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Relationship between Ship Structural Response and Ice Conditions in Antarctic Ocean

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ABSTRACT

This paper investigates the relationship between the ship structural response and the ice conditions. Japanese Antarctic research icebreaker Shirase encountered various sea ice conditions during its voyage in the 55th Japanese Antarctic Research Expedition (JARE 55) from December 2013 to February 2014.The ice thickness, ship motions and structural response along its route were measured. The repetitive small peak stresses were measured during the continuous icebreaking in the level ice. The ship eliminated the ice floes in the pack ice, and broke the plate ice by ramming icebreaking in the hummock and multi-year ice. The large peak stress at the hull frames and the large longitudinal deformation (strain) on the deck were measured when the icebreaker Shirase navigated in the pack ice, hummock ice and multi-year ice. This study reveals that the peak stress at the hull frames significantly correlated with the ice thickness in the level ice, but not in the pack ice, hummock ice and multi-year ice. The deck strain measured, when Shirase was in the pack ice, level ice, hummock ice and multi-year ice, was shown to be highly correlated with the ice thickness.

KEY WORDS Full-scale measurement; Antarctic sea ice; Structural response.

INTRODUCTION

Japanese Antarctic Research Expedition (JARE) began in 1956. Japanese Antarctic research icebreaker Shirase has engaged in the transporting cargoes and scientists in order to operate and maintain the Japanese Antarctic research station Syowa since 2009. Antarctic Ocean near the Syowa station is covered by multi-year ice with extremely thick ice and snow. In order to ensure its safe voyage in Antarctic Ocean, the motions of the icebreaker Shirase and the ice conditions were monitored. In order to understand the ship-ice interactions such as the ice-induced load and the structural response, several full-scale measurement campaigns for the ice-going vessel have been performed (e.g., Kotisalo, K. et al., 1999, Krupina, N.A., et al., 2009 and Nyseth, H., et al.). However, more full-scale measurements data on ship-ice interactions are needed. The icebreaker Shirase encountered various kinds of the ice conditions such as pack ice, level ice, hummock ice and multi-year ice during the 55th Japanese Antarctic Research Expedition (JARE 55). This paper presents the measured ice thickness and the structural response of the ship during the expedition. The relationship between ship structural response and ice condition are investigated.

MONITORING SYSTEM

The monitoring system aboard the icebreaker Shirase recorded the ship speed, motion (heave, pitch and roll angle), shaft power, thrust, rudder angle, frame stress with the time interval of 0.01 s (Yamauch, et al., 2011). The total ice thickness (snow + ice) was measured by electro–magnetic induction sensor (EM sensor) located at the starboard shoulder. The sampling frequency of the EM sensor was 1 Hz. The locations of the icebreaker Shirase were recorded by GPS every second. For the structural response, the strains of the frames on the side hull at the starboard shoulder and those of the deck plate were measured by strain gauges. In this paper, the ship speed, ice thickness, deck strain, frame shear stress and GPS data were analyzed. Table 1 gives the characteristics of the Japanese icebreaker Shirase. Figure 1 shows the onboard monitoring system. Figure 1 (a) illustrates the instruments of Shirase onboard system. Figure 1 (b) illustrates the arrangement of the strain gages. In total, twenty strain gauges were placed on 10 frames (FR01 – FR10) on the side hull at the starboard shoulder. Specifically, two gauges installed at the upper (U) and lower (L) side along each of these 10 frames. The frame strain measured by the strain gauges in Figure 1 (b) were transferred to the shear stress. The shear stress was plotted in the following figures. The sampling rate of the strain in both frames of the side hull and deck plate was 100 Hz.

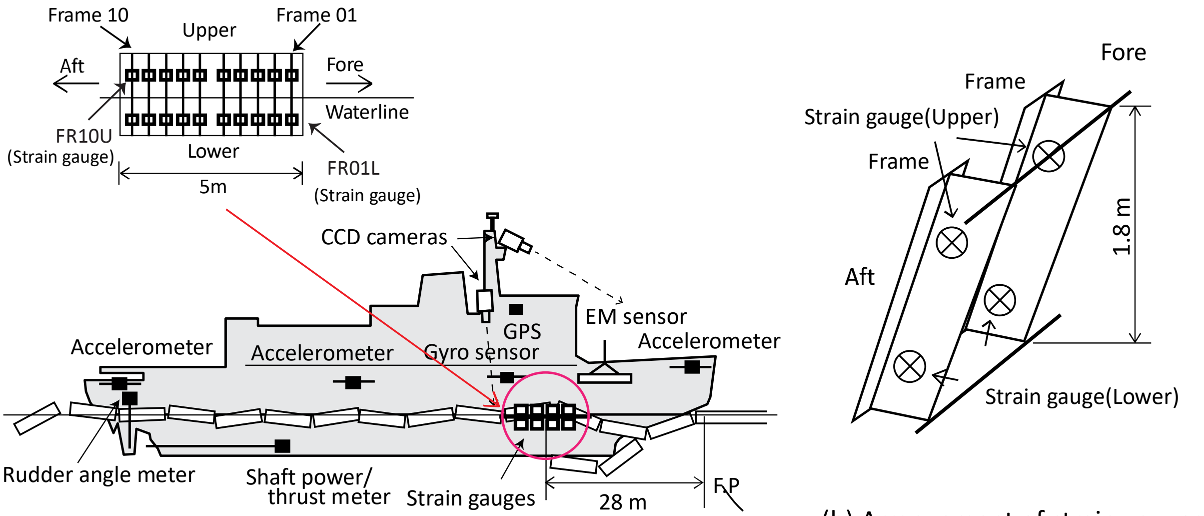
Table 1. Main characteristic of the Japanese icebreaker Shirase.

Length of water line	126.0 m
Maximum breadth	28.0 m
Design draft	9.2 m
Maximum displacement	abt. 20,000 t
Continuous icebreaking (at 3kt.)	1.5 m level ice
Maximum speed	19.5 kt
Propulsion power	abt. 22,000 kW
Number of propeller	2
Number of rudder	2

ICE CONDITIONS AND STRUCTURAL RESPONSE

Ship Route

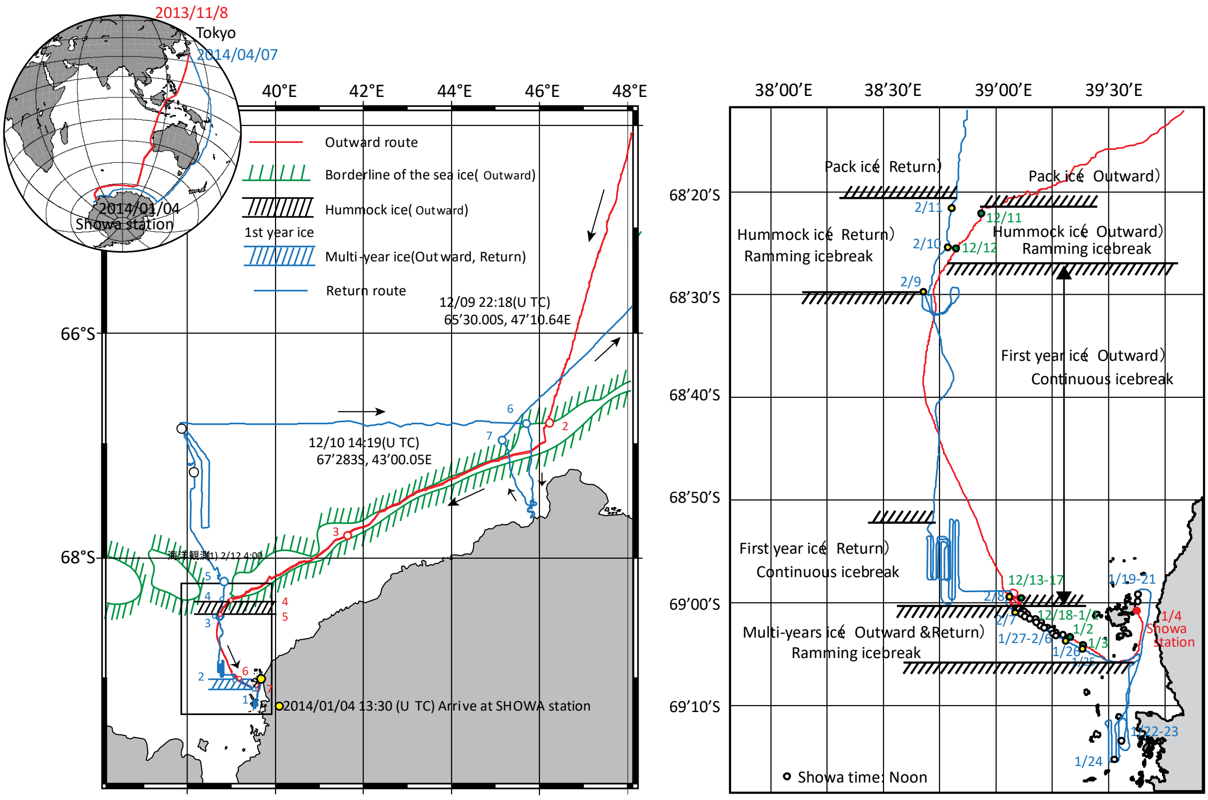
Figure 2 presents the ship route of the icebreaker Shirase in Antarctic Ocean during JARE 55. The icebreaker Shirase started its voyage from Harumi-futo (Tokyo, 35.65° N, 139.77° E) to the Syowa station located on the East Ongul Island in Lutzow-Holm Bay (69.37° S, 39.96° E). The icebreaker Shirase entered the ice-covered water December 9 2013 (63.85°S, 48.33° E), and sailed until January 4 2014 (69.08° S, 39.6° E) in the outward voyage. In its outward voyage, various ice types were observed: the pack ice (December 09 – 11, 2013), hummock ice (December 11 – 12, 2013), level ice (December 12 – 13, 2013) and multi-year ice (December 18, 2013 – January 04, 2014). This paper analyzes the ice conditions and the structural response measured in outward voyage.



(b) Arrangement of strain gauges

(a) Instruments of Shirase onboard system

Figure 1. Onboard monitoring system.



1) 12/9 12:30 (UTC) 63°51'S, 48°20'E: Enter pack ice
2) 12/10 08:04 (UTC) 66°50'S, 46°10'E: Enter OOTONE Channel
3) 12/10 19:00(UTC) 68°02'S, 40°42'E: OOTONE Channel
4) 12/11 00:30 (UTC) 68°21'S, 38°55'E, Enter hummock ice
5) 12/12 21:00 (UTC) 68°27'S, 38°47'E, Enter level ice
6) 12/18 04:00 (UTC) 68°54'E, 39°06'E. Enter multi-year ice
7) 2014 1/04 07:00 (UTC) 69'05'S, 39°36'E, Retreating from multi-year ice

Figure 2. Route of the icebreaker Shirase during JARE55.

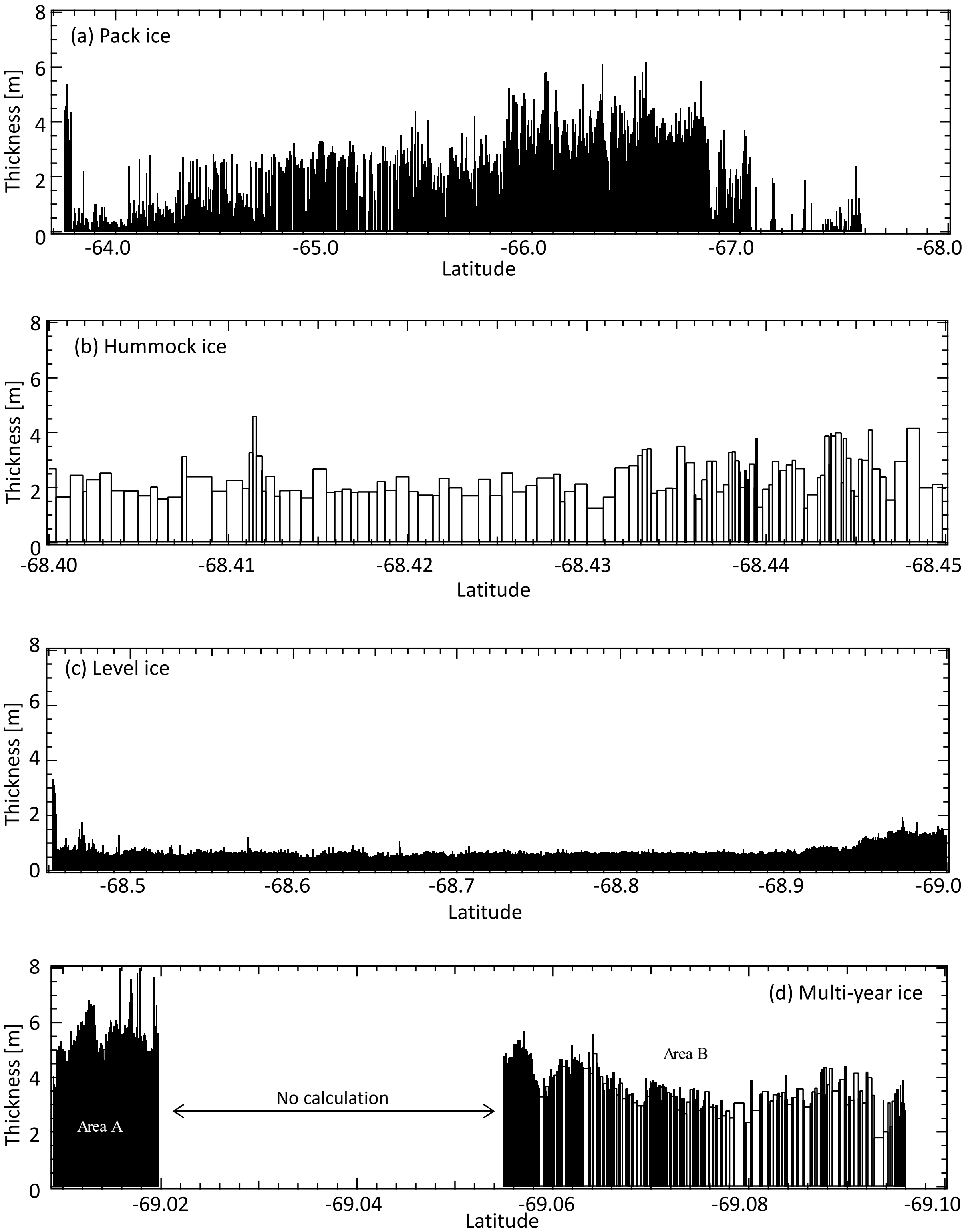


Figure 3. Measured ice + snow thickness during JARE55 (outward trip). (a) Pack ice. (b) Hummock ice. (c) Level ice. (d) Multi-year ice.

Ice Thickness

Figure 3 presents the measured ice thickness (ice + snow) along the outward ship route. The pack ice distributed between 63.85° S, 48.3° E and 66.83° S, 46.17° E as shown in Figure 3 (a). The open channel (OOTONE Channel) was seen until 68.35° S, 38.93° E. The ice thickness in the pack ice zone gradually increased from below 1.0 m (at the entrance) to 6.0 m (at the edge of the pack ice), and the ice concentration in this region rose from 10 % (in the thin pack ice) to 100 % (in the thick pack ice). As seen in Figure 3 (b), the hummock ice extended from 68.37° S, 38.93° E to 68.45° S, 38.78° E. The ice thickness in the hummock ice area was between 2.0 m and 6.0 m. The ice near the level ice was relatively thicker than that at the entrance of the hummock ice zone. In Figure 3 (c) illustrated the distribution of the level ice from 68.37°S, 38.93°E to 68.91° S, 39.10° E and thickness around 1.0 m. In contrast, the ice condition in the multi-year ice region from 68.91° S, 39.10° E to 69.16° S, 39.60° E was extremely severe. The ice thickness in the multi-year ice area gradually decreased from the entrance to the end of the multi-year ice region. The thickness data between 69.02° S, 39.20° E and 69.05° S, 39.30° E is missing, but the thickness of ice in this area was approximately 5.0 m. Table 2 lists the average and maximum thickness in aforementioned ice zone.

Table 2. Ice thickness (ice + snow) along ship route.

	Average [m]	Maximum [m]
Pack ice	1.4	6.2
Hummock ice	2.9	6.3
Level ice	0.9	3.4
Multi-year ice	4.5	9.0

Structural response

Pack ice

Figure 4 presents the time history of the shear stress on the hull frame, No. FR04U, when the icebreaker advanced in the pack ice. The corresponding maximum and average ice thickness is 4.9 m and 2.2 m, respectively. The icebreaker pushed away the pack ice by the ship-ice collisions. The large and small peak stresses induced by the ship-ice collisions were measured. The total number of the peak stresses is 56. The maximum and average peak stress is 17.3 MPa and 1.47 MPa, respectively. The peak stress of the hull frame is affected by the collision conditions between the ship hull and the ice contact edge such as the ice thickness, collision speed, the edge shape of the ice floe. The ice thickness is the most important determining factor among various parameters to describe ice conditions for the frame stress. Figure 5 presents the relationship between the ice thickness and (a) the frame stress (frame No. FR04U), (b) the deck strain. The average ice thickness and the deck strain resampled every 300 s displayed in Figure 5 (b). The frame stress becomes larger than 3 Mpa when the ice thickness is higher than 2 m and the ice concentration is larger than 50 % as shown in Figure 5 (a). The ice floes were smoothly pushed away without obstruction from surrounding ice floes in the small ice concentration. Therefore, the frame stress in low ice concentration becomes small even in the thick ice. Various ice floe shapes were observed in high ice concentration. Therefore, a large scatter of frame stress is seen when the ice concentration is high. The deck strain proportionally increases with the ice thickness. The deck strain induced the longitudinal deformation of the ship global structure. It can be seen that the structural response of the ship global structure occurred during the ship-ice collisions depends on ice thickness.

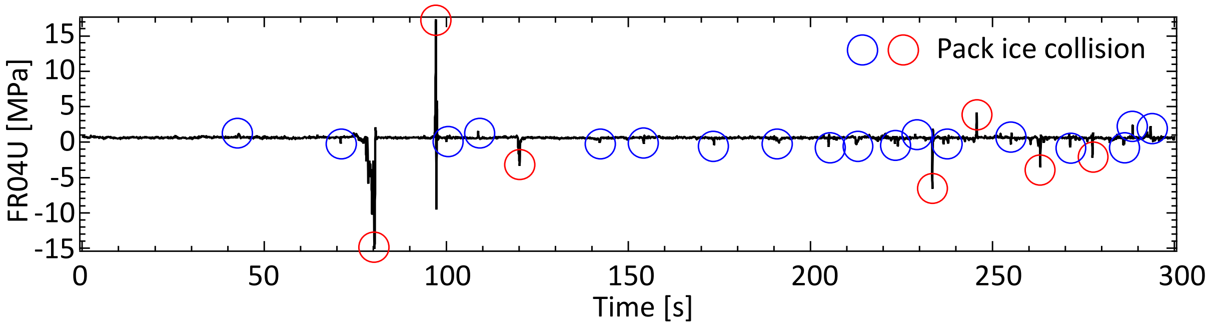


Figure 4. Measured time history of the shear stress on the hull frame (No. FR04U) in the pack ice between 66.39° S, 46.52° E and 66.41° S, 46.51° E.

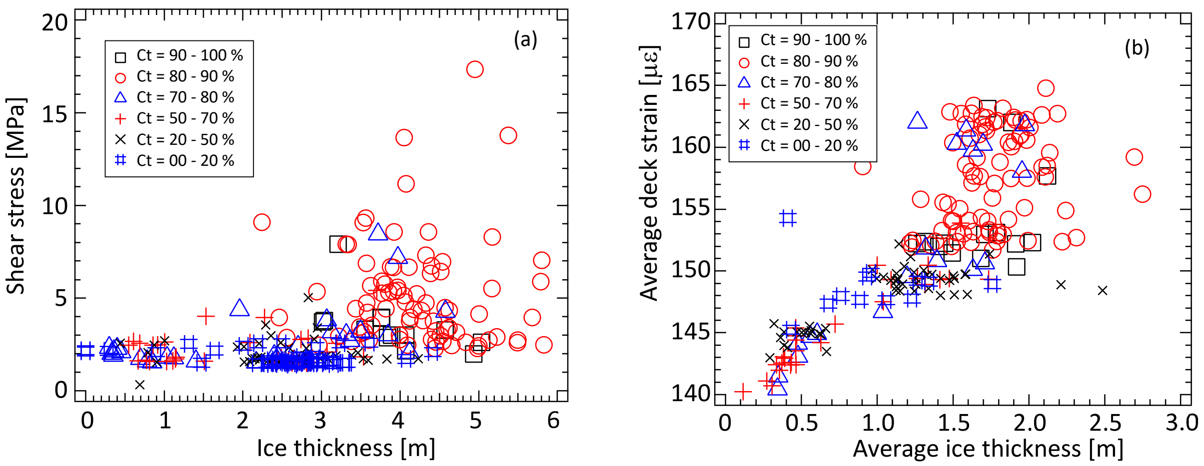


Figure 5. Relationship between the ice thickness and (a) frame stress (FR04U), (b) the deck strain during the collision with the pack ice.

Level ice

Figure 6 illustrates the time history of the shear stress experienced on the hull frame, No. FR05U, when the icebreaker advanced in the level ice. The corresponding ice thickness is: the maximum value 0.8 m and average value 0.6 m. The icebreaker broke the level ice by continuous icebreaking. The repetitive peak stress when the plate ice was broken by bending failure was shown. The number of peak stress is 200. The maximum and average peak stress is 2.1 MPa and 0.95 MPa, respectively. The peak stress is smaller than that in the pack ice and the number of peak stress is larger because of the ship-ice collision with the large and thick ice floes in the pack ice. Figure 7 presents the relationship between the ice thickness and (a) the frame stress (frame No. FR05U), (b) the deck strain. The average ice thickness and deck strain resampled 300 s are shown in Figure 7 (b). The frame stress increases with the ice thickness at the high ship speed (larger than 3 kt). The small differences between the straight (black markers in Figure 7) and 8 loop (red markers in Figure 7) track are shown. It is suggests that the ship-ice collision force in the continuous icebreaking does not depend on the ship speed and ship advancing mode (straight and 8 loop advancing), but on the ice thickness. The deck strain proportionally increases with ice thickness. The structural response of the ship global structure in level ice depends on the ice thickness. The same applies in the pack ice.

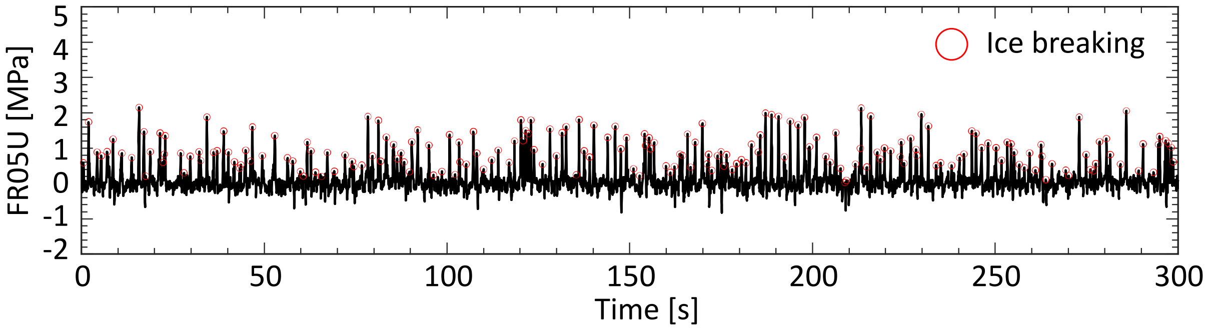


Figure 6. Measured time history of the shear stress on the hull frame (No. FR05U) in the level ice between 68.86° S, 38.90° E and 68.88° S, 38.92° E.

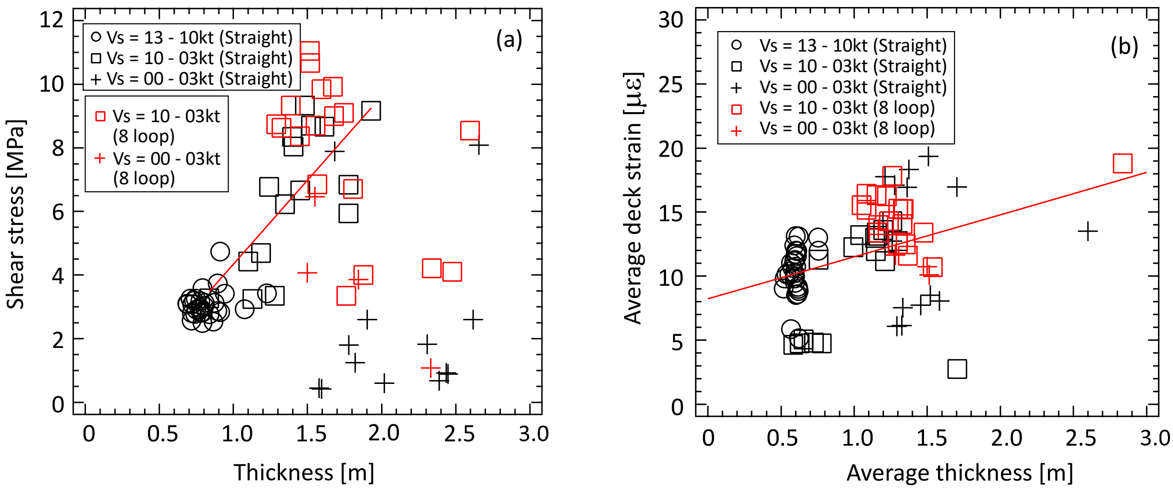


Figure 7. Relationship between the ice thickness and (a) frame stress (FR05U), (b) the deck strain during the continuous icebreaking in the level ice.

Ramming icebreaking (Hummock ice and multi-year ice)

Figure 8 shows the time history of the ship motion (ship velocity, roll angle and pitch angle), and the structural response (deck strain, shear stress of the frame No. FR05U and FR05L) when the ship broke the hummock ice by ramming icebreaking. In Figures 8, the pitch motion in the bow-up direction expresses a positive value. The ship accelerated to 9.0 kt and collided with the hummock ice at the maximum speed (9.0 kt). The ship speed decreased after the ship–ice collision, and the pitch angle increased as the ship slid up the plate ice. The roll angle varies frequently during ramming. The deck strain increased after the ship-ice collision. The tendency of the time history of the deck strain coincides with that of the pitch angle. The deck strain is induced by the longitudinal response of the ship global structure. The ship longitudinal deformation occurred when the ship slid-upon the plate ice, in which the pitch angle increased with ship sliding-up. This implied that the deck strain collated with the pitch angle during the ramming icebreaking. The peak stress of the hull frame became large when the ship hull plate collided with the plate ice. Figure 9 illustrated the relationship between the maximum deck strain and (a) the maximum pitch angle, (b) the ice thickness during one cycle of the ramming icebreaking. The maximum strain during the ramming icebreaking increased with the pitch angles. Additionally, the maximum strain increased with the ice thickness. This implies that the pitch motion during the ramming icebreaking indicated the ice thickness of the multi-year ice.

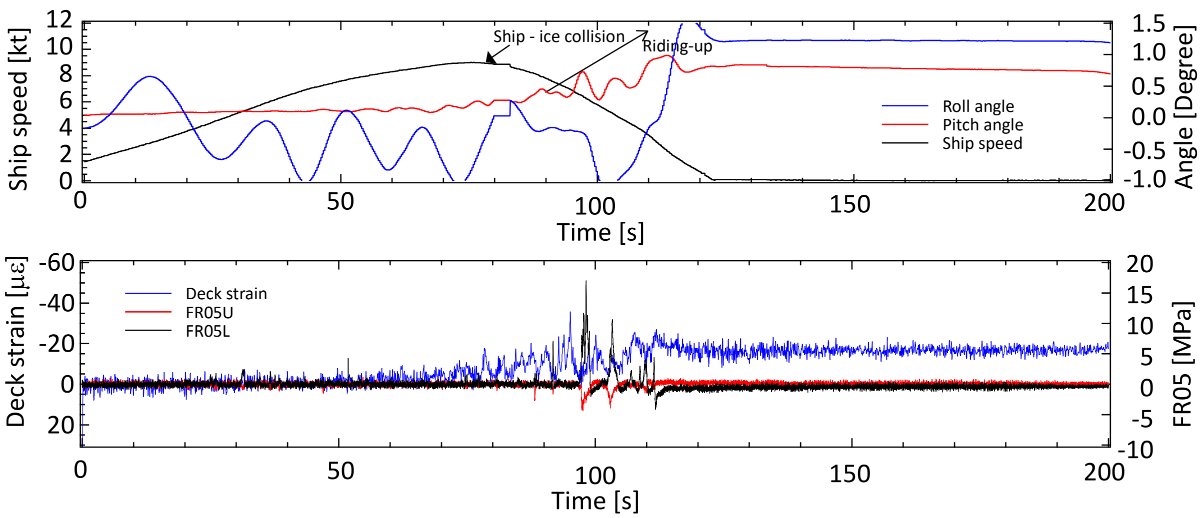


Figure 8. Measured time history of the ship motion and the structural response during ramming icebreaking in hummock ice between 68.38° S, 38.92° E and 68.38° S, 38.92° E.

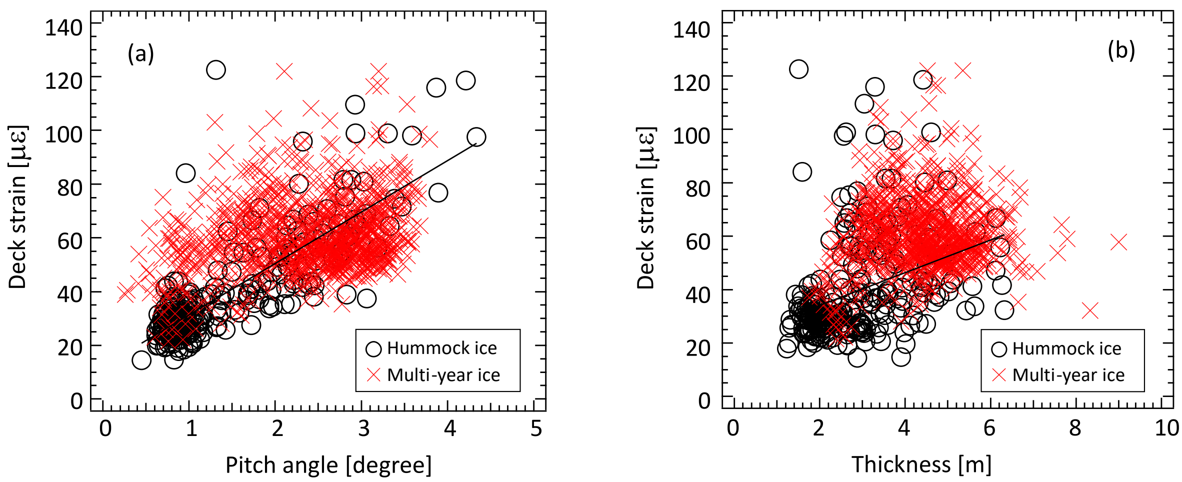


Figure 9. Relationship between the maximum deck strain and (a) the pitch angle, (b) the ice thickness during the ramming icebreaking in hummock ice and multi-year ice.

CONCLUSIONS

This paper presents the measured ice thickness and the structural response during the ship-ice interactions in Antarctic sea ice. The relationship between the ship structural response and the ice thickness was investigated. The thickness in the level ice was below 3 m. The level ice was broken by the continuous icebreaking. The repetitive small peak stresses were measured in the level ice. The maximum ice thickness was larger than 4 m in the pack ice, multi-year and hummock ice. The icebreaker eliminated the ice floes by the ship-ice collision in the pack ice and broke the plate ice by the ramming icebreaking in the hummock and multi-year ice. The large peak stress at the side hull and the large longitudinal deformation on the deck were measured in the pack ice, multi-year and hummock ice. The repetitive peak stress at the side hull correlated linearly with the ice thickness, but showed no relationship with the ship speed during the continuous icebreaking. Additionally, the deck strain measured in the pack ice, level ice, hummock ice and multi-year ice had a linear relationship with the ice thickness. Lastly, the deck deformation measured during the ramming icebreaking showed a strong correlation with the pitch angle.

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