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The Icebreaking Performance of SHIRASE in the Maiden Antarctic Voyage

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ABSTRACT

The Japanese Antarctic research icebreaker makes a voyage in Antarctic severe ice condition every year for the transportation of cargoes and scientists to Japan's Antarctic basin and for the Antarctic expedition. The new icebreaker *Shirase* took her maiden voyage to the Antarctic from November 2009 to April 2010. She had encountered with extremely severe ice conditions including 4 m or even thicker ice and broke through such an ice field by her expected icebreaking capability with some technologies such as a water flushing system. The *Shirase*'s icebreaking performance, the influence of snow on ramming performance, the effect of water flushing, the ice pressure and so on were investigated for the Antarctic navigation hereafter.

KEY WORDS: Icebreaker; Antarctic; ramming; snow-covered ice; water flushing; ice pressure.

INTRODUCTION

Japanese new icebreaker *Shirase* was completed in May 2009, and took her maiden voyage to support the 51st Japanese Antarctic Research Expedition (JARE51) from November 2009 to April 2010.

Syowa station, Japan's stronghold for the Antarctic expedition, is located on the East Ongul island (69°00'S, 39°35'E) in Lutzow-Holm Bay well-known for its very severe ice condition. It is not rare case that the ice thickness of fast ice is over 3 m and it is covered with snow of 1 m thick or more in Lutzow-Holm Bay. An icebreaker should break through that ice field by many times of ramming. Through the voyage experiences of the former icebreakers in Lutzow-Holm Bay, the importance of ramming performance to keep the voyage schedule had been recognized. Several effective technologies were introduced into the *Shirase* to improve the icebreaking capability.

In her maiden voyage, the *Shirase* encountered with one of most severe ice conditions in the Japanese icebreakers' Antarctic voyages for the last fifty years. The ice thickness of multi-year ice was more than 4 m and it was covered with compacted snow of 1 m thick or more. She broke through the severe ice field by ramming operation, making good use of some technologies such as the water flushing system for improvement of icebreaking capability.

The ship speed, motion, shaft power, steering, shoulder frame stress and so on were recorded by the some permanent measuring equipment through the icebreaking navigation. We verified the icebreaking performance of the *Shirase* from those data. As some of them, the snow influence on ramming performance was investigated and the effects of the water flushing system during ramming were confirmed. Moreover, the ice pressures acting on the shoulder part during ramming were estimated from the measured stress values and the stress-pressure relation calculated by FEM. The relations among approach speed, ice and snow thickness, penetration distance and ice pressure were obtained from those investigations. We would show the appropriate approach speed from the viewpoints of ramming performance and safety.

MAIN PARTICULARS OF *SHIRASE*

Main particulars of the *Shirase* are shown in Table 1. The icebreaker was designed to a continuous icebreaking capability of 1.5 m thick ice at 3 knots and 22 MW. To reduce snow resistance, water flushing

Fig.1 Ramming operation with water flushing

system of 260 m^3/min is equipped at the bow part as shown in Fig.1. It was estimated that the water flushing system extended the penetration at ramming by 10% or more in the deep snow-covered ice, by the model tests at the design development stage (Yamauchi, Mizuno and Tsukuda, 2009). Newly-developed high-anticorrosive stainless cladding steel is applied to the ice belt, and keeps low friction surfaces for long time. The propulsion system is composed of four main generator engines, four electric motors with PWM (Pulse Width Modulation) controlled inverter and two fixed pitch propellers.

Table 1 Main particulars of the new icebreaker *Shirase* (Tsukuda, Yamauchi and Kishi, 2007)

Ship name	*Shirase* *
Delivery	May 2009
Length over all	138.0 m
Length of water line	126.0 m
Maximum breadth	28.0 m
Depth	15.9 m
Design draft	9.2 m
Maximum displacement	abt. 20,000 t
Continuous icebreaking capability	1.5 m level ice at 3 knots
Maximum speed	19.5 knots
Propulsion system	Diesel-Electric (PWM inverter)
Propulsion power	abt. 22 MW
Number of propellers	2
Number of rudders	2
Officers and crews	175 p
Scientists, etc.	80 p
Cargo capacity	1,100 t
Helicopter	CH101 x 2 A355 class x 1

*) same name as the previous icebreaker for JARE

SHIRASE ROUTE AND ICE CONDITION IN LITZOW-HOLM BAY

The *Shirase* made a voyage in the fast ice of Lutzow-Holm Bay for 27 days in the term from December 28 until February 14 and anchored near the Syowa station for 24 days from January 10 to February 3. Supplies and fuel totaling 1,100 tons in weight were carried to the station and about 80 scientists and observers landed from the *Shirase*. She sailed about 100 n.m. in the fast ice including 56 n.m. in multi-year ice. The ship track to Syowa station from the fast ice edge and the main icebreaking modes are shown in Fig.2 on SAR image.

Hummock field

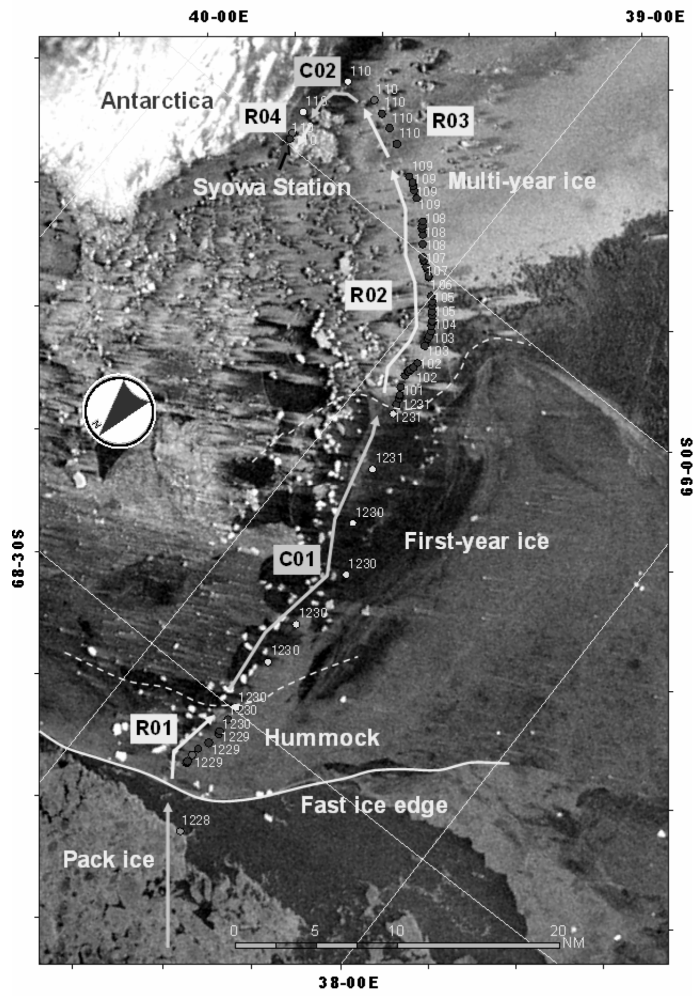
Hummock covered the field of about 6 n.m. from fast ice edge in the way to the Syowa station. The depth of hummock was 2 to 4 m and the snow depth was 0.5 to 2 m. The Shirase broke through the hummock field mainly by ramming operation and the average speed was about 0.2 knot.

First-year ice field

For about 22 n.m. after breaking through the hummock field in the way to the Syowa, the *Shirase* navigated in the first-year level ice which was 1 to 2 m thick and covered with snow of 0.5 m thick or less. In the way from Syowa station, it was about 15 n.m. She sailed those first-year level ice by continuous icebreaking at speed of 2 to 8 knots.

Multi-year ice field

There were severe multi-year ice fields near the Syowa station, where sail distance was 28 n.m. in both ways. On some points along the ship route in the multi-year ice fields, the ice thickness was measured by drilling. Also ice cores were sampled for measuring the salinities and the temperatures. By those measurement and visual observation, it was found ice thickness was about 5 m with 1 to 2 m thick compacted snow. The average flexural strength was assumed to be 0.8 MPa from brine volume of ice core sample by use of empirical formula. Brine volume was estimated from salinities and temperatures of ice (Frankenstein and Garner, 1967). The *Shirase* broke through the multi-year ice fields in the back and forth way by ramming over 3,120 times. It was hard even for this new icebreaker to get a long penetration distance at ramming in those severe conditions.



SAR image on Nov. 27th by *Ice Nav*

Fig.2 Ship track to Syowa station in the fast ice of Lutzow-Holm Bay (CXX; continuous icebreaking, RXX; ramming mainly)

MEASUREMENT SYSTEM ON ICE NAVIGATION

In order to verify the icebreaking performance, the *Shirase* was equipped with some permanent instrumentation units as shown in Fig.3. Ship speed, motion, shaft power, thrust, steering, frame stress at the shoulder part, etc. were recorded at 0.01 second interval continuously through the icebreaking navigation. The resolutions were 0.01 second for frame stress and acceleration, 0.1 second for gyro meter and steering angle, 1 second for power meter and GPS. Although ice thickness had planned to be measured by an electro-magnetic induction device, it went out of order under blizzard early in the fast ice and ice thickness was observed mainly by a visual observation after that.

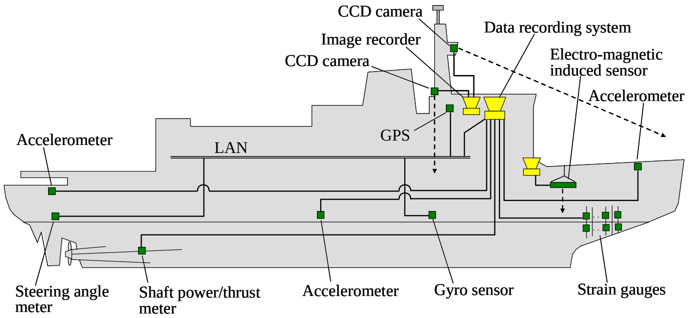


Fig.3 Instrumentation unit on navigation provided for *Shirase*

ICEBREAKING PERFORMANCE

Continuous Icebreaking Capability

Required shaft power with ship speed and ice thickness

The *Shirase* sailed by continuous icebreaking with water flushing in almost all of the level first-year ice. The continuous icebreaking capability was evaluated from the ship measurements and the ice observation. The flexural strength of first-year ice was estimated to be about 0.5 MPa from analysis of core sample although the core was picked at only one place near the Syowa station.

The relation between ship speed and total shaft power, measured by shaft power meter, is shown in Fig.4. Equivalent ice thickness *hie* is defined as Eq.1 and assorted into two groups in the figure. Fig.5 shows the relation between the shaft power and the equivalent ice thickness.

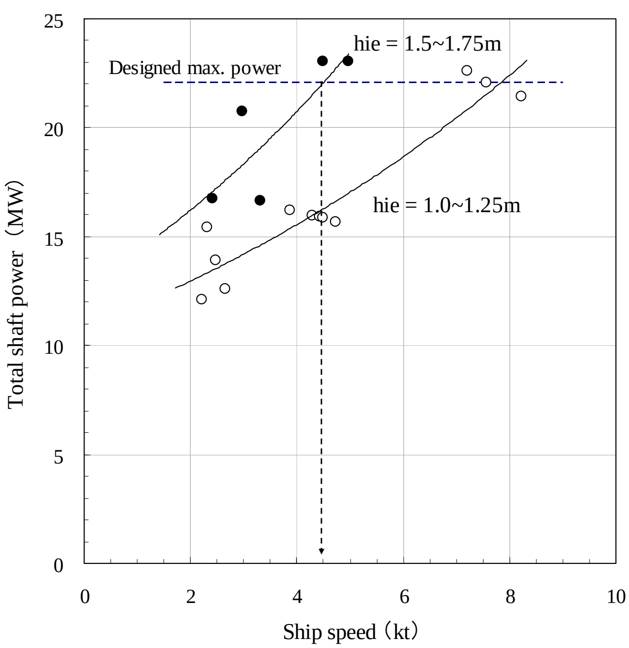


Fig.4 Shaft power versus ship speed at continuous ice breaking

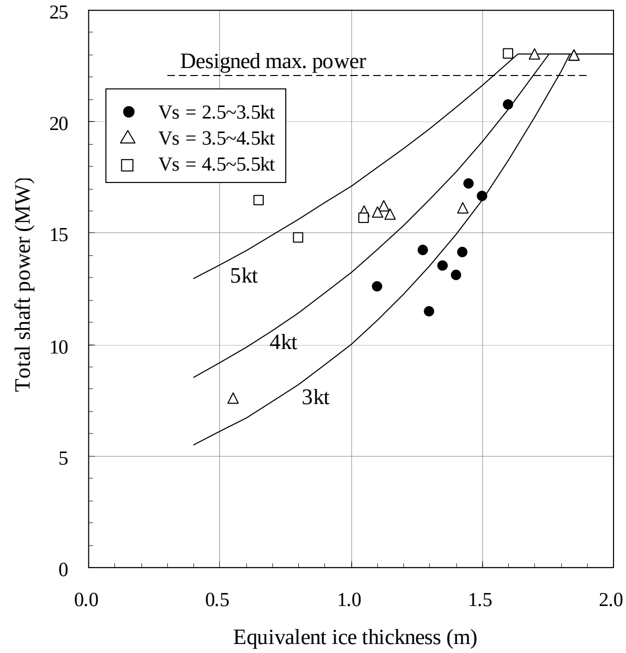


Fig.5 Shaft power versus equivalent ice thickness for various ranges of ship speed

$$hie = hi + 0.5 \cdot hs \qquad (1)$$

hi; ice thickness, *hs*; snow depth

The *Shirase* broke the level first-year ice continuously if the equivalent ice thickness was less than 1.8 m. She was capable of sailing at 4.5 knots by the maximum shaft power when the ice thickness was 1.5 m, corresponding to 1.5 to 1.75 m in equivalent ice thickness. If the ice thickness was less than 1 m, she sailed at speed of 8 knots and over. So, it fulfilled the designed performance on continuous icebreaking, which was 3 knots sailing in 1.5 m level ice at 22 MW shaft power.

Icebreaking resistance

Icebreaking resistance was estimated from Eq.2, where the propeller thrust was measured by shaft thrust meter and the thrust deduction coefficient in ice-covered water was obtained from model test results. The model test had been conducted at the ice model basin of Technical Research Center of Universal Shipbuilding Corporation.

$$Ri = (1 - t_{ice}) \times T_p \qquad (2)$$

Ri; icebreaking resistance, T_p; total propeller thrust,
t_{ice}; thrust deduction coefficient in ice

Fig.6 shows the relation between icebreaking resistance and ship speed for two ranges of equivalent ice thickness. Also model test results are plotted in this figure for comparison. The model tests were carried out in the level ice, flexural strength of which was corresponding to 0.5 MPa in full scale. The resistance against 1.5 m thick ice is 2,150 kN at 4 knots and it agrees with the model test result well. The thrust deduction coefficient is 0.04 to 0.05 at that condition.

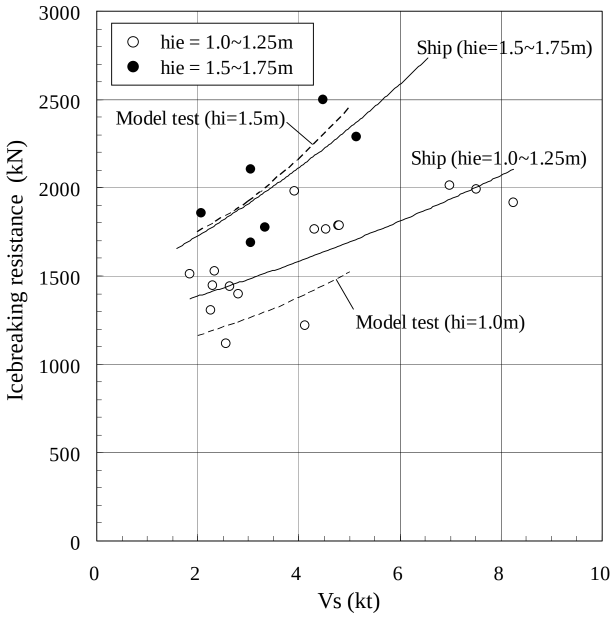


Fig.6 Icebreaking resistance at continuous icebreaking

Ramming Performance

Influence of snow on ramming performance

Multi-year ice and hummock fields were covered with great amount of snow more than 1 m in thickness. In those ice fields, the *Shirase* repeated many times of ramming, the initial contact speed of that was adjusted 4 to 12 knots with her approach distance. The penetration distance was shortened remarkably corresponding to the snow depth. Fig.7 shows the influence of snow on the penetration distance at ramming against the multi-year ice field. Those results are obtained on the initial contact speeds V_0 from 9 to 12 knots. Moreover, the water flushing system was used in those navigations.

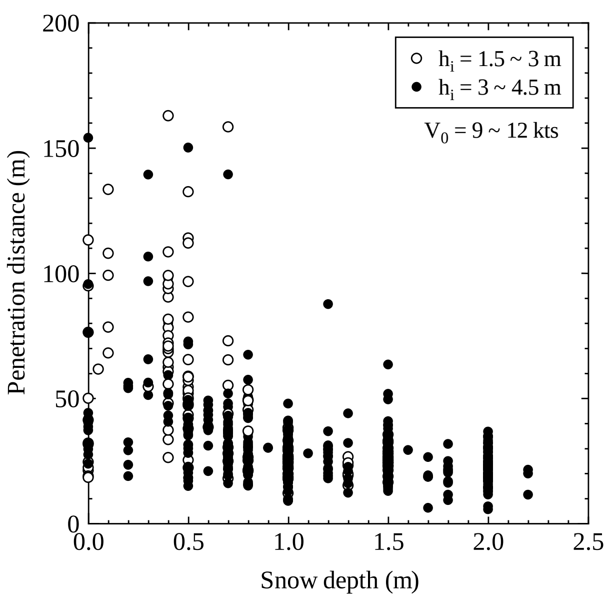


Fig.7 Snow influence on penetration distance at ramming against multi-year ice

The penetration distance often exceeded 100 m when snow depth was less than 0.5 m even if ice thickness was 3 m and more. On the other hand, it was hard to get long penetration over 100 m when snow depth was 1 m or more.

Ramming performance with initial contact speed

Fig.8 shows the relation between the penetration distance and the initial contact speed at ramming against the multi-year ice for two ranges of equivalent ice thickness. Those approximated lines fitted against contact speed are shown in this figure also. The penetration distance increases with the initial contact speed. The relation concentrates on the approximated line in the case of equivalent ice thickness more than 3 m. The icebreaker breaks the ice at ramming operation by both of the inertial force with approach run and the propeller thrust. Although the ship speed drops fast with consumption of the kinetic energy during penetration, it continues icebreaking by the propeller thrust for a while after that in the case of thin ice. On the other hand, in the case of the equivalent ice thickness more than 3 m, the icebreaking resistance is too large in comparison with the propeller thrust to continue icebreaking. In such severe conditions, the icebreaker penetrates the ice almost by consumption of the kinetic energy and the penetration distance much depends on the initial contact speed.

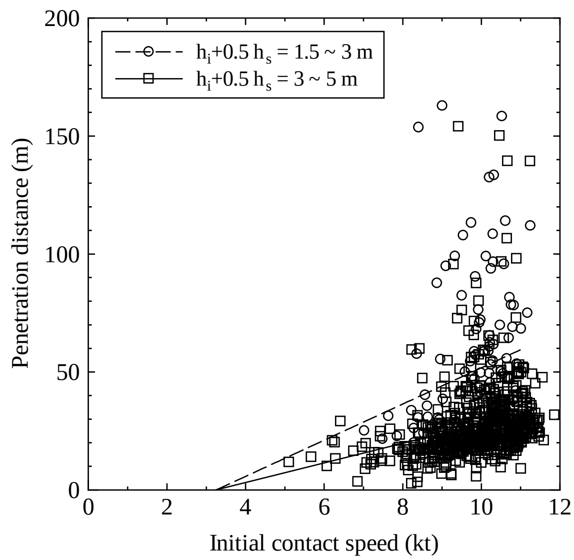


Fig.8 Penetration distance versus initial contact speed at ramming against multi-year ice

Effect of water flushing on ramming performance

A water flushing system is well known to have much effect when an icebreaker breaks snow-covered ice continuously. In the trial of *Oden* (Liljestrom and Renborg, 1990) or *Mudyug* (Hoogen and Delius, 1987), the reduction over 10 % in the total power has been verified and reported. On the other hand, there are few quantitative investigations into the effect of that system at ramming operations. The *Shirase* had rammed against the multi-year ice field both with and without water flushing. In order to confirm the effect of water flushing, penetration distances in two ramming operations, with and without flushing, were compared. The authors had investigated the effects by model tests at the ship planning stage and estimated the extension of penetration distance to be 10 to 15 % in 2 m thick snow-covered ice (Yamauchi, Mizuno and Tsukuda, 2009).

Fig.9 shows the average ratio of the penetration length with water flushing to that without water flushing. Also model test results are plotted in this figure for reference. It seems the effect is great at a snow depth range from 0.6 to 0.8 m. In that snow depth range, water flushing makes the penetration distance 15 % longer when ice thickness is 3 to 4.5 m. In another ice thickness range 1.5 to 3 m, it shows that the extension rate comes to about 50 %, but it should be noted that only a few ramming were made without flushing for that range of ice thickness.

Pitch motion at ramming

An icebreaker repeats pitching motion by bow's running up onto ice during ramming. A large pitching usually appears soon after initial contact. The relation between maximum pitch angle and penetration distance is shown in Fig.10. It is found that the penetration distance is shorter as the pitch angle is greater. When ice condition was severe like 3 m or more thick ice, the kinetic energy of the icebreaker was easy to be consumed on bow's running up. The icebreaker was restrained to about 50 m or less penetration when it ran up onto ice with pitching of 2 degrees or more, even if it charged into the ice at speed of 10 knots or over.

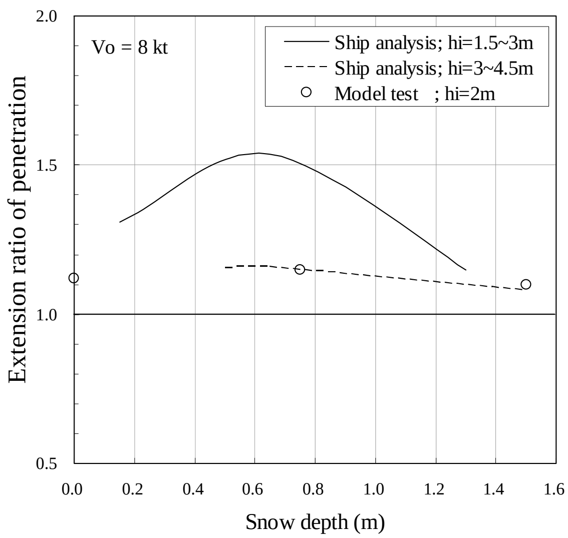


Fig.9 Effect of water flushing on penetration distance

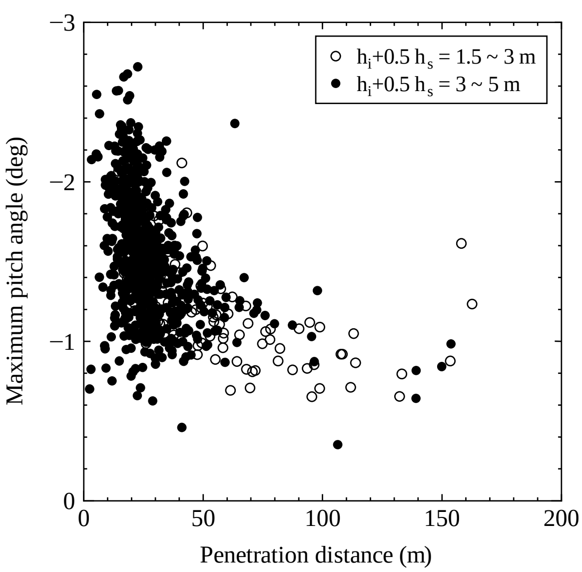


Fig.10 Relation between maximum pitch angle and penetration distance

ESTIMATION OF ICE PRESSURE ON SHOULDER

Ice pressure on a ship hull is very important factor for icebreaking navigation, especially at ramming operation. Initial contact speed should be decided in consideration of hull strength. In order to estimate the ice pressure during icebreaking, several strain gauges were fitted at bow shoulder part.

Arrangement of Strain Gauge

Two gauges were bonded at right angle on upper and lower points within about 1.4 m range of ten hull frames each, which were located in the starboard shoulder part near design water line, as shown in Fig.11. Shear stress at each point was continuously measured during icebreaking navigation.

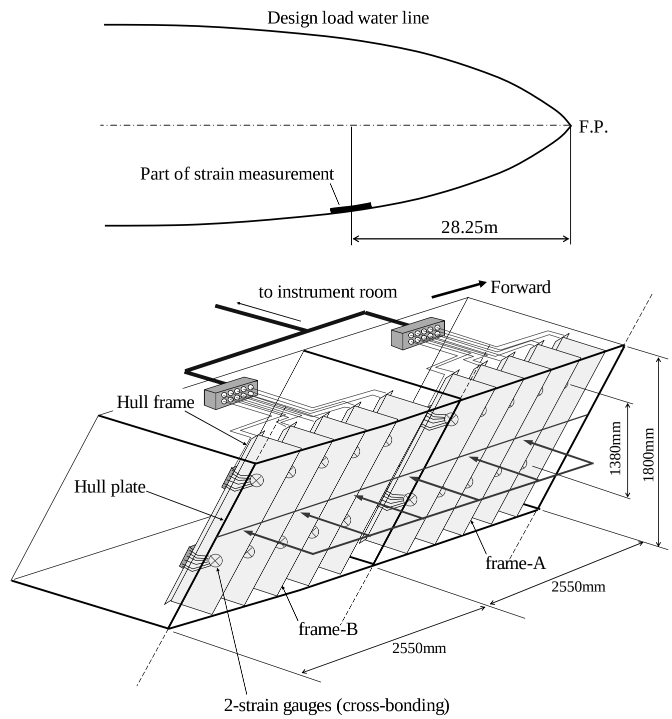


Fig.11 Arrangement of strain gauge bonding

Strength Analysis by FEM

A strength analysis on the shoulder part was carried out by use of the MSC Nastran in order to estimate an ice pressure corresponding to full-scale strain measurement. A structure model for the strain measurement part was made for the analysis as shown in Fig.12. The mesh size of the evaluation part was set to be about 0.1 m. It was assumed that ice load distributed uniformly on area like a belt, height of which was set to be 0.2, 0.6, 1.0 and 1.6 m. Shear stresses at measurement points, induced by unit pressure (1 MPa), were calculated on some vertical centers of load, considering change of draft through the voyage.

As an example of calculations, Fig.13 shows the shear stress distribution on frame-A and frame-B shown in Fig.11, which is located at 27 m and 29.5 m aft ward from the fore perpendicular, when the vertical center of load is located at 8.4 m height above the ship bottom. Fig.14 shows a relation between shear stress at upper and lower strain measurement points and height of load center. The height of load belt and the ice pressure is 1 m and 1 MPa respectively in those examples.

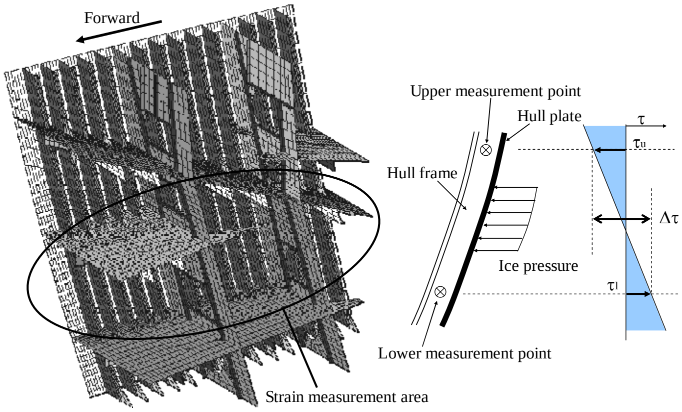


Fig.12 Structure model for strength analysis

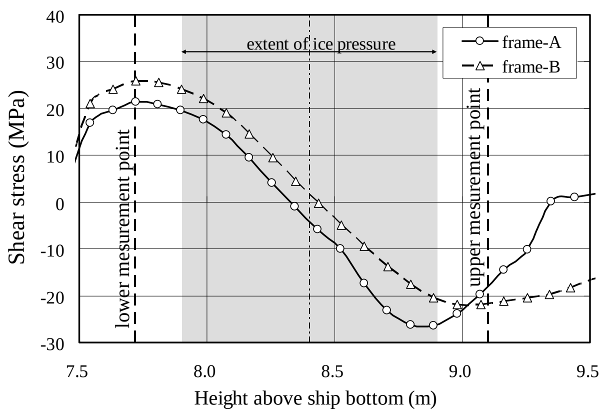


Fig.13 Shear stress distribution on hull frame (load belt of 1 m height, load center located at 8.4 m above ship bottom and ice pressure of 1 MPa)

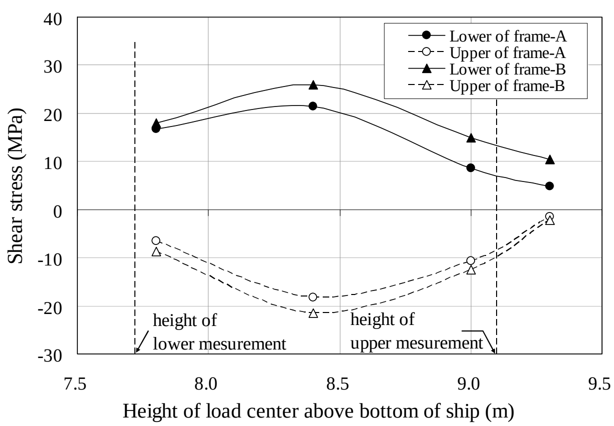


Fig.14 Shear stress versus height of load center (load belt of 1 m height and ice pressure of 1 MPa)

Estimation of Ice Pressure at Ramming

A very large shear stress occurred in an instant just after the icebreaker collided with ice edge at ramming in multi-year ice fields. Fig.15 shows an example of stress change which was recorded during one ramming at the frame-B, mentioned above.
Ice pressure acted on the shoulder was estimated approximately from measured shear stress by use of results of the strength analysis for each frame, as shown in Eq.3.

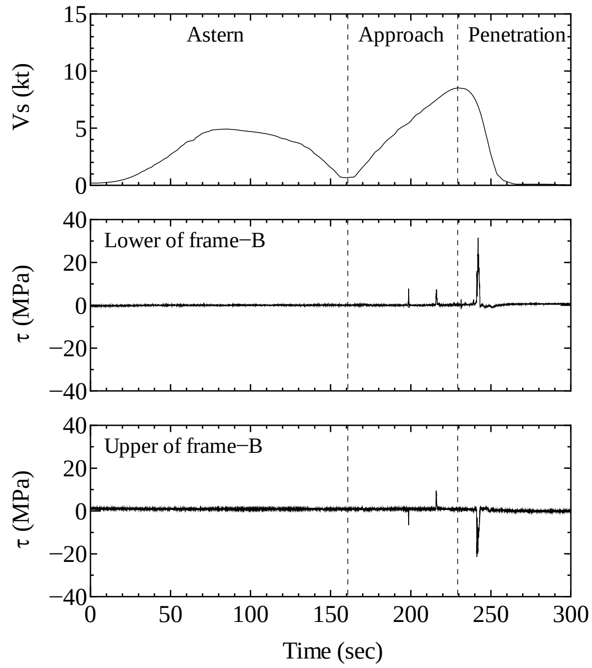


Fig.15 Shear stress records on hull frame at ramming

The height of load belt was assumed to be 20 % of the ice thickness which was encountered at each ramming. The shear stress difference induced by unit pressure was interpolated for the sailing condition, ice thickness and the draft, from the calculation results. Ice pressure at ramming was estimated as a ratio of measured stress difference to the calculated stress difference.

$$p_i = \left(\Delta\tau_m / \Delta\tau_c\right) \times p_{unit} \qquad (3)$$

$\Delta\tau_m$; difference in stress measured at two points of each frame,
$\Delta\tau_c$; difference in stress calculated at two points of each frame induced by unit pressure,
p_{unit} ; unit pressure for calculation (= 1MPa)

The analysis of ice pressure peak was carried out for about 350 cases of ramming operations in multi-year ice fields, ice thickness range of which was 2 to 4.5 m. We focused on the relation between the ice pressure and snow depth especially because the difference of the impact with snow depth was notable on board. Fig.16 shows a relation between the ice pressure peak and initial contact speed in three groups of snow depth, where the ice pressure peak means the largest pressure among ten frames at each ramming. In order to make the trends more clear, average of peak pressure for every speed range of 1 knot is shown in Fig.17 also.
Those results show not only trend of ice pressure increase with initial contact speed but also that of decrease with snow depth. It is considered that deep snow acts like a damper and absorbs the impact on the hull during snow compaction. On the other hand, when the snow depth is small, the icebreaker collides with the ice directly and the ice pressure increases remarkably with initial contact speed.

CONSIDERATIONS ON RAMMING OPERATION

Those investigations clearly show that the influence of snow on penetration distance at ramming is notable. Water flushing system is considered to be effective means to extend a penetration in severe condition with deep snow.

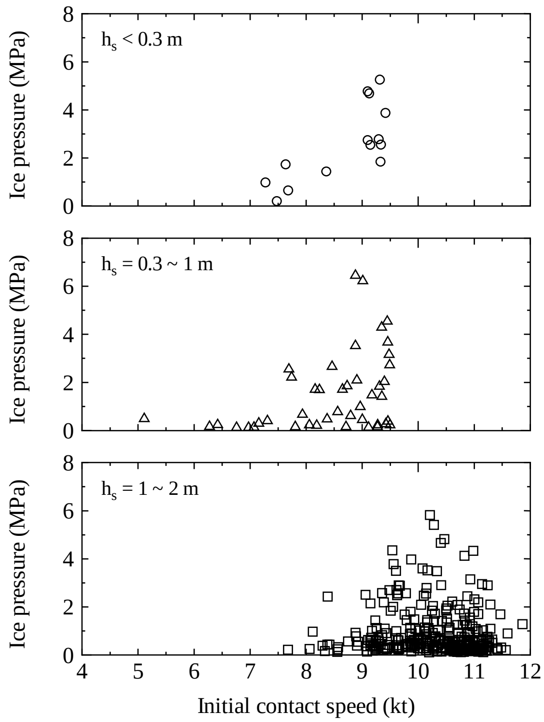


Fig.16 Estimated ice pressure on shoulder part at ramming

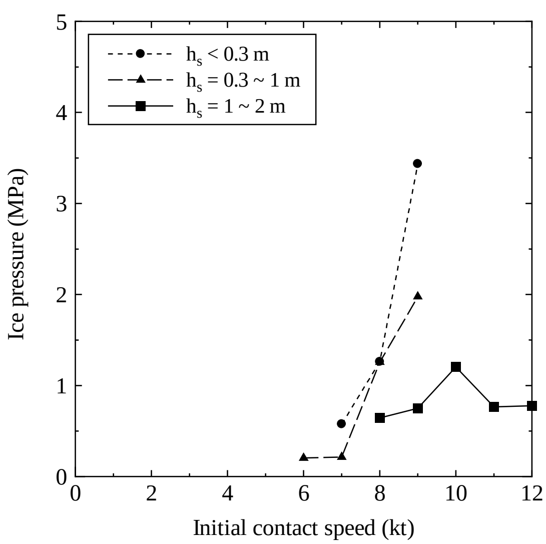


Fig.17 Average ice pressure at each contact speed notch of 1 knot on shoulder part at ramming

On the other hand, the basic consideration that initial contact speed is predominant factor for penetration distance does not change. When the contact speed is adjusted by approach distance, the characteristics of ice pressure as shown in Fig.17 should be considered well.

If the snow depth is very small or not exist, extremely fast contact speed should not be chosen because large ice pressure easily occurs on hull surface. In such situation, the icebreaker can obtain relatively long penetration distance as shown in Fig.7, and then it does not need to fight the danger of the high ice pressure at fast contact speed.

If there is large amount of snow on ice, the operation with high contact speed is effective to extend penetration. In such situation, extremely large ice pressure hardly occurs even at high contact speed. Off course, the degree of speed increase should comply with hull structure strength. In the case of the *Shirase*, she kept the ramming performance by such operations that the contact speed was about 11 knots for snow depth of 1 m and more although the contact speed was 9 knots or less for thinner snow cover.

CONCLUSIONS

Full-scale data on icebreaking navigation of the *Shirase* were recorded during the Antarctic maiden voyage, and the icebreaking capability, the effect of water flushing, the ice pressure trend on the shoulder and so on were measured and investigated.

The *Shirase* continuously broke the first-year level ice, thickness of which was less than 1.8 m. For 1.5 m thick level ice, she was able to sail at speed of about 4.5 knots by the maximum shaft power. It was confirmed that the continuous icebreaking capability satisfied the initial designed performance.

In her maiden voyage, influence of snow on ramming was very large. Especially in deep snow exceeding 1 m thickness, she hardly made the penetration distance over 50 m. Water flushing system operated effectively at not only continuous icebreaking but also ramming in deep snow-covered ice. It makes the penetration distance longer by 10 % at least.

Ice pressure on the shoulder part was estimated from the shear stresses measured on the frames and the results of strength analysis by FEM. A typical ice pressure peak occurred soon after she collides with the ice at ramming and its values were related to not only contact speed but also snow depth. In the condition of little snow, large ice pressure occurred easily due to the impact from ice, and it became larger with increase in contact speed. In the condition of heavy snow, large ice pressure hardly occurred in comparison with little snow case because the snow absorbed the impact. To increase contact speed is effective to extend penetration distance in that condition.

In order to establish the icebreaker's navigation manual, further icebreaking tests would be performed although several findings for icebreaking navigation were obtained through the maiden voyage.

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