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A ship in compressive ice: an overview and preliminary analysis

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ABSTRACT

Compressive ice is among the most dangerous ice conditions a ship may encounter when she is sailing through ice-covered area, since she may get stuck due to additional resistance and get damaged on hull due to crushing load. However, research on this topic has been relatively rare and proper methods to evaluate the associated risk are scarce. This paper reviews the previous efforts made on this subject, especially those by model-scale tests and full-scale observations. Cases when ships encounter compressive ice in Baltic Sea are presented and summarized based on a series of previous survey. Preliminary analysis on ship-ice interaction process are presented in order to clarify the critical issues regarding ships in compressive ice. The results provide valuable insights for understanding the process and can be applied as the reference for future theoretical modelling and model scale tests related to ships in compressive ice.

KEY WORDS: ship performance, ice loads, compressive ice, dynamic ice, model test

INTRODUCTION

Ship performance in ice have been studied extensively with regards to level ice, ridged ice, channel ice and packed ice (e.g. Lindqvist, 1989; Kuuliala et al, 2017; Riska et al., 1997; Lubbad et al., 2018). The approaches include semi-empirical formulas, numerical simulation and probabilistic methods (Li et al., 2018). However, these all deal with cases when ice is static, where the contact between ship and ice arises from ship's motion. In these cases, the resistance mostly comes from the contact at ship's bow part rather than midship.

The situation becomes more dangerous for ships when ice is dynamic. Ice can drift once driven by wind or current (Leisti et al., 2009). In some cases, a ship may sail through a closing ice channel, where the edges of the channel may contact with ship's hull significantly. This is usually referred to as compressive ice. According to Eriksson et al. (2009), this is the most hazardous case for a ship to navigate through ice-covered area. This is because that in this case, there can be heavy contact between ice and midship hull, where the hull is less strengthened compared to bow area and therefore is more vulnerable to damage. For a ship being escorted by an icebreaker, the closing ice channel may lead to additional resistance on the assisted ship, which may get stuck in ice and even damaged (Eriksson et al., 2009).

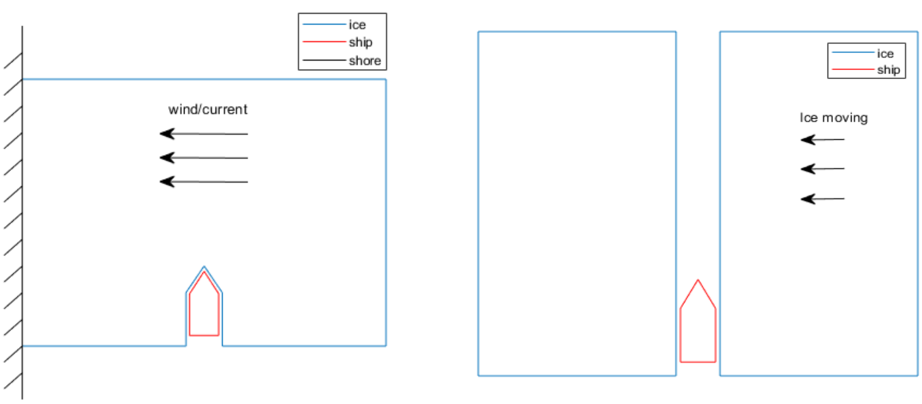
Research related to dynamic ice has been relatively few compared to other ice conditions. In 1990s, a project named 'a ship in compressive ice' was conducted in a joint research project between Helsinki University of Technology, Laboratory of Naval Architecture and Marine engineering, and Academy of Sciences in USSR, Institute for Problems in Mechanics (Kujala and Kuuskoski, 1992). This project tried to get an insight into the ice loads on a ship's hull both theoretically and experimentally when the ship encounters compressive ice. In 2010s, another project named SAFEWIN was conducted partly in Aalto University to find both the additional resistance and ice loads when a ship is moving through a compressive ice channel (Suominen & Kujala, 2012). There are a few other studies related to this topic (Riska et al., 2006; Zhou et al., 2017; Kubat, 2012; Kubat et al., 2013; Tomac et al, 2014), but the work has been few that most of the problems remain unsolved.

This paper gives an overview of the previous effort on this topic in order to analyze and summarize the failure mode and critical issues related to ship navigation through compressive ice channel. The two aforementioned projects are used as the main reference for demonstration and analysis. Firstly, the background information in terms of the compression scenario is described. A compression survey with ice-going ships in Baltic Sea conducted in a previous project is presented to demonstrate the frequency and severity of compressive ice. Then the interaction between ship and ice is analyzed in order to identify the most critical issues determining ship resistance and ice loads. Finally, the conclusions are made.

SHIPS IN COMPRESSIVE ICE: THE SCENARIO

Background information

Compressive ice can be classified as static compressive ice (Figure 1a) and dynamic compressive ice (Figure 1b). The former refers to cases when ice is not moving, but due to wind or current there is internal compression (e.g. fast ice with wind blowing towards the shore). In this case, the compression rarely leads to additional interaction between ship and ice, therefore is not hazardous (see later section). The latter refers to cases when ice is drifting towards the ship also due to wind or current. In this case, although the internal compression is also present, the interaction with ship mostly comes from the inertia of the ice floe. This induces significant additional resistance and loads to the ship and therefore is hazardous. It can be further realized that the most dangerous case is when a ship is going through an ice channel, where the ice sheets are moving towards the ship perpendicularly to ship's course (Figure 1b), since in this scenario the ship cannot move transversely and therefore has to bear the ice force totally with structural deformation. Based on these reasoning, the research target



(a) (b)

Figure 1. Illustration of static and dynamic compression

is focused on compressive ice channel.

Eriksson et al. (2009) has conducted comprehensive study on the cause of ice drifting and how it comes into contact with a ship. Compression in an ice field is formed when winds and/or currents push open pack ice against an immovable boundary. This boundary can either be the edge of landfast ice, or the coastline itself. Figure 2 illustrates the formation process of compression in reality. Some big ice floes are driven by wind and drifting towards each other. If a ship was sailing in between the ice floes, the channel which the ship was previously sailing in gets closed as the ice floes move closer to each other. The ship then gets compressed and encounters additional resistance to get through. Eriksson et al. (2009) then suggest that the ship should try to avoid going in the direction perpendicular to ice moving direction and instead go in parallel.

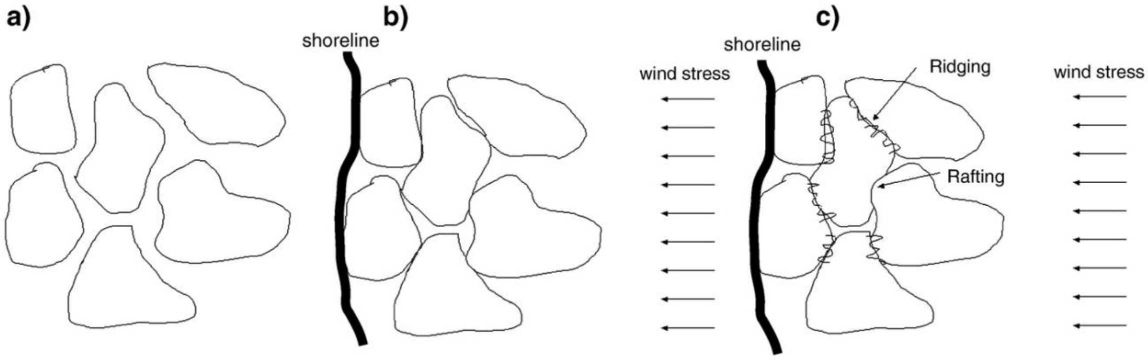


Figure 2. Formation process of ice compression (Leisti et al., 2009)

A compression survey

During winter 2010/2011, researchers from Aalto University conducted a survey in terms of cases when ships encounter compressive ice in the Baltic Sea. The survey collected reports from ship crew and records the description, position and difficulties the ships met during the compressive scenario. AIS data and ice forecast of Finnish Meteorological Institute were collected for the area to see the ship speed reduction and ice movement. All together over 1000 reports about compression in the Baltic Sea were received during this winter, which demonstrates the extensive existence of compressive ice. The locations of the reported compressive cases are presented in Figure 3. The cases spread all over the Bothnia Bay and the Gulf of Finland, mostly along the main shipping route. In this paper, we present one representative case to analyze the influence of compressive ice to ship's operability.

The ship under investigation is MT Tempera (MMSI: 230944000), which is double acting, 1A Super ice going Aframax tanker of 106 000 DWT. On 6th June, 2011, she departed from Primorsk before midnight and reported a severe compression about 9 nm north from Ostrov

Table 1. The ships operating at the same area

Ship name	Length×width	Type	Comments
Alexander B	153m×23m	Cargo	Stuck in ice and drifting 0.1kn
Andrea	134m×23m	Cargo	Having problems but still can operate by herself
Apollo	168m×26m	Tanker	Stuck at the same point
Baltic Swan	149m×22m	Cargo	Stuck but gets loose from ice, drifting with ice 0-0.1kn
BF Victoria	101m×18m	Cargo	Stuck in ice for several hours, drifting 0.1-0.2kn
British Kestrel	251m×44m	Tanker	Stuck for several hours
Christopher	171m×26m	Cargo	Stuck
St Petersburg	115m×27ms	IB	Assisting ships that are stuck in the same area

Malyy. The speed reduced from 5kn to 0.4kn at 5:50. According to the gathered AIS data, ships operating at the same time and area also had problems to go through. Some of them are presented in Table 1.

There are 17 more ships operating at the same time and area where most of them also met problems navigating through this area. As presented in the table, most of the ships get stuck in ice and have to wait for icebreaker assistance or wait for the ice getting loose by itself. The cargo vessels and tankers all have big problems while the icebreaker can still operate well. As the consequence, series delays occur up to several hours.

Figure 4 shows the speed and course over ground of MT Tempera with forecasted movements of ice and pressure in the ice field on 6th of March. The Finnish Meteorological Institute provided the ice information. The speed drop is clearly shown at around 5:50, where the ice pressure is considerably high. The difference between the direction of COG and ice direction is about 90 degrees, implying that the ice moves to the ship from lateral direction. Generally, the ship speed correlates well with the ice pressure magnitude, where higher pressure corresponds to lower speed. After 8:00, the forecasted pressure decreases further and the speed of MT Tempera is then increasing to normal operation. However, the peak value of ice pressure happened at the beginning of the voyage but the ship speed was not significantly affected. This can be explained by Figure 4 that the compression might be static or the ice was moving so slowly that little additional resistance was exerted on the ship, as the ice drifting information is not given in the figure. As a summary, compressive ice exists widely in the Baltic Sea and can lead to serious halt of transportation.

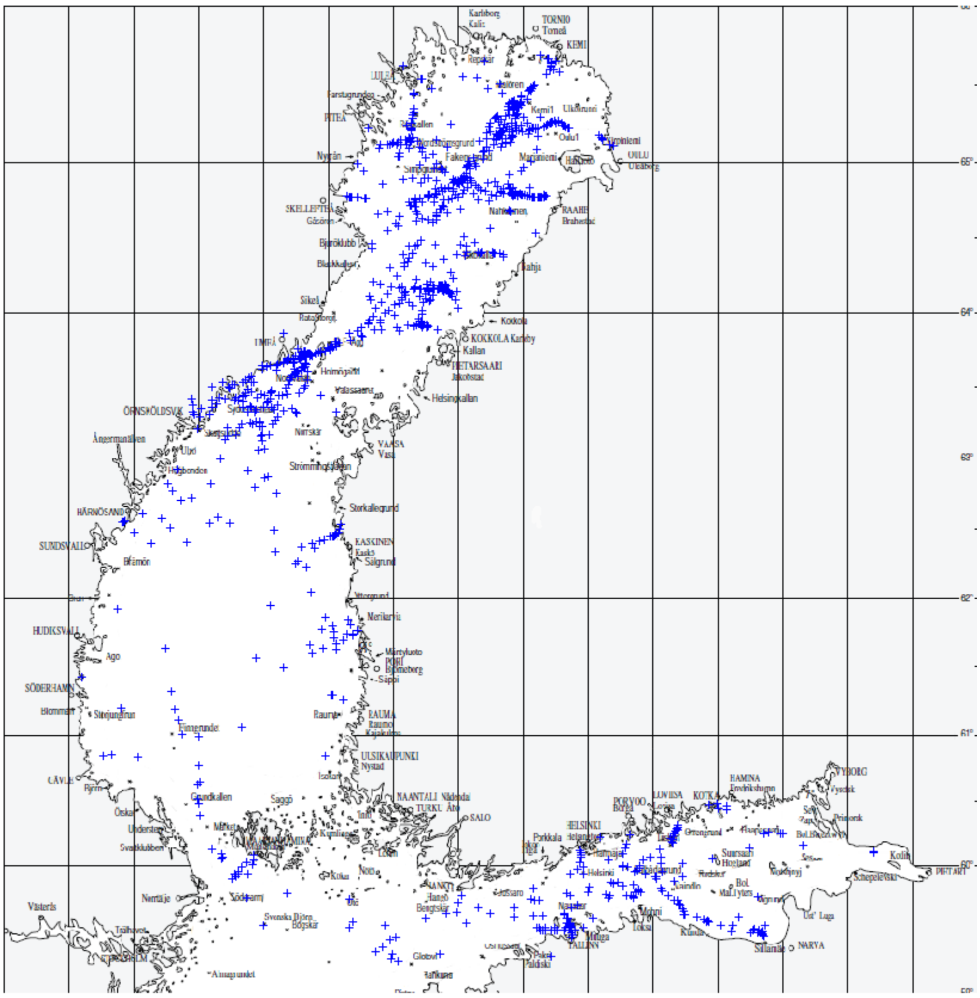


Figure 3. Location of reported compressive cases

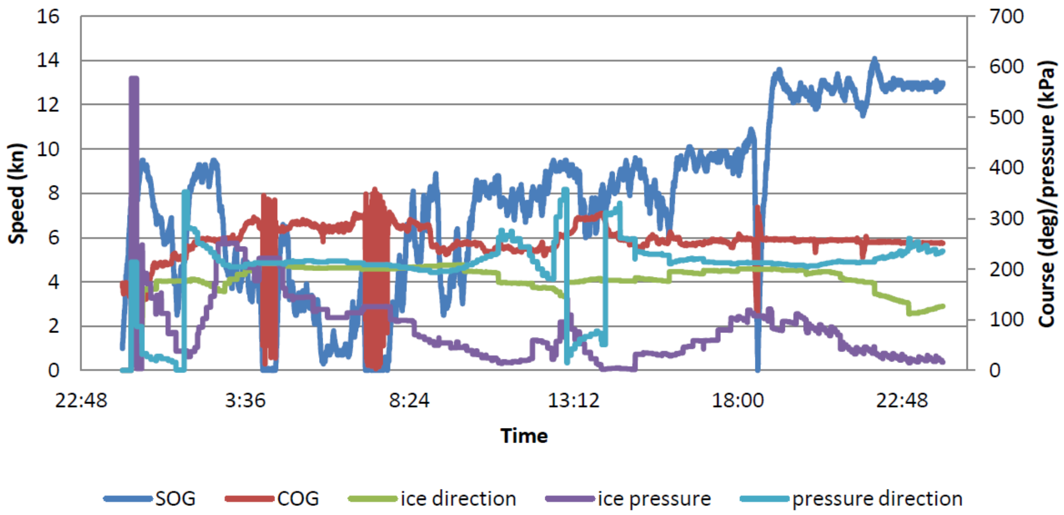


Figure 4. Speed and course over ground of MT Tempera with forecasted ice movements on the 6th of March (Anders and Suominen, 2011)

SHIPS IN COMPRESSIVE ICE: ICE LOADS AND RESISTANCE

Ice loads on a beset ship

There are two different scenarios depending on ship's motion, i.e. whether the ship is moving or not. The first scenario is that a ship is standing still (e.g. stuck) in a compressive ice channel, where the ice sheet moves against the ship and the broken ice pieces are accumulated against ship hull. To investigate the ice loads under this scenario, the project 'a ship in compressive ice' was conducted in 1990s. Kujala and Kuuskoski (1992) conducted model scale test on this scenario and later Kujala et al. (1993) proposed a theoretical model to calculate the ice-induced loads. According to the result, ice fails firstly by crushing. After a certain time, the broken ice pieces accumulate above and below the ice sheet, and produce vertical force on the ice sheet due to the weight. The force grows until the weight is high enough to break the ice by bending, which is the time point where the peak load is achieved. After the bending, the force drops to a lower level and grows again until the next bending failure. Therefore, the ice loads show periodic pattern. Figure 5 presents an example of the result, where the x-axis is the distance which ice moved and y-axis presents the load on ship hull. The interaction process is similar as an ice sheet moves towards a fixed vertical structure, which is relatively more researched. According to Timco (2007), ice sheet can fail by crushing, bending and buckling when interacting with a vertical structure. Since in this scenario the ship is standing still, ice load is the main problem while ice resistance does not

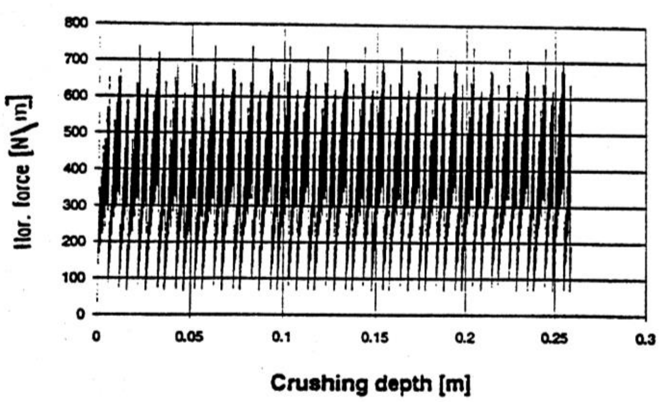


Figure 5. Ice loads history on ship's hull (Kujala et al. 1993)

exist.

In SAFEWIN project, model scale test was conducted in the ice tank of Aalto University to investigate the additional resistance to the ship and ice loads on ship's hull in compressive ice channel (Suominen & Kujala, 2012). The ship under test is bulk carrier *Credo*, which has long vertical parallel midship. A video camera is installed at the bow shoulder and another at midship to record the ice failure process. There was one test conducted for a beset ship being compressed by the incoming ice sheet. Figure 6 presents photos of the ice interaction with the ship at the midship area. As shown in the video, the contact start with a buckling failure of the ice sheet (Figure 6a), followed by a series of bending failure which creates more and more ice cusps. These ice cusps are turned, re-broken and transported against the ship hull and gradually accumulates. The height of the accumulated ice cusps stopped increasing after about one minute and then remains relatively constant. After that, it is hard to see whether the ice sheet contacts the ship hull or not, since the ice cusps pile in front of the ship hull. However, the breaking of ice sheet can be indirectly identified. This is because periodically, the height of the accumulated ice increases gradually and then drops suddenly. This indicates the failure of the ice sheet. The magnitude of height change is quite small in the periodic process. Figure 7 gives the time history of the compression force on the pressure foil at midship area, where the periodic pattern is clearly seen.

(a) (b)

Figure 6. Ice compressing ship hull (a) beginning of the contact (b) 1 minute from the beginning

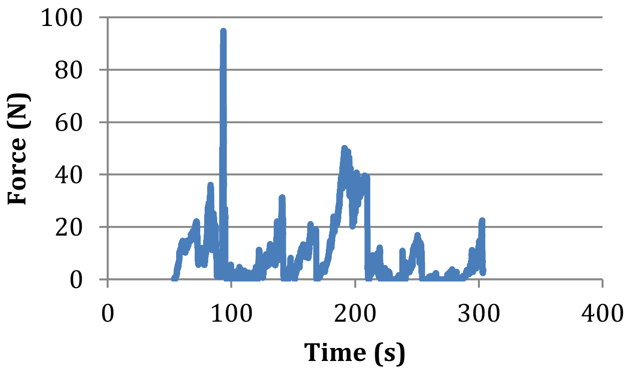


Figure 7. Ice force on the pressure foil at midship area

Ice resistance on a moving ship

The second scenario is associated with a ship moving in a compressive channel. In this case, ice resistance becomes an important factor determining whether the ship can go through the channel without getting stuck. Since the ship is moving, the broken ice pieces cannot considerably accumulate against the ship hull. Therefore, the interaction of these ice pieces with structure is much less for a moving ship than for a beset ship.

In SAFEWIN project, model scale tests were conducted systematically to investigate the additional resistance on ships due to the compression of dynamic ice. Figure 8 presents the test arrangement during SAFEWIN model test. A level ice test is conducted as the first test, followed by a compressive level ice (static compression) test, which creates an ice channel. The ice sheet is then split into two sheets. A pusher is installed at the end of one sheet and pushes the ice sheets to close the ice channel. Then the ship is towed by a winch to travel through the closing ice channel. The towing force is measured as the total resistance R_{total}. The ice channel resistance R_0 is also measured in some tests by towing the ship through the ice channel without pushing. The additional resistance R_{add} is then calculated as the difference between R_0 and R_{total}. In addition to resistance, ice loads are measured by an ice

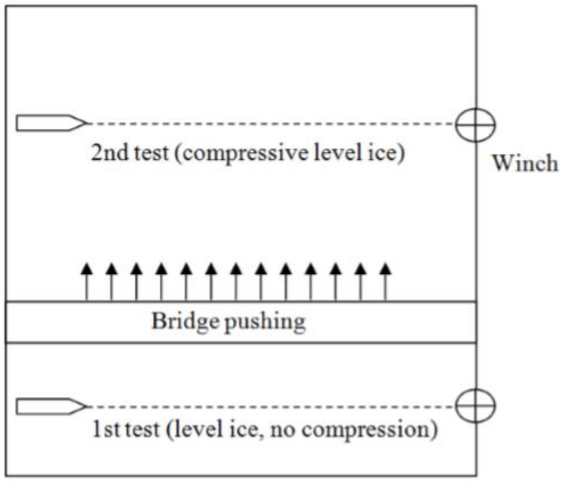


Figure 8. SAFEWIN test arrangement (Suominen & Kujala, 2012)

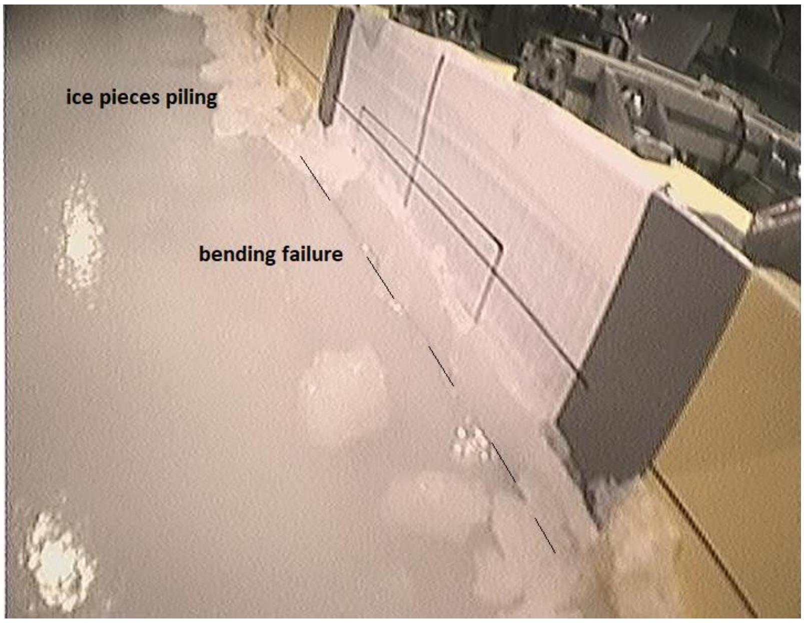


Figure 9. A typical bending failure when a ship is moving in a compressive ice channel. The black dashed line illustrates the bending crack location.

loading panel and pressure foil. The measured areas are the bow shoulder and midship area.

The model test was conducted with ice thickness ranging from 0.023-0.041m. Figure 9 presents a photo from the camera showing ice failing at midship area. It clearly shows a bending failure in process where a long ice piece is detached from the intact sheet and turned against ship hull. After going through all the videos, several conclusions can be drawn based on the observations:

a) With the ice conditions in the test, ice commonly fails in crushing-bending mode both at bow and at midship area. Considerable bending failure are observed in most of the tests.

b) Buckling failure is very rare compared to bending.

c) The vertical motion (heave, pitch and roll) of the ship is clearly observed and present for almost all time. It may be reasonable to assume this has considerable contribution to the bending failure.

d) When the ship is moving, many ice pieces can be seen on top of the ice sheet (see Figure 9), but much less than the case when the ship is beset (Figure 6).

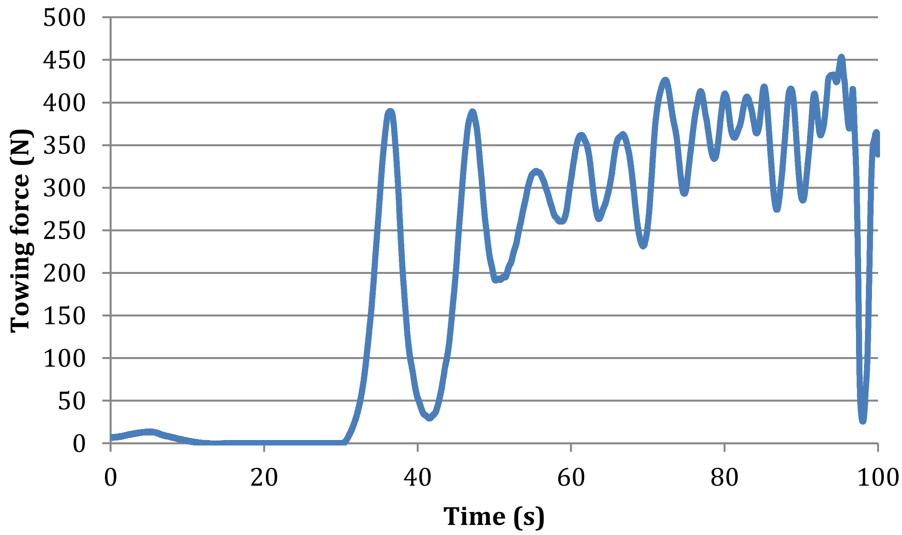


Figure 10. A typical time series of towing force in a closing ice channel

Figure 10 shows a typical time series of the towing force in a closing channel test. The towing starts at 32nd second, which accelerate the ship to a desired speed. The channel then starts closing at around 41st second, which increase the resistance and therefore the towing force. The channel gets closed at around 80th second and after that remains closed. The towing force then levels up until the end of the test.

Figure 11 presents the measured resistance in a static channel and in a closing channel for different ice moving speed. The chart is made based on the measured values by Suominen & Montewka (2012). It shows that there is considerable additional resistance due to ice compression. The additional resistance can be as large as twice of the ice channel resistance. In addition to closing channel test, the researchers also conducted test in closed channel, in level ice and in level ice with static compression. From the results, we can draw following conclusions:

a) Static compression does not lead to additional resistance.

b) Closed channel does not lead to much additional resistance.

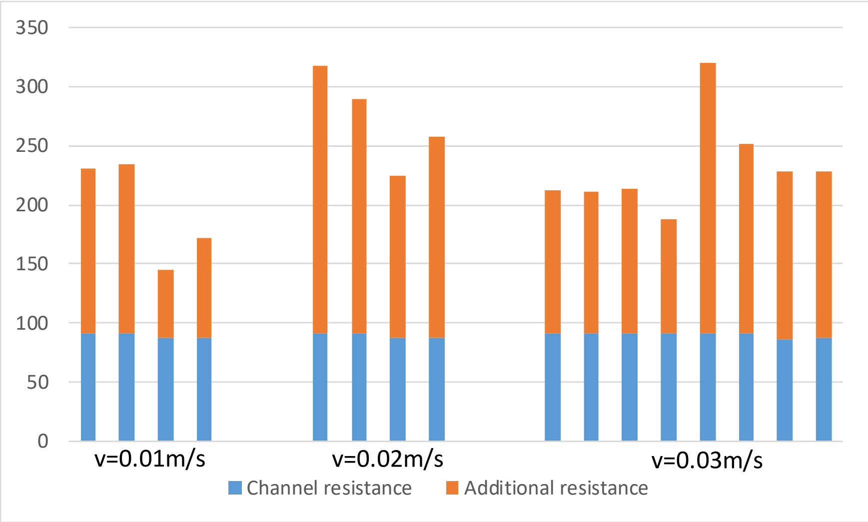


Figure 11. Resistance decomposition of the model test results in compressive ice channel

c) Ice resistance increases when ice drifting speed grows from 0m/s to 0.02m/s, but levels up when the speed further grows to 0.03m/s.

As already mentioned, the ship resistance in compressive ice channel R_{total} can be decomposed as the resistance in ice channel R_0 and the additional resistance due to moving ice R_{add}:

$$R_{total} = R_0 + R_{add} \tag{1}$$

R_{add} can be further divided into the resistance due to the interaction at ship's bow and that at midship (Figure 12). The former is similar as a ship going through level ice, where the ship crushes and bends the ice downwards, after which the broken ice pieces are turned and submerged until those are cleared from the ship (Li et al. 2019). The latter is different because in midship area the ship hull is parallel to ship moving direction, therefore the ice resistance comes mainly from ship-ice friction arising from the contact. The hulls of many ships in midship area are vertical, making it much more difficult to develop the crushing force to fail the ice by bending compared to the bow area. The friction resulting from the crushing force at midship area leads to large additional resistance, which is likely to be the main component of R_{add}.

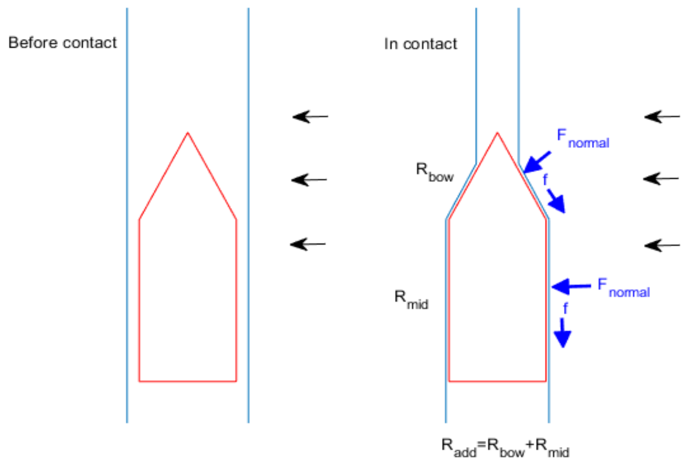


Figure 12. Resistance decomposition for a ship in compressive ice channel

MECHANICS OF SHIP-ICE INTERACTION IN COMPRESSIVE SITUATION

According to the aforementioned observations from SAFEWIN project, crushing and bending failure are the main failure modes at midship area. It is worth mentioning that even though the ship hull in midship area is vertical and thus perpendicular to the sheet, considerable amount of bending failure can still be observed. From the viewpoint of resistance, the presence of bending failure is an important factor determining how ship-ice contact is temporarily released until getting into contact again. When an ice piece fails by bending, crushing stops and the ship-ice contact becomes the turning of the ice pieces, which should be much less significant than the continuous crushing force. Therefore, it is crucial to understand how bending failure develops and how frequent it occurs. Timco (2007) observed the thickness dependence of ice failure mode and concluded that when ice thickness increases, bending and buckling become rare.

Leisti and Riska (2010) discussed the ice failure process at ship side in detail. To summarize, the ship-ice interaction starts with crushing of ice, along with flaking of the ice edge, which leads to the fluctuation of the contact force. Besides crushing, bending failure happens when the ice piles generated from crushing create enough out-of-plane force to fail the ice by bending. The force then drops significantly until the hull crushes the ice again. In addition, as mentioned in the previous section, according to the observation from the model scale test, the vertical motions (heave, roll and pitch) may also lead to considerable out-of-plane force, which contributes to the bending failure.

As another outcome of SAFEWIN project, a model was proposed to simulate the additional resistance. Kaups (2011) and Külaots et al. (2013) proposed the model, which firstly idealize the ice channel geometry and then numerically simulate the closing channel interacting with a ship. The model made a valuable step towards correct modelling of the process. However, it only takes crushing into consideration for midship area without bending failure, which rationally leads to too conservative estimation of ship speed. The ship may be then too easy to get stuck. Based on the above discussion, the bending failure should be present in the model in order to get realistic estimation of ship speed.

SUMMARY

This paper reviews the previous research regarding a ship in compressive ice field and discusses about the key issues influencing ice loads and resistance. Model test results are presented and analyzed for the understanding of the physical process. Compressive ice is found to be a common issue which causes considerable delay in transportation. Ice accumulation is an influential factor when a ship is beset in compressive ice channel, while the bending failure of ice sheet is found to be a key factor to calculate additional resistance.

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