DEVELOPMENT OF ICE CLASS ARC4 208K MK III TYPE LNG CARRIER

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1. Introduction

As arctic energy resources are attracting public attention, arctic shipping market is also growing in large. Natural gas is one of the most important energy resources and it is expected a great increase in Liquefied Natural Gas (LNG) trade from Arctic area to the western countries by shipping. For this reason a 208K MK III^{TM} type LNG carrier with Russian Maritime Register of Shipping (RMRS) Ice class Arc4(old name is LU4) is developed by Samsung Heavy Industries Co. Ltd. (SHI).

LNG carriers for Arctic navigation must have not only sufficient strength of ship hulls for ice operation but also sufficient safety for environmental pollution prevention in expected accidental cases. In this paper, the basic hull structure of this vessel is developed initially based on the RMRS rule and the hull strength is examined by a direct assessment method which the authors propose.

2. Design conditions

This vessel is designed in order to transport the natural gas from Murmansk to the Gulf of Mexico through the Barents Sea. Therefore, ice region navigation as well as non-ice region navigation are considered. Among them, Arctic ice region is focused on this paper. The scenarios considered for design are summarized in Fig.1.

The safety of this vessel were verified for all the scenarios. However, mainly the following three scenarios are explained in this paper.

- design scenarios
- accidental scenarios
- fatigue scenario

1) Design scenarios

The design scenarios are extreme conditions that are expected generally and the vessel must be designed in a way that it doesn’t lose its structural safety and function under the design scenarios.

Three kinds of scenarios are considered tangent impact, tangent impact with hummock and finishing breaking. Among these scenarios, tangent impact is a normal scenario for ice navigation vessel and is the basis of RMRS rules. The others are special scenarios for large vessels. It needs a lot of experience with regard to ice region navigations to decide the ice conditions. These scenarios are explained in Fig.2.

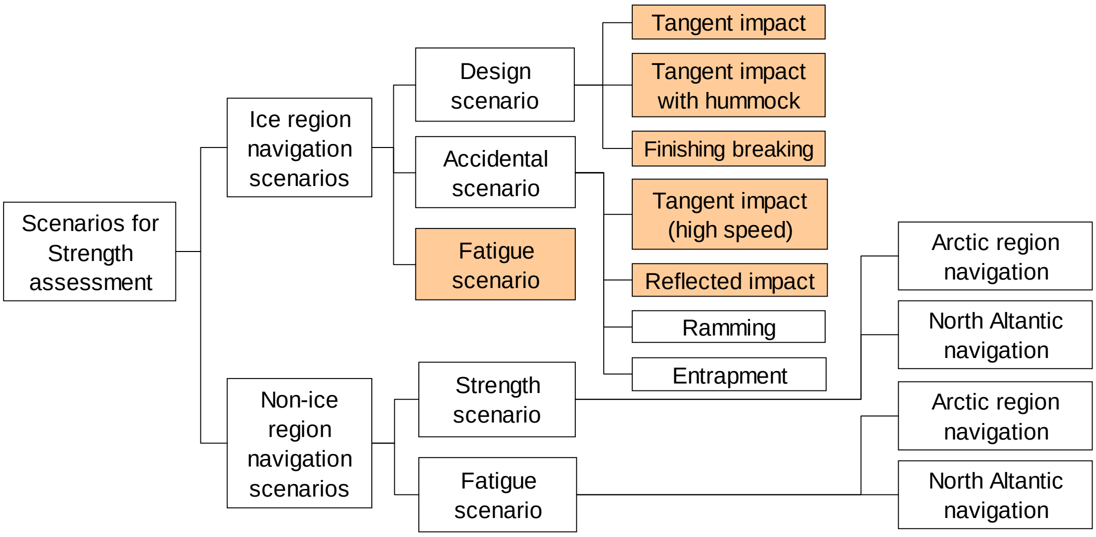
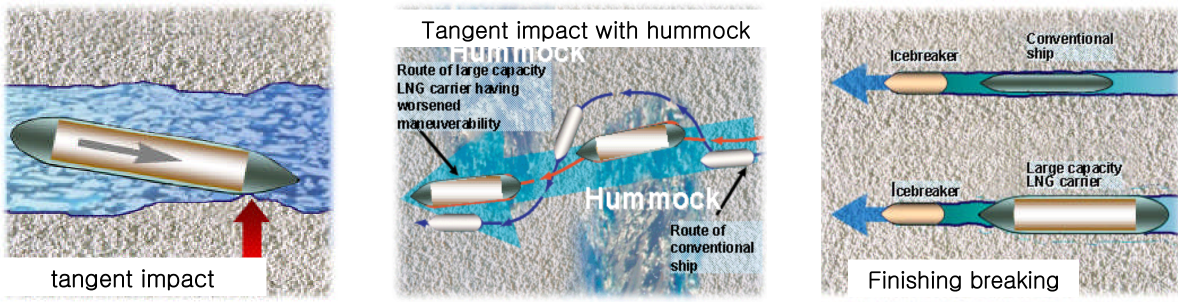


Fig.1 Summary of scenarios



(a) Tangent impact (b) Tangent impact with hummock (c) Finishing breaking

Fig.2 Design scenarios

2) Accidental scenarios

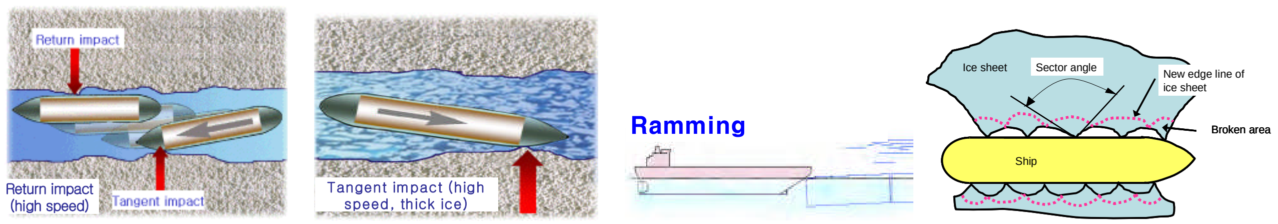
The accidental scenarios are unexpected situations and the vessel must be designed to survive even if a certain amount of damage happens. The RMRS rules don't require the verifications of structural safety under accidental scenarios. However, high reliability for the structural safety is required for LNG carriers. Especially, LNG leakage is a critical problem. Therefore, LNG carriers are required to be designed to prevent LNG leakage under accidental scenarios. The investigations for accidental scenarios are focused on the verification of the structural safety of the cargo containment system.

Four kinds of scenarios are considered. First is the tangent impact with high speed and thick ice. Second is the reflected impact. Third is ramming. Fourth is entrapment. As mentioned above, the accidental scenarios, especially ramming and entrapment, are over the RMRS requirement. Therefore, the speed, ice thickness and impact area are selected carefully based on the environmental conditions of navigation. These scenarios are explained in Fig.3.

3) Fatigue scenario

In case of ice-going merchant ship design, fatigue damage due to periodical ice loads is raised as an additional problem.

Bridges[1] measured ice loads using ice load monitoring system and estimated fatigue damage. However, researches are very limited and the classification societies haven't Rules or guidance. Therefore, this study is a pioneer study for this problem.



(a) Reflected impact (b) Tangent impact with higher velocity and thicker ice (c) Ramming (d) Entrapment

Fig.3 Accidental scenarios

3. Initial design

From the economic point of view, the cargo capacity is decided as 208,000m^3 and the MK III type cargo containment system is adopted. MK III type cargo containment system was developed by GTT and adopted to many LNG carriers by SHI. The safety of this system is well established.

This vessel's general arrangement and scheme of ice strengthening area are shown in Fig.4 and 5, respectively. Principal dimensions are as follows;

- Length O.A. : Approx. 315m
- Breadth (moulded) : 50.0m
- Depth (moulded) : 26.0m
- Designed draught (moulded) : 11.7m

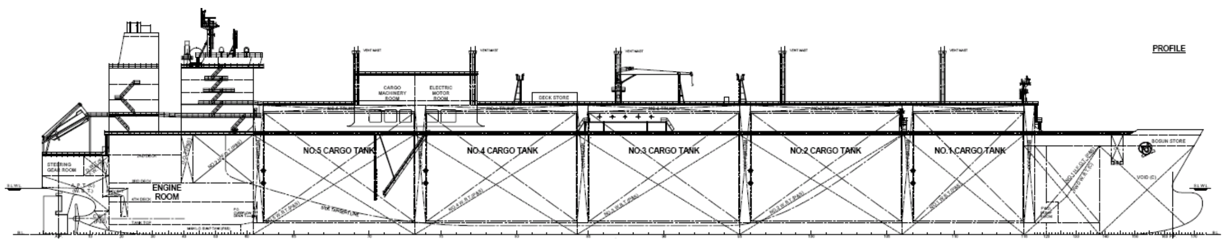


Fig.4 General arrangement

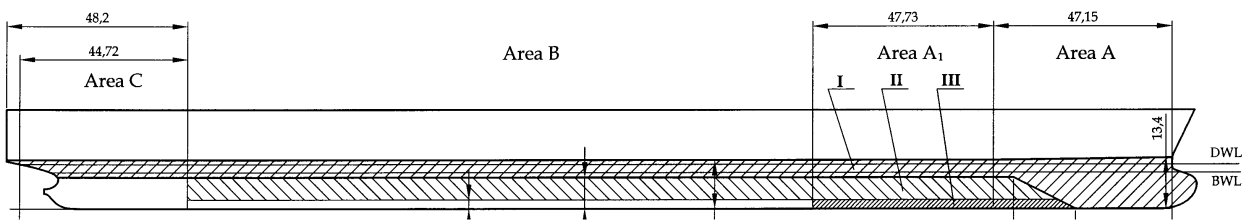


Fig.5 Scheme of ice strengthening areas

4. Direct strength evaluation for design scenarios

1) Ice load calculation for tangent impact scenario

When a ship (rigid body) intrudes into an ice floe, ice load is calculated by applying Kurdumov-Kheisin hydro-dynamic model (HDM)[2][3][4], which has been used in Russia for a long time. This method considers ice failure accompanied by forming a quasi-liquid intermediate layer and a corresponding viscous fluid. The intermediate layer between a rigid body and a crushed ice floe consists of crushed ice pieces and melted water. A differential equation describing intermediate layer is expressed as shown in Eqn. (1), which is a Reynolds equation for Newton viscous fluid.

$$\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}\right)h^3+3\left(\frac{\partial p}{\partial x}\cdot\frac{\partial h}{\partial x}+\frac{\partial p}{\partial y}\cdot\frac{\partial h}{\partial y}\right)h^2=-3\mu v \qquad (1)$$

where p = pressure of intermediate layer

h = thickness of intermediate layer

v = intruding normal velocity of a rigid body

μ = viscous coefficient

In the HDM, it is assumed that the pressure of intermediate layer(p) is proportional to the thickness of intermediate layer (h).

When the shape of ice floe is assumed as a circular plate with a radius R as shown in Fig.6, the contact area of the ship and ice floe becomes a part of ellipsoid. During the collision, the contact area increase gradually. Eqn. (1) can be solved exactly for this contact area by a numerical method or approximately by an analytical method employing some simplified assumptions.

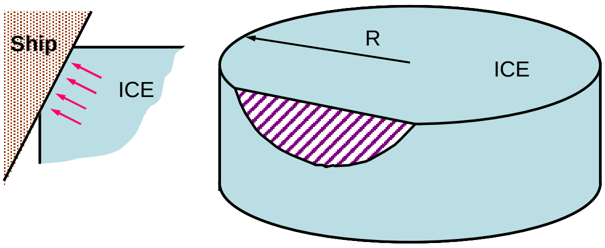


Fig.6 Contact area of ship and ice floe

2) Ice load calculation for tangent impact with hummock scenario

Hummock degree is introduced, which is defined by the sharing ratio of hummock ice to total iced area. The thickness of ice floe is increased depending on hummock degree. The increase ratio of ice thickness is given in Table 1 [4]. Ice load calculation for this scenario is the same as that of tangent impact scenario.

Table 1 Ice thickness correction due to hummock ice[4]

Share of hummock ice	40 to 70 %	70 to 100 %
Increase ratio of ice thickness	1.17	1.51

3) Ice load calculation for finishing breaking scenario

Two aspects are taken into account in this scenario. One is that the edges of channel have many cusps, thus ice failure happens easily. The other is that the number of occurrence of ice loads is much larger than that of usual operation, thus relatively large ice load may happen.

Due to lack of information and experiences of finishing breaking, it seems difficult to make a reasonable assumption at this moment. Therefore, it is assumed as a tentative hypothesis that the number of occurrence of ice loads due to finishing breaking operation increases one hundred times larger than that of usual ice operation. Investigating the existing ice load data [5][6][7][8], the resultant ice load increase coefficient due to finishing breaking is estimated as 1.7.

The breaking mode of ice floes due to finishing breaking can be considered mainly the bending failure by a concentrated vertical load at a cusp as shown in Fig.7. The bending failure load can be expressed generally as shown in Eqn. (2).

$$P_V = k_\sigma \sigma_u t^2 \qquad (2)$$

where P_v = bending failure load

σ_u = ice bending ultimate strength

t = ice thickness

k_σ = coefficient

The coefficient k_σ depends on the state of radial cracks around the cusp. In the case of free water channels discovered by an ice breaker, it is considered that there are many radial cracks in the vicinity of a cusp. Then, k_σ is set to be an average of two typical states, i.e. one is the state with no radial crack (k_σ = 0.52) [9] and the other is the state with many radial cracks (k_σ = 1.33) [10].

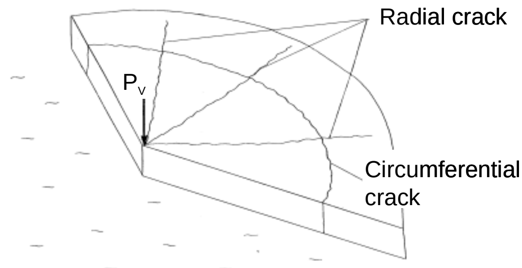


Fig.7 Ice plate failure under inclined side impact

4) Strength evaluation

It is neither practical nor economical through the experiences not to allow the occurrence of plastic strain when the strength evaluation is performed for ice going ships. Therefore, structural scantlings are based on the ultimate strength criteria and a certain plastic deformation is virtually admitted in RMRS rule. Standing on such situation, the ultimate strength criteria is also adopted here.

In this paper, ultimate strength of a structure is defined as the intersection of the two tangential lines in a load-deformation relationship, i.e. one is the initial tangential line of the load-deformation relationship and the other is the tangential line at the location of five times larger deformation than an initial plastic deformation point.

The non-linear FE analysis considering material and geometrical nonlinearity is carried out. The applied locations of ice load are selected with regard to the locations of main structural members as shown in Fig.8. The design loads calculated by direct calculation are shown in Table 2. The shape of ice load is assumed to be Fig.12.

Fig.9 is the results of the load-deformation curve of a structure at the area A, where the vertical axis represents the total load coefficient non-dimensioned by the design load, P_{Design}. It is found from the figure that the initial plastic deformation happens at around 60% level of the design load and that the residual deformation is 8mm. Though a certain extent of plastic deformation happens, the ultimate strength is higher than the design load, and it is judged that this structure is safe and acceptable.

Table 2 Summary of load parameters of design load scenarios

Ice Area	Pressure (MPa)	Distribution height, b (m)	Distribution length, l^H (m)
A-I	3.77	2.59	8.43
A_1-I	2.33	1.71	7.05
A_1-II	1.00	1.71	7.05
B-I	1.50	1.19	7.14
B-II	0.55	1.19	7.14

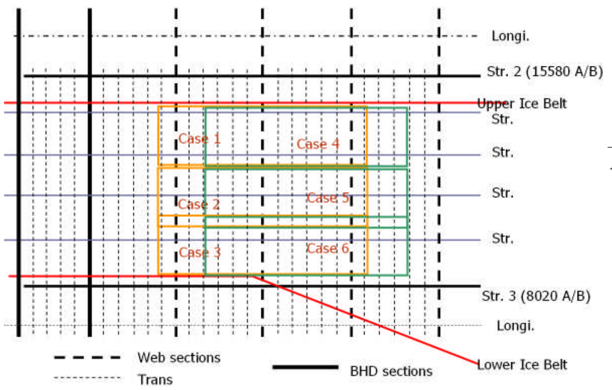


Fig.8 Locations of applied load

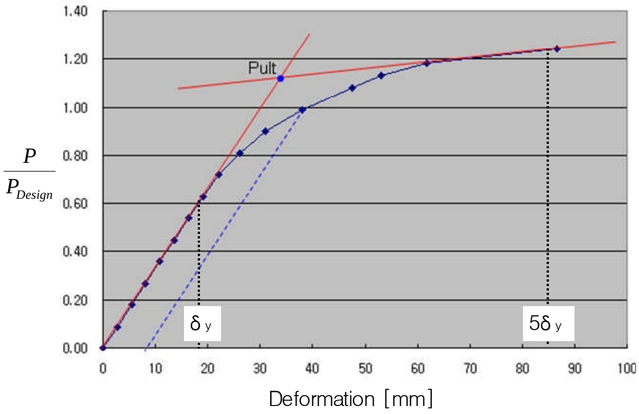


Fig.9 Calculated load-deformation curve

5. Direct strength evaluation for accidental scenarios

1) Ice loads in accidental tangent impact scenario and in reflected impact scenario

In tangent impact scenario with higher velocity and thicker ice, the initial impact velocity and the ice thickness are set to be 4.63m/sec (9 knots) and 3.5m, respectively. In reflected impact scenario, the location to be examined is the area from the stem to the middle of the ship. The initial impact velocity and the ice thickness are set to be 2.57m/sec (5 knots) and 1.75m, respectively.

The method to calculate the ice loads is the same as a tangent impact scenario.

The other accidental scenarios aren't explained in this paper since the effect to the safety is relatively small[11].

2) Strength evaluation

The same FE models for design scenarios and same methods are used for accidental scenarios. From the direct ice load calculations, accidental ice loads are obtained and they are summarized in Table 3. Since the area which corresponds to the cargo containment system is to be examined in the case of accidental scenarios, the design ice load is not specified for the area A.

The results of pressure-deflection curve for B area is shown in Fig.10. The maximum deflection of the FE model is 126mm.

The allowable criteria for accidental case should be defined based on the occurrence possibility of gas leak. From GTT's experience, even if 2.5m deflection of inner hull happens, the membrane containment system didn't loose its tightness. In case of No96™ cargo containment system, 70cm of inner hull deflection is used as allowable criteria for survival condition[13]. MK III cargo containment system is recognized to have much more deformation capacity of inner hull than No96 cargo containment system. Comparing above references, maximum deflection of 126mm is very small. Therefore, it is concluded that gas leak doesn't happen under the accidental scenarios.

Table 3 Accidental ice load parameters

Ice Area	Pressure (MPa)	Distribution height, b (m)	Distribution length, l^H (m)
A_1-I	3.10	2.60	6.09
B-I	2.60	1.75	10.22

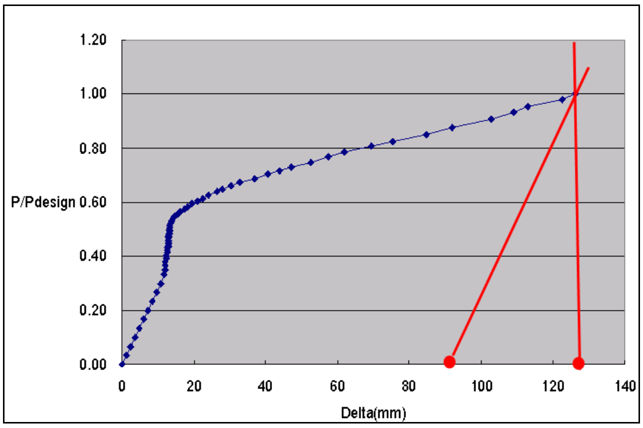


Fig.10 Result of pressure-deflection curve (B area)

6. Fatigue scenario

1) Estimation of load cycles

a) Operation mode

The operation mode of large commercial vessel is classified into three modes, independent operation, escorted operation by one icebreaker and escorted operation by two icebreakers. However, the last operation mode can be ignored practically since the probability of the operation is very small.

According to RMRS rule, the maximum operational ice thickness(h_m) for Arc4 is 0.7m. It was verified that the 208K LNG carrier can operate in 0.7m ice without escort of ice breaker from the test in an ice basin.

Independent operation is profitable for the ship owner and the impact force during independent operation is larger than that during escorted operation. Therefore, it can be assumed that this vessel only operates independently from the conservative judgment.

b) Operation conditions

During operation, many kinds of ice conditions like ice ridges, ice fields, ice cakes and brash ices will be met. In fatigue point of view, ice ridge can be ignored since the number of collision is relatively small. Also, the impact force due to the collisions against ice cakes and brash ices is relatively small and can be ignored practically. Consequently, large ices of which size are larger than 20m are considered for fatigue damage. In this condition, the ice load depends on the ice thickness. Therefore, we divided ice thickness into 3 levels as small, medium and high.

Another important thing to affect ice load is operation speed. The operation speed is assumed to Eqn. (3)

$$\upsilon_0(h) = \upsilon_{ow} - (\upsilon_{ow} - \upsilon_{\min})\frac{h}{h_m}, \quad (3)$$

where, υ_{min} = operation speed in the compact level ice of thickness h_m , 2.2knots

υ_{ow} = operation speed in the open water with the engine power when vessel operate with υ_{min} in the ice of thickness h_m.

h = given ice thickness

The operation conditions of this vessel are summarized as shown in Table 5.

c) Frequency of ice load

In level ice, ice failure due to bending happens as shown in Fig.11. If an ice failure happens, next ice impact will happen after a ship moves as much as l_c. Therefore, frequency of ice load can be expected as Eqn.(4).

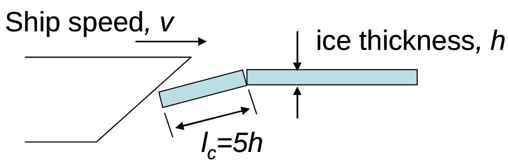


Fig.11 Shape of ice failure

$$f = \frac{v}{l_c} \quad (4)$$

where, f = ice load frequency, times/s

v = operation speed, m/s

l_c = length of ice-floe chopped off at operation in level ice, m

l_c is proportional to ice thickness. Here, the proportional coefficient is assumed to 5.0.

The modified frequency of ice load at a certain location is estimated considering ice load patterns as shown in Eqn.(5).

$$F = k_1 \cdot k_2 \cdot k_3 \cdot f \qquad (5)$$

where, F = modifed frequency of ice load at a certain location

k_1 = probability where the peak of impact load happens on the concerned location

k_2 = effect of the impact load of which peak happens near the concerned location

k_3 = probability of draft

f = ice load frequency

Generally, the pattern of ice impact load is considered as Fig.12. The length of the peak is 10% of total ice load length. Therefore, the probability where the peak of ice load happens on the concerned location can be considered to be 0.1 (k_1 = 0.1).

Also, if the peak of ice load happens near the concerned location, some level of stress happens at the concerned location. It means that the cases where the peak of ice load happens near the concerned location should be considered. But it is very difficult to consider this effect accurately. Instead of this, the number of ice load is increased by 10% (k_2 = 1.1).

The location of the peak of ice load changes due to the vessel's draft. Since loaded condition and ballast condition are considered generally, the coefficient of 0.5 is considered (k_3 = 0.5).

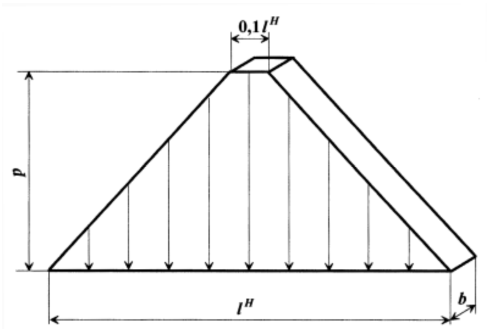


Fig.12 Ice load pattern for direct grillage strength calculations

d) Operation time

The operation time can be expressed as Eqn.(6).

$$T_p = k_A(1-k_{ow})(1-k_{2IB})k_T k_h T \qquad (6)$$

where, k_A = ratio of operation time in Arctic

k_{ow} = ratio of operation time in non-ice region in Arctic

k_{2IB} = ratio of operation time escorted by two ice breakers

k_T = ratio of operation time in compact ice (effective operation time in ice)

k_h = ratio of ice thickness for the operation condition

T = total life te of the ship = 24 years = 7.569×10^8 seconds

Based on the operation experiences of Russian icebreakers and the information of AARI(Arctic and Antarctic Research Institute), $k_A(1-k_{ow})(1-k_{2IB})$ is assumed to be 0.148.

The ratios of operation time in compact ice (k_T) are decided based on the experience as shown in Table 4.

According to the data of [14], during interaction with small floes, ice breaking mode is only 10 percents of the operation time and in the rest time, ship moves the ice fragments apart. Hence, the effective operation in small floes is thought to be 10%.

Table 4 Category of ice size and the probability of collision

Ice category	Size of ice	Operation time	Effective operation time (k_T)
Ice field	Larger than 500m	0.3	0.3
Ice field fragment	100~500m		
Small floe	20~100m	0.4	0.04
Ice cake	2~20m	0.1	0.0
Small ice cake and brash ice	Less than 2m	0.2	0.0

To define coefficient k_h, a special analysis was carried out based on the comparison of mean ice thicknesses data in the Russian Arctic seas with service restrictions of RMRS Rules. From the analysis, this effect is decided as follows;

- high thickness range = 0.1
- medium thickness range = 0.5
- small thickness range = 0.4

Considering all coefficients of Eqn. (6), operation time for each operation conditions are calculated and summarized in Table 6. The ratios of each operation time are shown graphically in Fig.13.

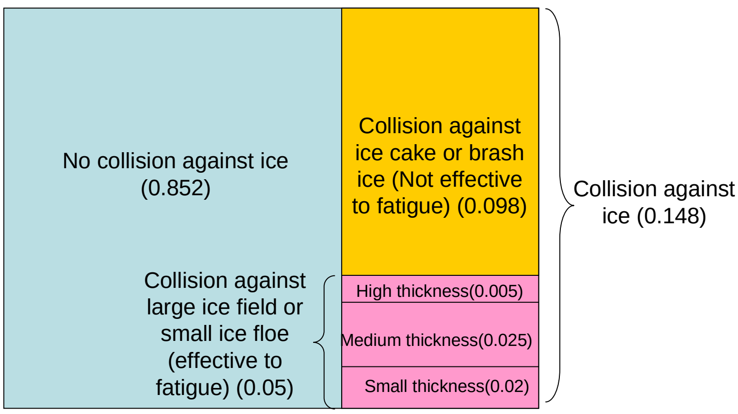


Fig.13 Ratios of operation time categorized by ice collision

e) Number of ice loads

The number of ice loads at the concerned location is the product of effective operation time in ice and frequency of ice load. By combining Eqn. (4), (5) and (6), this can be expressed as Eqn. (7).

$$n = k_1 \cdot k_2 \cdot k_3 \cdot f \cdot T_p = k_1 \cdot k_2 \cdot k_3 \cdot T_p \cdot v / (k_{lh} \cdot h) = 0.011 \cdot T_p \cdot v / h \qquad (7)$$

The numbers of ice loads at the concerned location of the 208K Arc4 LNG carrier are estimated as shown in Table 5.

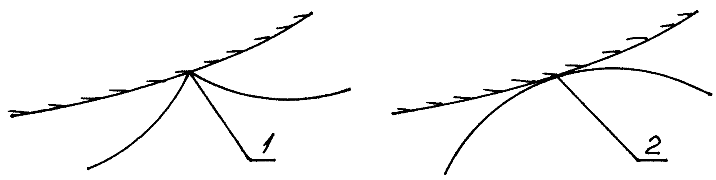
Table 5 Number of Ice load for each operation conditions for 208K Arc4 LNGC

Operation condition	Ice thickness(m)	Ship speed(m/s)	Ratio of ice thickness(k_h)	Operation time (sec)	Modified ice load frequency (F)	Number of ice load
Small	0.117	6.19	0.4	1.52×10^7	0.58	8.55×10^6
Medium	0.35	4.17	0.5	1.90×10^7	0.13	2.49×10^6
high	0.583	2.14	0.1	3.81×10^6	0.040	1.54×10^5

2) The estimation of fatigue loads

The design ice load of RMRS rule is formulated under conservative conditions. One of them is the shape of ice edge. In RMRS rule, the edge shape is assumed to be rounded as shown in Fig.14(b). However, the most of the edge shapes are angular as shown in Fig.14(a). In angular edge shape, ice can be failed easily compared with rounded edge shape and the ice load is small.

In order to estimate the ice load for fatigue evaluation, $k_c(v)$ is introduced as shown in Eqn.(8). $k_c(v)$ is the ratio of the design ice load(q_{DES}) and the actual ice load($q_{BDSC}(v)$). The actual ice load is the ice load under the Base Dangerous Service Condition(BDSC) defined in RMRS rule.



(a) angular edge shape (real situation) (b) rounded edge shape (for RMRS load)

Fig.14 Ice edge shape

$$k_c(v) = \frac{q_{BDSC}(v)}{q_{DES}} \tag{8}$$

Introducing the fatigue ice load, $q_{fatigue}$, into Eqn.(8), Eqn.(9) is autimatically drived.

$$\frac{q_{fatigue}}{q_{DES}} = k_c(v) \cdot \left(\frac{q_{fatigue}}{q_{BDSC}(v)} \right) \tag{9}$$

From the experimental data and experiences, the followings are assumed.

- ice pressure, p is proportional to ice load height, b and ice load length, l^H is proportional to $\sqrt{b}$
- ultimate ice flexural strength for the ice thickness, σ_b is proportional to (ice thickness, h)$^{0.8}$

Under these assumptions and Eqn.(2), Eqn.(10) is derived.

$$\frac{q_{fatigue}}{q_{DES}} = k_c(v)\cdot\left(\frac{h}{h_{BDSC}(v)}\right)^{2.24}\left(\frac{k_{\sigma,fatigue}}{k_{\sigma,BDSC}}\right)^{0.8} = 0.859\cdot k_c(v)\cdot\left(\frac{h}{h_{BDSC}}\right)^{2.24} \quad (10)$$

where, $h_{BDSC}(v)$ = ice thickness at the ship speed v

$k_{\sigma,BDSC}$ = 1.33 for BDSC conditions

$k_{\sigma,fatigue}$ = 1.1 for fatigue conditions

From Eqn.(10), ice load parameters for fatigue evaluation are estimated as shown in Table 6.

Table 6 Summary of ice load for fatigue evaluation for AI area

Operation condition	h (m)	v (m/sec)	$h_{BDSC}(v)$ (m)	$k_c(v)$	$q_{fatigue}$ (MN/m)	p(MN/m^2)	b (m)	l^H (m)
small	0.117	6.19	0.8	0.189	0.021	0.17	0.12	1.31
medium	0.35	4.17	0.88	0.203	0.216	0.54	0.37	2.33
high	0.583	2.14	1.42	0.416	0.475	0.80	0.55	2.84

3) intermediate ice load

Ice loads may be divided into three categories based on number of occurrences. Low-intensity load case with high cycles is introduced in the previous sections, while high-intensity load case is not relevant to fatigue strength. Then, intermediate loads are considered here.

- High-intensity loads (n = 1 ~ 10)
- Intermediate loads (n = 10^2 ~ 10^5)
- Low-intensity loads (n = 10^6 ~ 10^7)

The experiment data of [14] and [15] are used to estimate intermediate ice loads. An empirical relationship between the ice load and the number of occurrence is emplyed here as shown in Eqn.(11). Using the ice loads and number of cycles in Table 5, K is estimated to be 0.1893.

$$q(n) = q_{DES}\cdot(0.5 - K\cdot\sqrt{\ln(n)}) \quad (11)$$

where, K = experience coefficient = 0.1893

4) Evaluation of fatigue damage

A FE model is developed as shown in Fig.15. In order to find out the most critical locations, six kinds of load cases are considered as shown in Fig.8. From the results, the most critical locations are selected and the principal stresses are evaluated.

The results of the fatigue damage evaluation using ABS E curve is summarized in Table 7, where both of low-intensity load and intermediate load are taken into account. The fatigue damage is found to be negligibly small. Therefore, the fatigue damages due to ice loads will not happen in the 208K Arc4 LNG carrier under discussion.

Table 7 Fatigue life estimation for AI area

Operation condition	*q* (MN/m)	*p* (MN/m^2)	*b* (m)	l^H (m)	n (cycle)	Stress range (MPa)	Fatigue damage
small	0.021	0.17	0.12	1.31	$8.55x10^6$	0.6	$2.94x10^{-10}$
medium	0.216	0.54	0.37	2.33	$2.49x10^6$	11.3	$1.96x10^{-4}$
high	0.475	0.80	0.55	2.84	$1.54x10^5$	30.8	$1.82x10^{-3}$
intermediate	1.55	1.50	1.03	3.90	$1x10^3$	149.9	$3.24x10^{-3}$

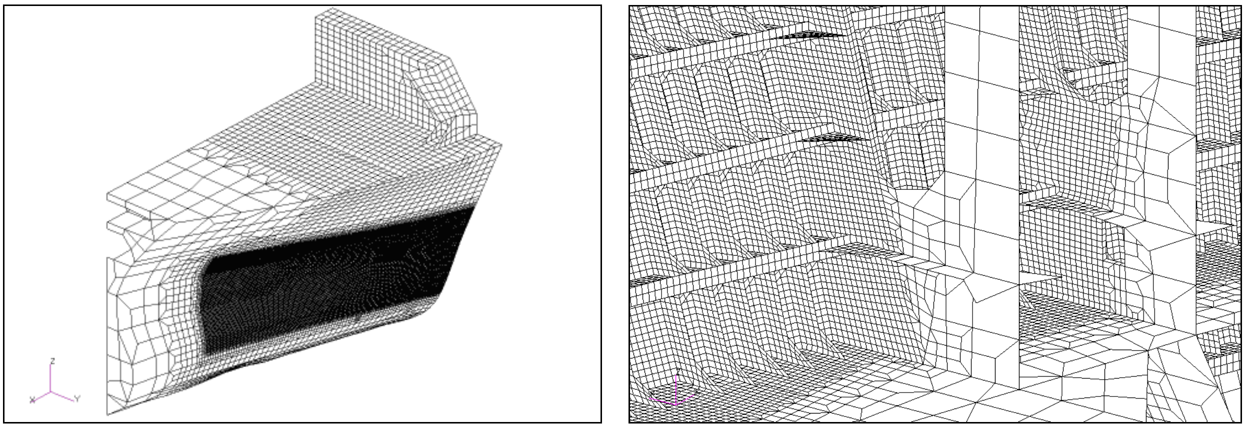


Fig.15 FE model for fatigue evaluation (AI area)

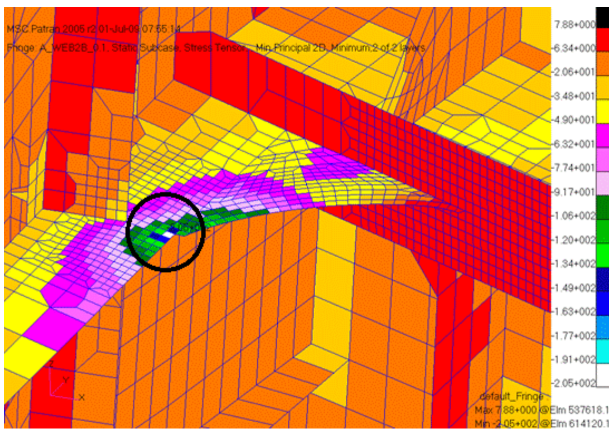


Fig.16 Principal stresses at hot spot

7. Conclusions

The structural strength of 208K Arctic LNG carrier including cargo containment system is investigated. The following scenarios are considered in this study.

- design ice load scenarios
- accidental ice load scenarios
- fatigue due to ice loads scenario

Through the whole investigation, it is focued that the developed vessel - 208K MK III^{TM} type LNG carrier with RMRS Ice class Arc4 - has enough strength and safety for operation in Arctic area. The strength assessment method, the ice load calculation method and the calculated results are authorized by RMRS.

As far as the authors know, direct assessments of hull strength of ice-going large merchant ships have not been carried out yet. Several hypotheses are inevitably introduced to perform the direct assessment, which are to be modified by more reasonable ones through new information and expected experiences in the future.

References

[1] Robert Bridges, Kaj Riska, Sheonming Zhang, Preliminary results of investigation on the fatigue of ship hull structures when navigation in ice, ICETECH 2006

[2] Kurdumov V.A., Kheisin D.E., Hydrodynamic Model of Solid Body Impact against the Ice, Applied Mechanics. V. XII. Issue 10, 1976

[3] Kurdumov V.A., Triaskin V.N., Kheisin D.E., Ice Load Definition and Hull Ice Strength Evaluation for Transport Ships. Proceedings of Leningrad Shipbuilding Institute, Collection Ice Passability and ice strength of Ships, pp.3-12, 1979

[4] Popov Yu.N., Fadeev O.N., Triaskin D.Ya, Yakovlev A.A., Strength of Ships Operating in the Ice., Sudostroenie, 1983

[5] Arctic and Antarctic Research Institute, Ice Certificate of a Ship of M.S. Norilsk Type, L., 1984 (in Russian)

[6] Kujala P., On the Statistics of Ice Loads on Ship Hull in Baltic, Me 116, Acta Polytechnica Scandinavica, Mechanical Engineering Series N 116, Helsinki, 1994

[7] Vershinin C.A., Ice Field Breach and Carrying Capacity under Short-term Static and Quasi-static Loads, Materials of conferences on Hydraulic engineering, L., “Enegry” , 1979

[8] Appolonov E.M., Nesterov A.B., Timofeyev O.Y., The Way of Regulation of Allowable Ice Conditions for Operation in Ice within the Framework of the Requirement to the Arctic Class of Arctic Ship, Proceeding the 13th International Conference. «POAC'95». Vol.1. Murmansk, Russia, 1995

[9] Kashtelian, V.I., Approximated Deformation of Forces Breaking Ice Cover, Problems of the Arctic and Antarctic, Issue. 5, Ll, 1960

[10] Kheisin, D.E., Ice cover strength under loading applied to its edge, Transactions of AARI, V.237, L., 1960

[11] Suh, Y.S. et al., Development of MK III Type Large Arctic LNG Carrier, The Society of Naval Architects of Korea, SOTECH Vol.11, No.3, pp.24-38, 2007

[12] Han, S.K. et al, Structural risk analysis of a NO.96 membrane type LNG carrier in the Baltic ice operation, Proc. of PRADS, 2007

[13] Goldstein R.V., Osipenko N.M. Fracture Mechanics and Some Issues of Ice Failure/ Ice Mechanics and Physics, M., Nauka, 1983, pp.65-94.

[14] Appolonov,E.M. and Nesterov, A.B., The investigation of Ice Damage and Increase of the Requirements to Ice Strength of Arctic Ships, Proc. of the 13th International Conference «POAC’95», Vol.1. Murmansk, Russia, 1995

[15] Kujala, P., On the Statistics of Ice Loads on Ship Hull in Bltic, Me 116, Acta Polytechnica Scandinavica, Mechanical Engineering Series N 116, Helsinki, 1994