the local area of side shell between transverse frames. Local deformation of the side shell has a cushioning effect.

In the following sections, we propose improvement of modeling of ice load, considering the ice crushing. First, we propose a pressure based analysis. Second, two types of sophisticated finite elements are tested to represent the ice crushing.

6.2 Ice Load Modeling Based on Pressure Distribution

A structural analysis is carried out using pressure distribution from the results of the experiment by Terry Fox¹⁴⁾ shown in Table 2.

Based on the results of the experiment, the pressure distribution in time and space is defined as the envelope curve shown in Fig.16. (Exponential distribution for space and triangular distribution for time are applied for simplification.) The same FE model and analysis program (LS-DYNA) as used in Chapter 3 is applied.

Fig.16 Pressure distribution by bergy bit collision

Fig.17 shows distribution of deformation at the time of maximum response ($t=0.12\text{sec}$ in Fig.18) by the analysis. The

time of maximum response agrees with the time of maximum load.

The maximum out-of-plane deformation and residual strain in side shell and longitudinal stiffeners are shown in Fig.18 and Table 3. The residual plastic strain is 2.4% in side shell and 2.6% in transverse frame, which are much lower than the breaking level of 10%. There is little effect of residual deformation around the cargo tank system.

a) Outer shell

b) Side longitudinals and Transverse webs

Fig.17 Displacements and Von Mises stress contour
(t=0.12sec, displacement factor=5.0)

Fig.18 Time history of out-of plane displacement of outer shell and side longitudinal

Table 3 Results of pressure based analysis

Max. out-of-plane displacement (Outer shell)	123 mm
Max. out-of-plane displacement (Side longitudinal)	81 mm
Residual plastic strain (Outer shell)	2.4 %
Residual plastic strain (Side longitudinal)	2.6 %

In the analysis with rigid cube shown in Fig.4 in Chapter 3, the extent of deformation spreads over five transverse frame spaces. On the other hand, in this analysis, the deformed part is localized within one transverse space.

The following can be considered reasons for the differences.

- Kinetic energy of this analysis (Terry Fox experiment) is smaller than the analysis in Chapter 3.
- In this analysis, pressure distribution correctly takes into account the ice crushing and shape of bergy bit.

The pressure based approach in this section is considered a possible solution for modeling of ice impact load, but the method of adjustment of collision condition (adjustment of kinetic energy of collision) remains for further study. In case kinetic energy of collision is bigger, the effective area of the ice pressure may become wider.

6.3 Modeling of Ice Crushing by Special Elements

In this section, we apply the following two numerical methods, to simulate the ice crushing behavior during iceberg collision to ship structure.

- Lagrange element
- SPH (Smooth Particle Hydrodynamics Method)

These elements are available in LS-DYNA¹⁵⁾.

In both cases, the material properties shown in Table 4 are adopted, based on the paper by Carney¹⁶⁾. In the analyses, we also try to simulate the tendency of load distribution in space and time by the full scale measurement by Terry Fox¹⁴⁾.

Regarding shape of ice, cube shape is adopted, where a corner is set to hit the hull structure as shown in Fig.19. The modeling of steel structure is simplified as shown in the figure, considering that the main purpose of this analysis is to see contact load and ice crushing behavior, rather than the deformation or the energy absorbed by the hull structure.

The mass of ice block is set to 1900 ton based on the Terry Fox measurement. The contact speed is decided based on the full scale measurement, so the maximum speed is 3.3 m/s.

Table 4 Ice model parameters at -10 degree¹⁶⁾

Density	$8.79 \times 10^2 \text{ kg/m}^3$
Young's Modulus	$9.30 \times 10^3 \text{ MPa}$
Poisson's Ratio	0.33
Pressure Cutoff in Compression	3.00 MPa
Pressure Cutoff in Tension	0.226 MPa

6.3.1 Analysis with Lagrange elements

Lagrange element (MAT155) in the library of LS-DYNA program is applied to representation of crushing ice. The model is shown in Fig.19.

Fig.20 shows deformation of ice block around the time of maximum load. At the area of contact with the steel structure, the corner of the ice block is crushed and the contact area is increased, due to the effect of crushing. Fig.21 shows time history of the contact load. The maximum load is about 15MN, which is much lower than the analysis of rigid cube (571MN in Table 2) and closer to the order of the load measured by Terry Fox¹⁴⁾ (about 5MN).

As shown in Fig.21, the duration of the contact load by this analysis is about 1 second. This result has much better agreement

with Terry Fox measurement¹⁴⁾ (0.2-0.5 seconds) in comparison with rigid cube case (0.002 second in Fig.8).

However, the Lagrange element is difficult to apply to large deformation case due to existence of hourglass mode (zero energy mode), which is deformation without strain.

Fig.19 FE model of ice using Lagrange element

Fig.20 Deformation of ice (Lagrange element, t=0.4sec)

Fig.21 Time history of contact force (Lagrange element)

6.3.2 Analysis with SPH method

Smoothed Particle Hydrodynamics method^{17,18)} is one of the mesh-free analysis methods, in which a continuum is represented by a set of particles, and calculations of density and velocity are carried out particle-wise. This method is robust in case of very large deformation and therefore considered a suitable method to represent the issue concerned here.

Fig.22 shows deformation around the contact area using SPH elements. Same modeling as Fig.19 is applied. As shown in the figure, the ice block represented by SPH elements is crushed. The analysis represents well the break-down of the ice block corner. Fig.23 shows the time history of contact force. Maximum contact load is 3.5 MN, which is lower than that of Lagrange elements (15MN) and closer to the Terry Fox measurement¹⁴⁾ (5MN). On the other hand, the duration of the contact load is about 2 seconds. This is longer than the full scale measurement, similar to the analysis by Lagrange elements.

Fig.22 Deformation of ice (SPH element)

Fig.23 Time history of contact force (SPH element)

The modeling of the ice crushing needs further study. Application of the other methods, for example, Euler element¹⁹⁾ or Distinct Element Method²⁰⁾ may be solutions for improvement of numerical simulation of ice crushing behavior.

7. Conclusions

In this paper, the methods for assessment of structural integrity of Arctic or sub-Arctic LNG carriers with different extreme ice load scenarios are proposed and the following conclusions are drawn.

- From the result of the midship collision analysis with rigid model of a bergy bit (small iceberg), it is concluded that the ice crushing has significant effect on the result of the analysis, as well as selection of the shape of iceberg model. Consideration of the energy absorbed by the ice crushing is necessary.
- Reverse analysis to simulate photograph of actual damage by iceberg collision is confirmed as an effective method to take account of the energy absorbed by the ice crushing into the analysis condition.
- Instead of using rigid model of ice block, pressure based method or SPH method are possible methods for better representation of ice load.
- A global FE analysis in ice breaking operation is carried out as a feasibility study. A design with spherical independent type LNG carrier with continuous tank cover has advantage against this load scenario.

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