SHIP – ICE INTERACTION IN SHIP DESIGN: THEORY AND PRACTICE

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Contents

Summary

There are three aims for this chapter; First, to categorize different ice types encountered by ships in cold regions, second, to describe different scenarios in an ice field a ship may experience and third, to present estimates of ice forces under different scenarios. This chapter serves to set the foundation for ship design for ice covered seas. When designing a ship the function of which is to operate in ice conditions, the designer needs knowledge of how ice is acting on the ship and how this interaction is modeled. The starting point of ship design is the description of what the ship must do. This is called functional specification and it describes the task of the ship and her performance – also in ice. Thus the design basis for ice capable ships is made by a description of ice conditions and other environmental factors pertaining to design. Further, the ship function must be defined and in order to gain insight of the functional requirements, a short description about the operational environment of ice capable ships is given. The ice action on ship or rather the ship – ice interaction (as when ship and an ice feature are in contact, the contact force depends on the response of the ship and ice) occurs in very many different forms. In order to aid the design, these interaction cases are usually categorized into some major ones highlighting the major forces and other ice actions. These are described in such depth that is suitable in gaining a qualitative understanding about ice action on ships. This chapter is followed by a description of the major design features that are based on understanding of the ice action.

1. Introduction

Ship design begins with defining of the tasks that the ship must perform. These tasks include the required operation, such as dredging, towing or transporting certain types of goods, the intended operational area for example Beaufort Sea or Kara Sea, and the required operational performance, such as extended summer operation in the Beaufort Sea or year-round in the northern Baltic. These requirements are stated in the functional specification of the ship that is developed by – and sometimes for - the ship owner. The size of the ship (displacement and deadweight i.e. payload and consumables) and other main particulars like machinery arrangement follow after the functional requirements are specified. The amount of transported cargo and the work the ship must perform together with the required speed, equipment, accommodation and operational periods determine, within limits of rules and regulations, these main particulars.

If the ship is to operate in ice, this must be taken into account in the early design phase. Design for ice capability influences all the ship characteristics: the hull shape and main dimensions, hull strength, machinery and equipment. If the requirements on ice capability are not very high because the operation is limited to thin ice conditions or occasional entry during early winter in ice covered waters, then it is sufficient to design the hull shape based on open water performance and in strength issues follow rules of classification societies or other regulatory bodies. Design of ship hulls intended for heavy ice conditions and regular traffic in ice is based on taking the ice action more explicitly into account. Even these ice going ships of high ice performance can be designed based on rules but sometimes a direct approach to design is used. This direct approach to design is started by defining the ice conditions and is then followed by estimating the adequate performance and strength in ice based directly on the defined ice conditions.

The direct design requires quantitative knowledge of the ice conditions in the operational area, in a form that can be used in designing the ship performance and strength. It also requires a quantitative description of the intended ship operations. This broad knowledge base required in direct design of the ship hull is illustrated in Fig. 1. In principle all factors influencing the final design must be known, especially when following a direct design path. This is impossible in practice and thus the actual design at best is a mixture of direct and conventional methods. Conventional design is based on knowledge from earlier designs. Ice model tests are also conducted for ships that will perform ice breaking tasks. Ice model testing is used to finalize the hull shape design and also check the propulsion requirement.

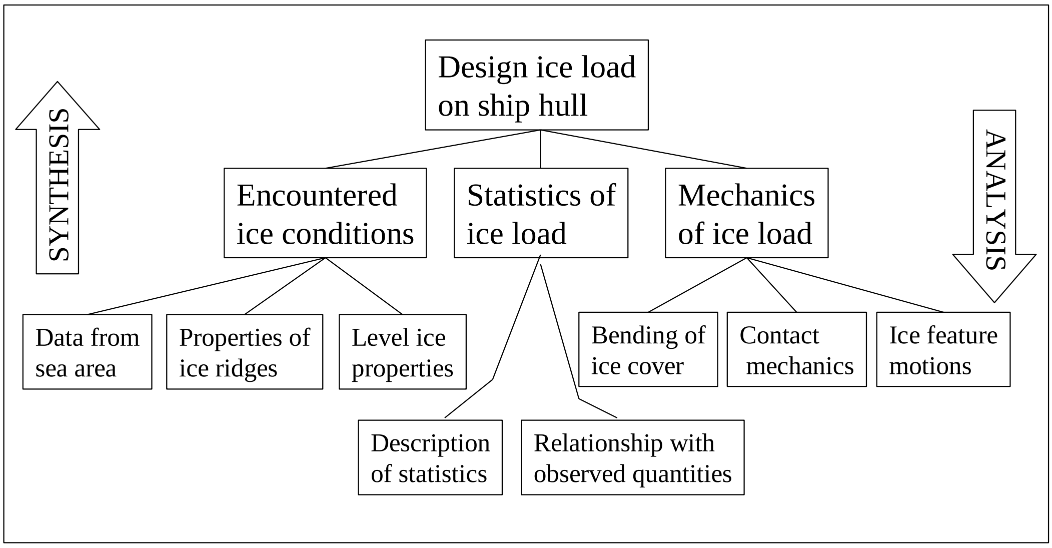

Fig. 1. The constituents of determining the ship hull ice loading for design.

The design for ice capability includes three aspects: firstly the ship structures must have an adequate strength, secondly the performance of the ship in ice must meet the functional requirements and thirdly the ship systems and equipment must function in the temperatures (or more generally - climate) encountered in the operational area. The ship hull and hull girder must be strong enough under the ice loading. The propulsion machinery and propeller shaft line must also have adequate strength to withstand the ice impacts. Strength design includes also checking for the fatigue strength, even though the ice-induced fatigue has not been a major problem for ice capable ships. Finally, structural design for ice includes checking on the vibration response to ice loading and noise transmission. The vibratory and noise response are different from those in open water conditions as the excitation in ice comes mostly from the bow which experiences the ice impacts.

The performance of an ice capable ship is evaluated by its forward speed under the design ice conditions. For many ships the speed astern is also a design feature as ships that are stopped by ice must go astern in order to either ram again or deviate from the direct route in search of easier ice conditions. An ice capable ship also needs to meet the requirement for the machinery to provide the required propulsion thrust in ice. These stated requirements influence the hull shape design and machinery design. Furthermore, in order to ease the operation in an ice field for the crew, the bridge design needs special attention for clear visibility to ship sides and astern.

The ship’s systems and equipment must be able to function in cold temperatures. This requirement applies to deck equipment, such as mooring winches, cranes, and cargo hatches, and to navigation and emergency equipment, such as life boats and fire fighting equipment. Operation in cold weather places also requirements for the general arrangement, especially for areas and spaces that are exposed to icing, snow and rain. Bridge, mooring equipment and lifting apparatus must be designed to guarantee adequate visibility. The construction materials for the ship hull and for all the exposed equipment must have proper strength and integrity in low temperatures. Common problems such as the brittleness of materials under low temperatures must be overcome.

In this chapter the major ice induced challenges on ship design are described. The actual design of ice capable ships will be the topic of the next chapter. The description in this chapter is qualitative and more formal physical description using the exact mathematical formulation is not given, with the exception of two cases. First is the description of the ice forces in general and second is to show a more detailed example how to calculate the ice force. These two cases serve the purpose of illustrating the main difficulties in determining the ice loads and also the effect of dominant parameters.

2. Ice and Weather Conditions

The description of the ice conditions in a way that is usable in ship design differs from the geophysical way of describing ice. Thus it is instructive to see how a ship designer views the ice conditions. The ice covered seas are located mostly in the high northern or southern latitudes (Arctic and Antarctic) where the temperatures are low and also the daylight hours are short in winter. Sea ice can, however, be found in surprisingly low latitudes like the Caspian Sea, Sea of Azov and the Bohai Bay. The main weather parameters that form the design basis for ships include:

- Description of ice cover;
- Sea and air temperatures;
- Winter or rather ice season lengths.

The natural ice cover is commonly dynamic because of the driving forces that are caused by the drag of the winds or currents. The driving forces break the ice cover, create leads when the ice field is diverging or ice rafting and ridging when the ice field is converging. Thus ships navigating in the middle of the sea basins very seldom encounter level ice. The ice ridges constitute the largest obstacle for shipping as even smaller ice ridges stop a merchant vessel. The ice ridges have a triangular or trapezoidal cross section, the largest ridges being about 30 m thick. A typical sea ice field is thus composed of some portion of level ice and open water with ice ridges scattered among the relatively level ice. Fig. 2 shows typical sceneries from a first year ice sea area – Fig. 2a is from the most northern Baltic, the Bothnian Bay, where strong winds often produce an immobile ice field. Fig. 2b is from the Gulf of Finland where of the ice coverage is not 100 % and the ice cover is more mobile.

Fig. 2a. A heavily ridged ice field in the northern Baltic.

Fig. 2b. More open sea ice cover with ice ridges, level ice areas and open water patches, a view from the Gulf of Finland.

The ice motion creates different zones of ice. Close to the shore is the fast ice zone where ice is not broken and stays stationary due to the support of the outer islands or a grounded ridge zone. In some coastlines this zone is extensive (for example the Pechora Sea in Russia) but in steep coastlines without islands, this zone may be negligible (like north-eastern coast of Sakhalin). Outside of the fast ice zone ice cover is broken and moving. The zone where the effect of the coastline is felt is called the transition zone. Examples of this kind of seas are the Beaufort Sea (Beaufort Sea gyro pushes ice against the northern coast of Alaska) and northernmost Baltic (westerly winds push ice against the Finnish coastline).

In those transition zones where ice cover is often converging, the ice coverage tends to be 100 % with heavy ridging. If the ice is diverging in the transition zone (like in many Antarctic seas) the coverage tends to be less and ridging less intense. The ridge size in the transition zone is stochastic. The statistics of ridges has been studied much and most often it is concluded that the ridge size (and density) follow an exponential probability distributions.

Finally, outside the transition zone is the pack ice zone. Some scientists state that the only pure pack ice zone is formed in the Arctic Pack – it is however difficult to see the difference between the transition zone and the pack ice zone and anyhow this difference does not matter for ship design. These different ice zones are illustrated in Fig. 3.

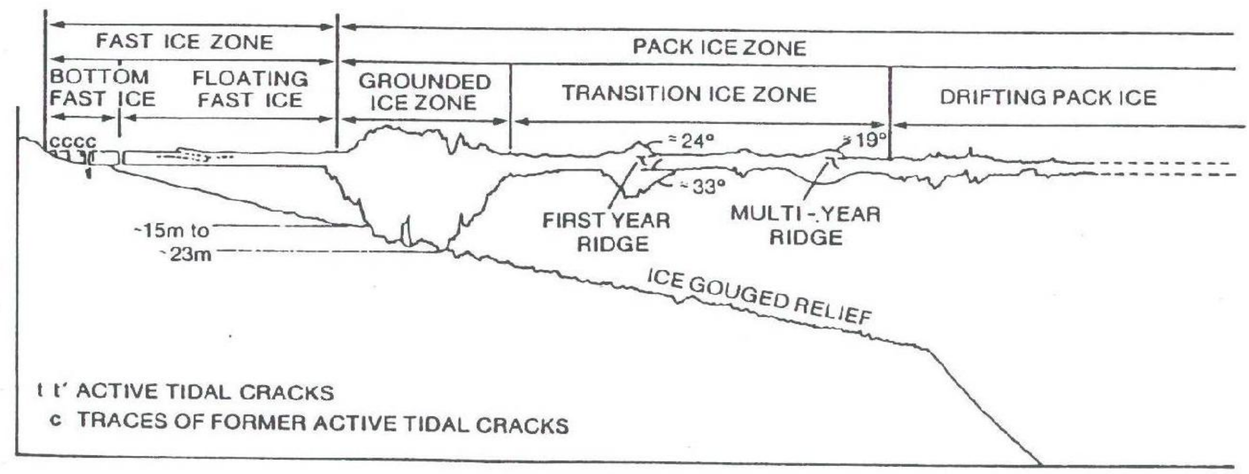

Fig. 3. The ice zones in a sea ice cover (Icex 1979).

Ice parameters

A ship sailing through a natural first year ice cover encounters thus level ice, open water and also penetrates ice ridges. The description of ship transit through this kind of ice cover requires the following data:

Coverage of ice	C	Portion of sea surface covered by ice (given usually in tenths of ice area relative to the total area)
Level ice thickness	h_i	If there are several different thicknesses, these are given versus the coverage of each thickness
Average maximum thickness of ice ridges	H_R	This thickness usually ignores the part above water which is called sail
Density of ridges	μ	Number of ridge sails along a straight route segment (in units of ridges/km)

Typical ice coverage in stationary ice cover is about 90 % and maximum level ice thickness typically in first year ice areas is 1 m (Baltic) and 2 m in the Arctic. Average ridge thickness in the

Baltic is about 5 m whereas the ridge density varies from 4 to 10 ridges/km. If the average ridge thickness is more than 10 m, the ice conditions can be considered severe.

The most important single ice parameter for ship design is, however, the existence of multi-year ice. For many sea areas it is clear that multi-year ice does not exist at all as all ice melts during the summer (Baltic, Okhotsk Sea, northern Caspian Sea, Sea of Azov, St. Lawrence Seaway) and in some other areas it is clear that multi-year ice must be reckoned with (Beaufort Sea, Baffin Bay, Russian eastern Arctic seas like the Laptev Sea).

If ice survives the summer melting season, multi-year (MY) ice is created. When level ice starts to melt during summer, the salt (brine) present in the ice cover drains into the sea water while the ice mostly melts on the surface forming melt ponds. When temperatures turn cold again, ice starts to freeze from the bottom. This cycle of freezing and melting quickly reaches an equilibrium thickness for multi-year ice at about 1.8 to 2.5 m. Only a few cycles are required to reach the equilibrium, and it has been stated that no layer in MY ice is older than about 20 years. When a first year ridge survives the summer melt, the voids in the ridge get filled with fresh water and the sail melts. This produces slightly wavelike top and bottom surfaces – and quite uniform thickness, typically somewhat in excess of 5 m. These multi-year ridges can be quite large in horizontal extents, several hundred meters across.

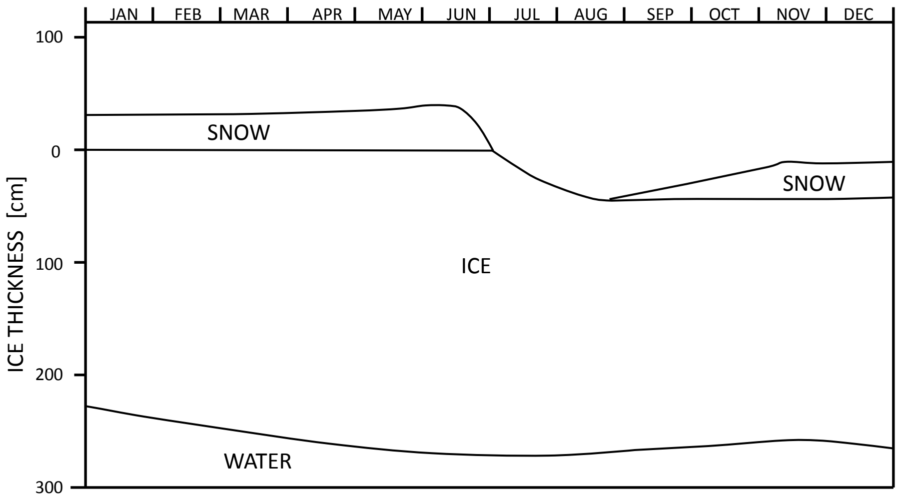

Fig. 4. Calculated example of the equilibrium cycle for Arctic sea ice (after Maykut & Untersteiner 1971). The thickness is not corrected for hydrostatics.

The requirements for ice performance given in the functional specification include usually the maximum level ice thickness where the ship can proceed continuously. As the ice resistance in level ice fluctuates in time based on the ice breaking pattern (more about this later), ships cannot maintain a very low speed continuously but get stopped when the ice resistance experiences a local peak. The limiting ice breaking thickness is given as the thickness where the ship can keep a continuous speed; usually a three knots speed on average is used as the minimum possible continuous speed – and the ship performance requirement is defined accordingly, for example it may be required that the ship makes 3 knots in 1.5 m thick level ice. Often, however, this requirement is supplemented with a requirement of higher speed in somewhat thinner ice, for example 8 knots in 80 cm thick ice.

As even the average size ridges cause a high resistance, higher than the ship thrust, ships must penetrate ridges by using their inertia. The capability of ridge penetration can be given as a requirement (certain size of ridge should be penetrated with one ram having a certain initial speed). The level ice performance is easy to verify in full scale and thus ridge penetration and level ice performance are sometimes coupled by using the so called equivalent level ice thickness. In the simplest terms, this is the average thickness of all ice in the area. Assuming ridges to be of triangular cross section with a 25^o base angle, an equation for the equivalent ice thickness, in terms of the quantities described above, can be derived from the ice cover cross section as

$$H_{eq} = (C - 4.28 \cdot \mu \cdot H_R) \cdot h_i + 2.14 \cdot \mu \cdot H_R{}^2 .$$

This equivalent ice thickness is used to describe the ship performance in the general ice conditions where the ridges are smaller than those that would stop the vessel.

The snow cover on top of the ice has an effect on ship performance but not noticeably on the ice loads. The reason for this is that snow influences the frictional forces. If the ship bow is very flat, as it often is for ships with good ice breaking performance, the effect of snow is amplified. There are no rigorous ways to take the snow cover into account and the present common practice in level ice performance descriptions is to use an equivalent level ice thickness, h_{eq}. This is obtained from the level ice thickness h_i and the snow thickness h_s as

$$h_{eq} = h_i + \kappa \cdot h_s ,$$

where the coefficient κ is commonly set at about 1/3.

Icing

Low temperatures must be taken into account in ship design; temperatures in higher Arctic can often be close to -40^{o}C, see Fig. 5. Low temperature influences the construction materials and also poses requirements for deck machinery, accommodation and main machinery. Typical requirement is that the ship must be able to operate in a temperature of -35^{o}C. Here the temperature should be defined carefully as many temperature definitions, especially what comes to the definition of the average, exist. The average temperature in Fig. 5 represents the daily average temperature averaged first over the stated month and then over the year range. The sea water temperature is needed in defining the ship cooling systems, commonly -2^{o}C is used.

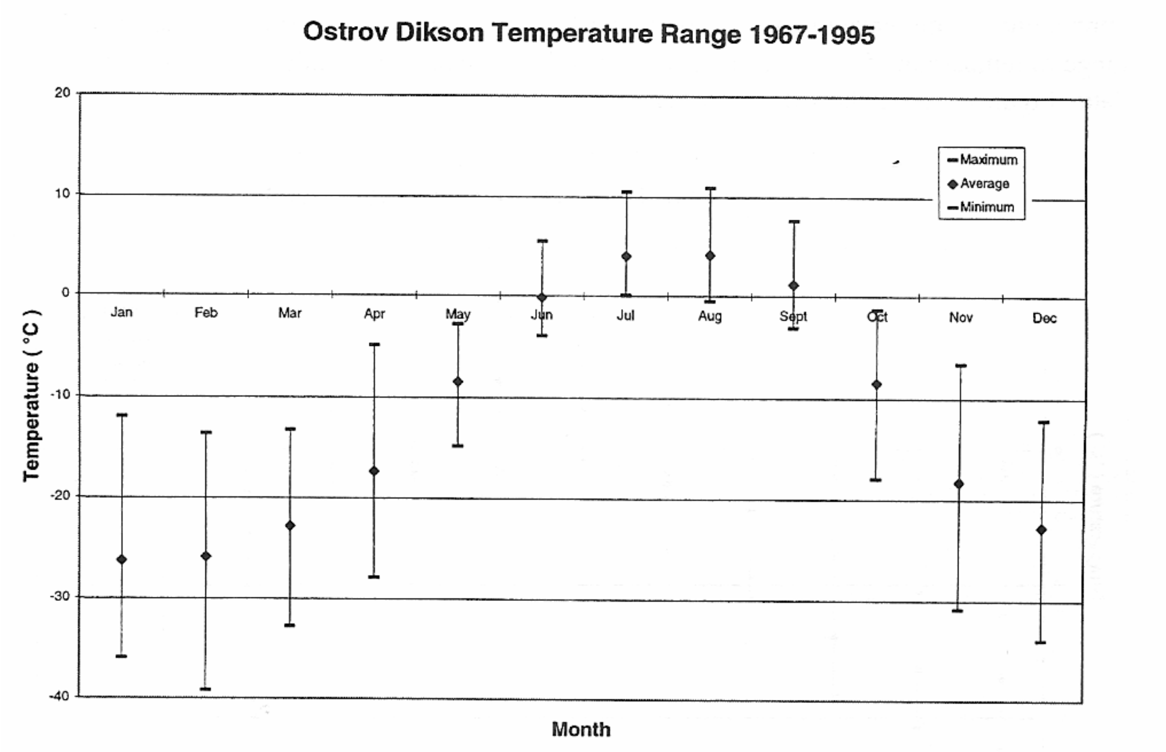

Fig. 5. An example of the annual temperature range in the Arctic areas (Kennedy & Patey 1997).

In low temperatures when there is no ice cover, the sea spray can freeze on decks and superstructure as Fig. 6 shows. The spray is generated by the ship bow wave and slamming, and it is blown onboard by the wind. Thus the wind direction ±45^o from the forward direction causes most intense icing. Operational measures like changing course or speed are best ways in avoiding icing but also proper design reduces the icing.

Fig. 6. Icing on the deck of a tanker (photo Mari Hoikkala).

The visibility is often restricted in ice covered seas. Reduced visibility can be caused by rain, snow or fog. In high latitudes also the daily period during the winter when sun is above horizon is limited and most of the operations must be performed under darkness. Measures to improve visibility are particularly important in designing the ship's bridge. Fig. 7a shows operation under darkness and Fig. 7b shows the day light hours in three northern locations.

Fig. 7a. Icebreaker operating in ice under darkness.

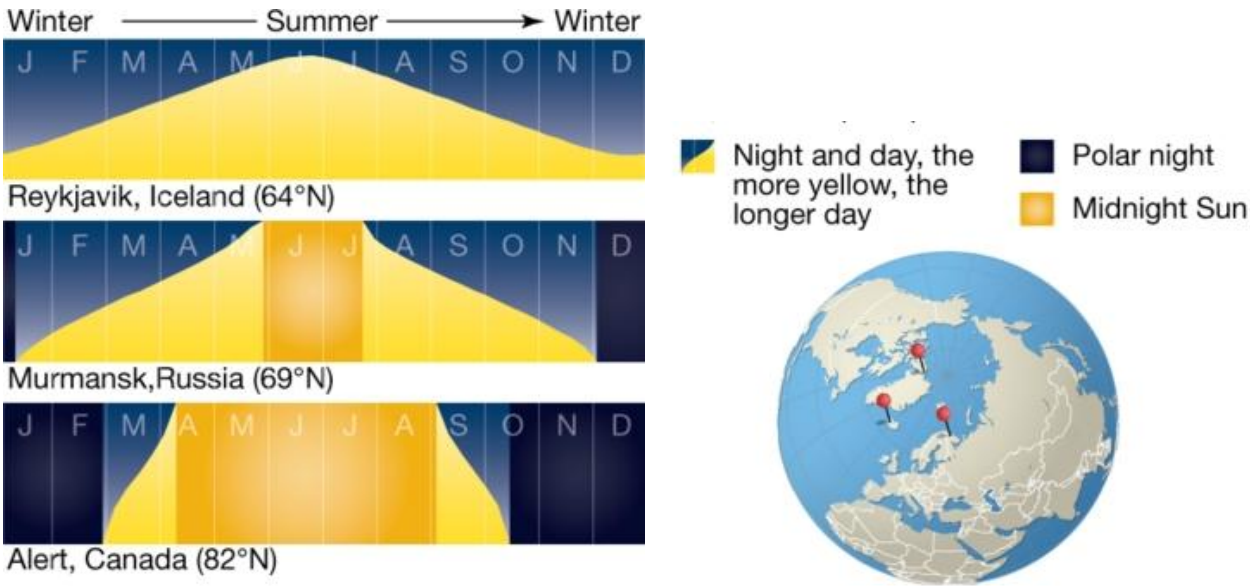

Fig. 7b. Day light hours in northern locations (www.maps.grida.no).

3. Ice Operations

An insight where and why ice capable tonnage is needed can be obtained once the driving force of the operations in understood. Thus a short description of the operational environment of these ships is given. Most of the needs for ice going ships can be traced to two operational environments.

There are two operational areas where merchant ships regularly encounter ice – as compared to some sporadic voyages through ice in Arctic and Antarctic regions. In the Baltic the trade has operated for more than a century year round to Finnish, Swedish, Estonian and Russian ports. Also the winter navigation in the Great Lakes and St. Lawrence Seaway has long traditions. At present the winter trade is increasing in the Okhotsk Sea and the Russian western Arctic – especially the trade to Norilsk through the southern Kara Sea should be mentioned. Characteristic for this regular winter trade is the use of icebreakers in escorting the shipping and the use of ice classed merchant ships of all types. In areas where only occasional visits are made, usually no icebreaker service is offered.

The other commercial area where ice operations are common is related to offshore – mainly hydrocarbon exploration and production in ice covered seas. In offshore operations, apart from ice capable drilling and production platforms, many different types of ships are needed like ice breaking supply ships, ice capable construction vessels, ice management ships etc. These two areas are described here briefly.

Winter navigation systems

The year round maritime trade is essential for those countries with harbors which are icebound part of the year. In these areas the whole maritime transport infrastructure must be able to cope with ice and low temperatures. This requires ice capable fairways and fairway markers, merchant ship tonnage that is ice capable and icebreakers to escort the merchant vessels. The merchant vessels operating in sea areas with seasonal ice cover must compete during the summer season with open water vessels having lower propulsion power, smaller light ship weight (and thus larger payload capacity) and lower equipment standards – and the ice capable tonnage is clearly at a disadvantage in this competition. This disadvantage is alleviated by the use of icebreakers escorting merchant ships to/from ports. When the icebreakers escort the merchant ships, the ice strengthening and ice performance of these can be less than that of the ships that can navigate independently in ice.

The overall economic balance in a marine winter transport system between the number of icebreakers, strength and performance requirements placed on merchant ships and the number and type of merchant ships is a delicate one. Also the requirements placed by the maritime authorities have a role in this balance. Thus if higher requirements are placed on merchant ships, less icebreakers are needed as the merchant ships are more ice capable. On the other hand, if the merchant ships are close to open water ships, and thus cheaper to build and operate, more icebreakers are needed to ensure continuous traffic flow. The balance in the Baltic has been achieved by gradually adjusting the components in the transport system. Fig. 8 illustrates the interaction between the components of the Baltic winter navigation system.

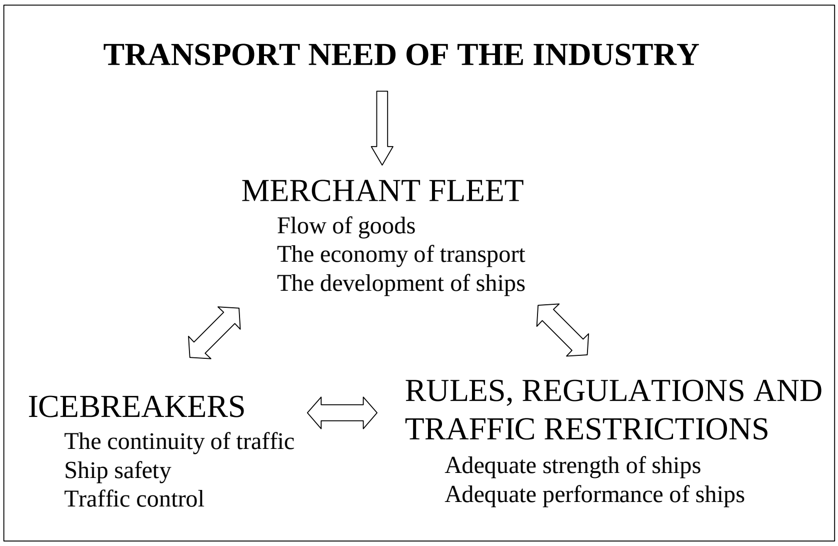

Fig. 8. The interacting components in a winter navigation system.

The different roles of the ships have an impact on ship design through the functional specification. All ships designed for some winter navigation system should fit into their intended operational spectrum. This brief analysis of winter navigation system shows clearly that three main types of ships with some ice going capability can be distinguished:

Ice strengthened ships

Ships, that have ice strengthening and some ice performance but need icebreaker escort in any heavier ice conditions. Most ice classed tonnage belongs to this category. The ship hull is usually designed for open water performance. These ships may have an awkward bow for ice breaking like a bulb.

Ice going ships

Merchant ships that do not need icebreaker escort and thus can proceed independently. The hull shape and strength is specially designed for ice. Machinery power is above those in open water ships. Capability to go astern in ice is needed in order to avoid getting stuck in ice. Only a few of this kind of ships exist (Norilsk Nikel, Norilsk-class multipurpose ships, MV Arctic, Umiak I, Lunni-class tankers).

Icebreakers

Ships that are intended to assist other ships in ice. These should be able to operate in all – even the most severe – ice conditions in the operational area. Icebreakers should not get stuck in ice. The concept of an icebreaker has diversified at present and more about this below.

The photograph below shows an often recurring view from the northern Baltic where an icebreaker is assisting some ice classed merchant vessels. These merchant vessels have typically an ice class IA or IA Super according to Finnish-Swedish ice class rules. This division into different types of ships intended to ice operations forms the basis of designing these ships. The operational spectrum of the ship according to her role in the winter navigation system sets all the functional requirements for the project ship.

Fig. 9. Ice strengthened ships (tanker, bulk carrier and a roro ship) and an icebreaker (MSV Botnica) operating in the northern Baltic (photo T. Leiviskä).

Offshore operations

The exploration and production of hydrocarbons from ice covered sea areas require ships for supporting and maintaining the offshore activity and also ships to transport the production (oil, LNG) to markets. The maritime transport system utilized in offshore production includes some main alternatives; a basic decision is whether to use ice going tankers or merely ice strengthened tankers with an icebreaker support. In the former case escort icebreakers are not needed. This alternative is being used in the Pechora Sea located in the Russian Arctic and the latter alternative in the Sakhalin area. Similar considerations apply to the offshore supply, construction and emergency vessels needed to support the production (or exploration). If the exploration and/or production are to operate year-round, high ice breaking requirements are placed on the support ships (as well as to the platforms). On the other hand, if the operation is seasonal or the ice conditions are relatively mild (like e.g. in the Bohai Bay in China), only ice strengthened tonnage is adequate. Fig. 10 illustrates the different types of ships needed at an offshore field.

Fig. 10. Ship types needed in offshore operations in ice covered seas – an example from Okhotsk Sea (photo Atso Uusiaho).

4. Ice Action on Ships

Understanding how ice and cold temperature acts on a ship is the basis for all design. The ice type encountered and the way ship is operated in ice determine the ship-ice interaction. The most demanding ship-ice interaction scenarios do not apply to all operational profiles; ships might not be required to encounter multi-year ice or might not be required to go astern in ice. The design for hull and propulsion machinery strength is based on evaluating the ship-ice interaction scenarios. Evaluating the different scenarios that a ship encounters in Arctic ice conditions is the basis of defining the different ice classes under the International Association of Classification Societies ice rules.

The ship may operate independently i.e. without any escort icebreakers and then she encounters all ice present in the operational area. Independent operation can be divided further into different operational scenarios; the ship may be on transit and then she can avoid the worst ice conditions. The encountered ice conditions are in this case less severe than the average conditions in the operational area. The maneuvering capability of ships transiting must be adequate in order to be able to avoid severe ice conditions. Ships that have to break ice for other ships or offshore platforms, like ice management ships or icebreakers, cannot avoid the worst conditions as especially fixed platforms cannot avoid ice that drifts towards them. When a ship is escorted by an icebreaker, the icebreaker breaks an ice channel the width of which is determined by the icebreaker beam – usually the channel width is about two ice thicknesses wider than the beam of the icebreaker. Thus if the beam of the escorted merchant ship is wider than this channel, then the merchant ship has to break ice. Thus the beam of available icebreakers in the planned operational area is a design factor.

Definitions related to ice loading

Before looking at the different ship-ice interaction scenarios, some of the definitions pertaining to ice action are in place. An actual ship-ice interaction situation may consist of a combination of several different cases acting simultaneously and the designer must form, at least qualitatively, a model of the ice forces from these scenarios. Here two distinctions are important. Firstly it is important for ship hull design to distinguish between global and local forces. For ship performance the distinction between average and maximum forces is important.

Local force refers to loading that is either a part of a single contact (the ice pressure on the considered area is important) or a total load on any single hull structural element (one frame, one plate panel). Thus the local forces (usually stemming from one interaction case) are important from design of the smaller hull structural elements. Global force refers to the total contact force from any one single interaction scenario such as impact on the edge of an ice cusp leading to bending failure of the ice sheet, or collision with a single ice floe. Global forces can also refer to the sum of all the ice loads acting simultaneously at the ship. Global loading is of importance in determining the strength of larger structural elements like double side structures or the hull girder.

The above description may be loosely formalized as follows. The ice pressure in one interaction e.g. impact with one ice floe is denoted $p(\bar{r})$ where $\bar{r}$ (location of points, bars indicate vectors) emphasizes that this pressure may be location dependent and especially nonuniform. The contact area in this impact is A_c, thus $\bar{r} \in A_c$. The nonuniformity of the contact ice pressure has been studied intensely in the 90's and some progress was made. This progress is still not sufficient to be applied in design and thus at present mainly two different approaches on ice pressure exists; the concept of the average pressure and the area A_c depending on the area (pressure-area approach) and the concept of crushed ice layer mediating the contact (the hydrodynamic pressure model). The total normal force to the area in question from one impact (denoted impact i) is

$$\bar{F}_{ni} = \bar{n} \int_{A_c} p(\bar{r}) dA ,$$

where $\bar{n}$ is the inward normal at the contact area. This formulation suggests at the difficulty of determining the frictional force, especially its direction (the magnitude of the frictional force can be assumed to be $F_\mu = \mu \cdot F_n$). The other difficulty is caused by the fact that the surface A_c can be curved – thus the normal changes direction in the contact area. This geometrical difficulty has been tackled only in case of normal load on a circular cylinder – in all other cases the contact area is assumed to be a plane represented by the tangent plane at the midpoint of the contact area.

Using these denotations, the local force acting on some subarea A of the total contact area is

$$\bar{F} = \bar{n} p(\bar{r}) A, A \subset A_c .$$

The global force can be the one stated above or the sum of all simultaneous forces (not mentioning the frictional forces)

$$\bar{F}_{TOT} = \sum_i \bar{F}_{ni} .$$

Ideally, the ship hull design could start from determining the local and global forces but this task is far beyond the present capability and knowledge. In some simplified cases the local force can be determined using semi-empirical methods i.e. making a simple theoretical model and determining the model parameters by fitting the calculated results to some measured results. This kind of load calculating methods exists for frame and plating loads for ships and the global loads pertaining to ship performance in ice. In the next chapters some simplified cases are described where the forces are estimated.

The definition of ship performance in ice is not based on the worst encountered condition (or largest encountered ice loads) but rather on an adequate average performance in 'average' ice conditions. Thus the ship is expected to get stopped in the locally worst conditions. The description of ice cover based on the equivalent ice thickness contains this idea of averaging. The basic case of all ice performance is sailing in level ice. Global ice loading is important in determining the ship performance in ice as the longitudinal component of global ice forces contributes to the ice resistance. The ice resistance is the time average of the longitudinal component of the global (or total) ice load. The maxima included in the time history of the ice load are not that important for performance as the ship inertia smoothens their effect.

As the ship performance depends on the ensemble of several contacts, the resistance forces are described in an average fashion by assessing the form of forces of various origins. This leads to a division of the resistance forces into components of similar origin. The most commonly accepted average forces are:

- Forces from breaking the ice;
- Forces from submerging the broken ice;
- Forces from friction along the ship hull (both ice pieces breaking and sliding along the hull);
- Hydrodynamic forces.

The breaking force is the largest of these accounted for about 50 % of the resistance in lower speeds.

The ship performance in level ice - either going ahead or astern or maneuvering - forms a yardstick of describing the ship performance Most of the qualities for good ice breaking performance are revealed in level ice breaking and a ship hull good in level ice is usually good in other ice conditions as well. Bow, stern and stern shoulder shapes – and the ship beam - are the most important ship properties for level ice performance.

The concept of ice loading from individual impacts can be extended to other ice conditions as well. If the ship operates behind an icebreaker, she must sail in a newly broken channel – this case is similar to operating in an ice floe field. Closer to land where the sea is shallow, the ice cover is immobile and the ships must follow fixed fairways. In the fairways the ice is repeatedly broken and refrozen; the result of this thermo-mechanical action is a brash ice field i.e. rounded ice pieces having a diameter about 30 cm. The brash ice layer can be quite thick; it is common that brash ice channels are more than 1 m thick in the Baltic. Unconsolidated brash ice behaves somewhat like a viscous fluid – thus the principles for hydrodynamic design are, with some restrictions, valid for brash ice performance.

The ice in pack ice cover is mostly broken and ridged. A ship sailing in pack ice must thus penetrate ridges. Ridges of even an average thickness induce high ice resistance, higher than the ship's thrust; and the ridges are consequently penetrated by using the ship's inertia. The same qualities that indicate good performance in level ice are valid in ridge penetration with the addition of ship's draught as the ship's cross sectional area to effect the energy consumed in ridge penetration. In case of ships operating independently in ice, the capability of extracting herself from a ridge where she has been stopped is important. Hence the capability to go astern or breaking the ridge by heeling tanks or bow propellers is required for ships that operate independently.

Ships are often stopped under ice pressure in converging ice fields. In this case ice is acting on the ship side and large forces are created. Whether this case of compressive ice is a design case of ships depends on the function of the ship. Ships that are intended to operate independently should be able to withstand compressive ice forces along the ship side but ice classed merchant ships depend usually on icebreaker escort and thus the icebreakers should be able to break ice before a compressive situation develops.

The analysis of a ship-ice interaction scenarios aims to determine the contact force during the interaction, this includes the maximum force for strength design and the time averaged force for determining the performance. Forces can be from inertial (rigid body and hydrodynamic), bending or crushing origin. Each of these forces requires individual analysis methods. It is important to understand the basic mechanics of each of the main ship-ice interaction scenarios. A thorough analysis of what kind of scenarios a ship may encounter contains more than 100 different cases. Here just the main ones are described.

Level ice

The most economic – and thus most common - way to break level ice is to break it by bending the ice downwards. Fig. 11a shows a side view of the forces acting on the ship with a landing craft bow when it is proceeding in level ice and breaking the ice by bending. In the beginning of each successive contact, the ice edge is crushed locally. When the contact area has increased enough to generate a vertical force component large enough to cause a bending moment in the ice cover that exceeds the bending strength of the ice cover, an ice floe is created by formation of a bending crack. The main forces acting on ice are the hydrodynamic support force from water, contact force (crushing force) and the frictional force opposing the relative motion. The hydrodynamic force arises when the water beneath the ice floe is displaced quickly. The hydrodynamic force is several times higher than the static buoyancy force as the bending cycle is short (duration is of the order of 0.1 s). This hydrodynamic reaction force is one of the sources of the ship velocity dependence of ice forces and ice resistance. The contact force is usually conveyed by crushing ice at the contact. The frictional force comes from ice floes sliding along the hull and also at the contact as the edge is pushed downwards. Fig. 11b shows a side view of the ice breaking process.

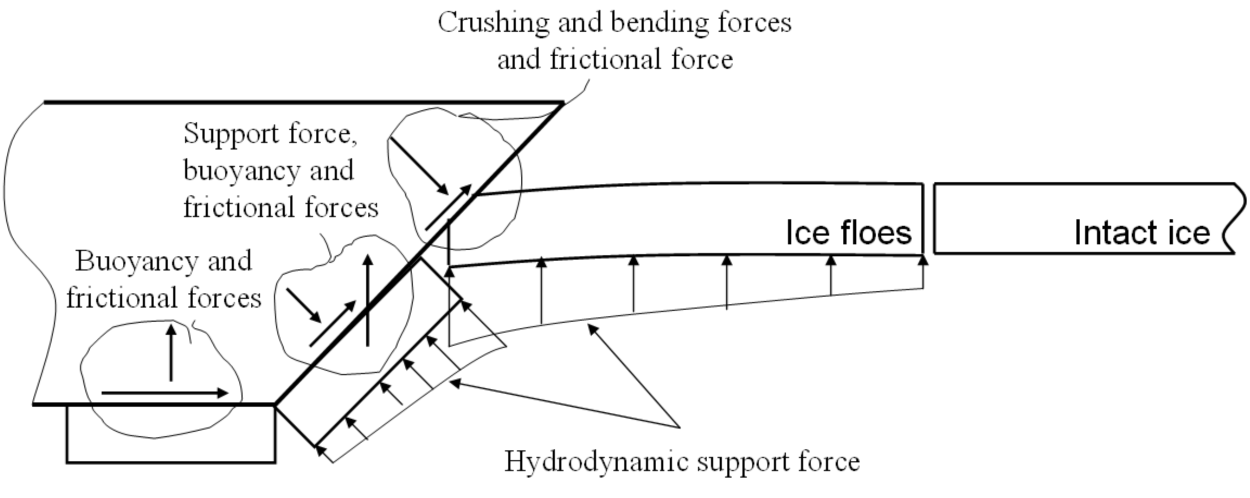

Fig. 11a. The forces in level ice breaking by a landing craft bow.

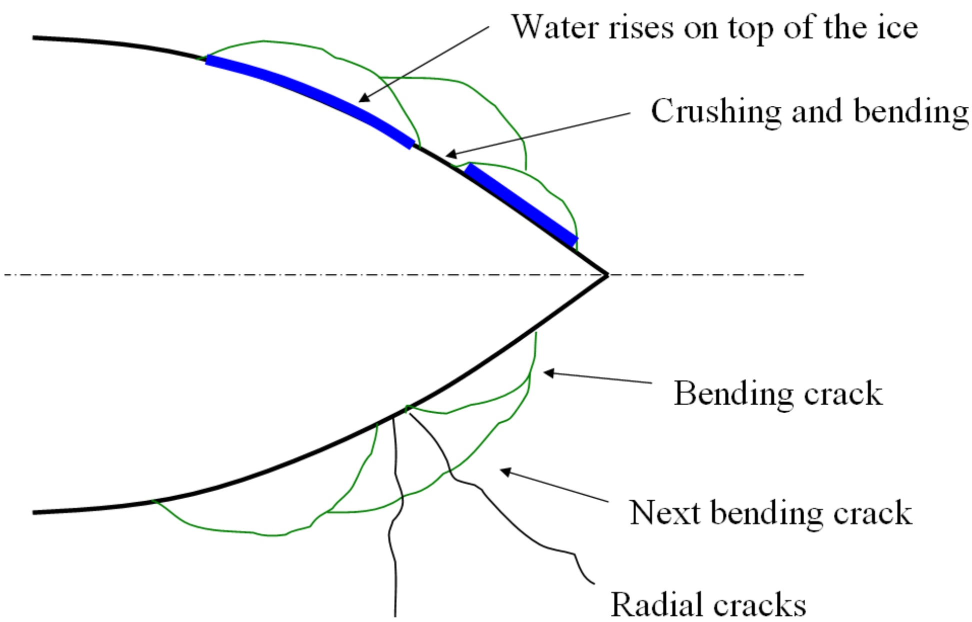

Fig. 11b. The breaking pattern in level ice created by the successive breaking of ice floes.

The ice floes broken off from the level ice cover by a normal ship bow are roughly semi-circular segments. The floe shape and repeated breaking creates a typical breaking pattern when a ship proceeds in level ice. The repetitive breaking pattern gives an insight to what kind of time history will the ice load on the bow have; the time history consists of a sum of triangular (with regards to time) force pulses, each corresponding to one ice floe breaking off from the intact ice sheet, see Figs. 12 and 13. At any one location on the ship hull, the frequency of the ice impact depends somewhat on ship speed and ice thickness, usually the duration of one ice impact is about 0.2 s and the frequency about 0.1 Hz i.e. one impact every 10 seconds. Along the bow, several ice pulses may act simultaneously.

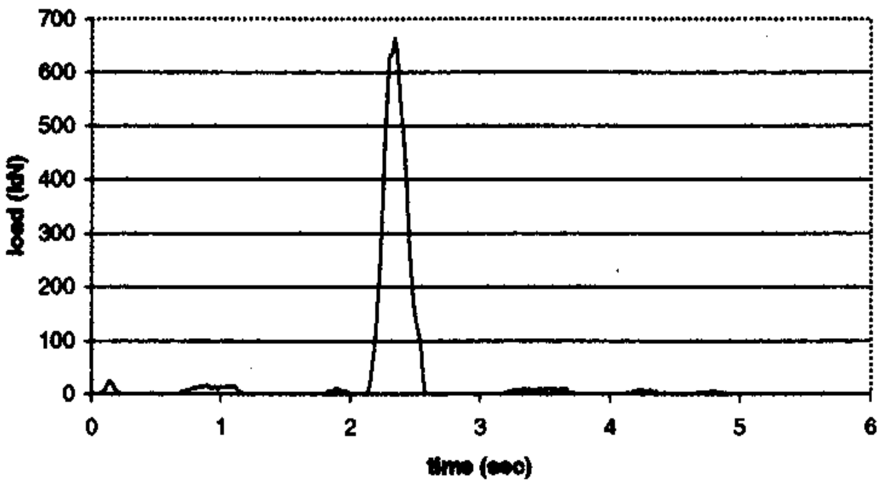

Fig. 12. An individual ice pulse acting on the ship hull.

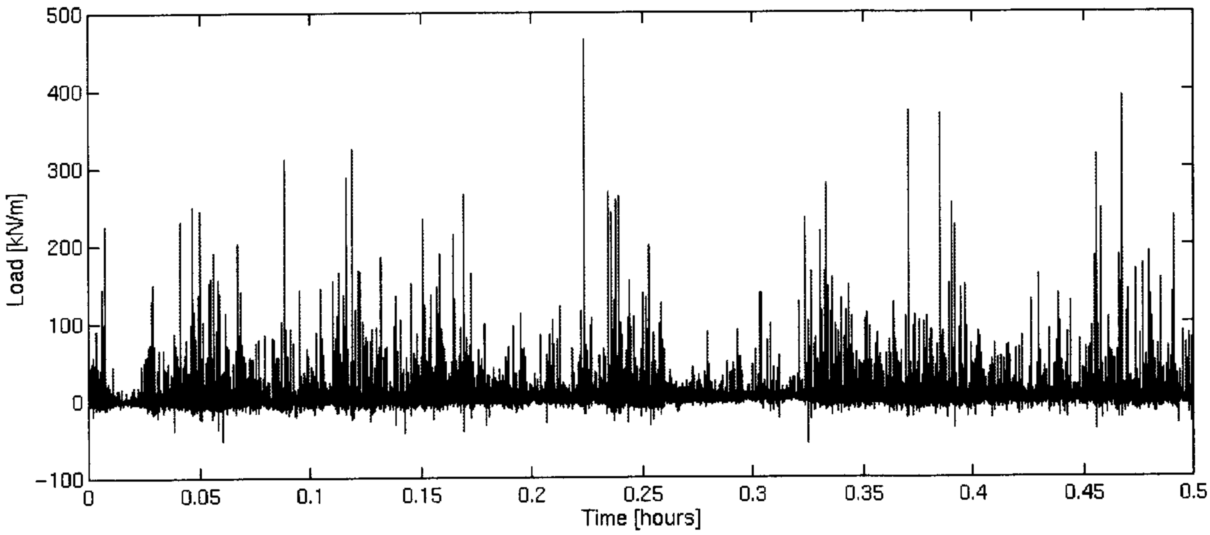

Fig. 13. Measured time history of the ice load acting on one frame at the bow of the ship.

If the ship is proceeding slowly, the hydrodynamic support force for the ice sheet is essentially a hydrostatic buoyancy force (proportional to deflection of the ice sheet and submerged volume) but at any speed larger than creeping speed (1 – 2 knots), the support force is dynamic. To describe the transient hydrodynamic force on the ice cover is the main difficulty in analyzing any question related to the ship progress in level ice. Several numerical approaches describe the problem but further investigation of this issue is necessary to gain an understanding of all the forces acting. Especially the influence of the water incompressibility and the related free surface problem has not been tackled.

The side view of ice forces given in Fig. 11a can be used to illustrate the determination of ice forces. Also a first estimate of the ice loads on ship hull as well as some insight of important design quantities is obtained. If the contact area between an ice floe and the ship is A and the contact pressure is assumed to be constant p_c (this is not the case generally but for present this simplification of constant pressure is enough), then the normal contact in direction of the ship hull outward normal is $F_n = p_c \cdot A$. The contact area is dependent on how deep the ship has penetrated into ice, and its increase versus penetration depends on the ice edge and ship geometry at the contact. Now, if the bow angle with vertical is β_n, the horizontal and vertical components (F_H and F_V) of the contact forces acting on ice are

$$\begin{aligned} F_H &= F_n \cos\beta_n + F_\mu \sin\beta_n \\ F_V &= F_n \sin\beta_n - F_\mu \cos\beta_n \end{aligned}.$$

If then the frictional force F_μ is assumed to follow $F_\mu = \mu \cdot F_n$, the dependence on the coefficient of friction μ becomes clear:

$$\begin{aligned} F_H &= F_n(\cos\beta_n + \mu \sin\beta_n) \\ F_V &= F_n(\sin\beta_n - \mu \cos\beta_n) \end{aligned}.$$

This equation shows that if the surface is rough (μ large i.e. more than about 0.1) the frictional force reduces the vertical component of the contact force which causes bending in the ice cover. The ice cover fails when the bearing capacity F_B is reached and thus larger normal force F_n must be applied with higher friction. The vertical bending component can be in a static case estimated based on the static bearing capacity of ice. The basic form of the bearing capacity is

$$F_V = F_B = C \cdot \sigma_f \cdot h_i^2$$

where σ_f is the bending strength of ice (somewhere between 250 to 800 kPa depending on ice temperature and salinity) and C is a constant depending on the ice floe horizontal boundary geometry, values between 0.25 to 1 have been suggested.

The horizontal force component is, on the other hand, increased when the frictional force component is taken into account – horizontal force is important as it contributes to the ship resistance through ice. If the ship hull shape i.e. angle β_n at the contact is such that the vertical force is nearly zero, then no net bending force is generated and ice cover is broken by local crushing of ice. This happens at an angle of about β_n = 8.5^o, if the coefficient of friction is 0.15 which can be considered as a typical value.

After the ice pieces are broken off from the ice cover, they are pushed down along the ship hull by the next floes. For a landing craft bow the ice floe follow straight trajectories but for a ship-shape bow the ice pieces follow first roughly the ship buttock lines but gradually the buoyancy force starts to make an effect which is pushing the floes upwards. This motion of ice floes is depicted in Fig. 14. The ship used in this figure is the Viking-class Swedish icebreaker.

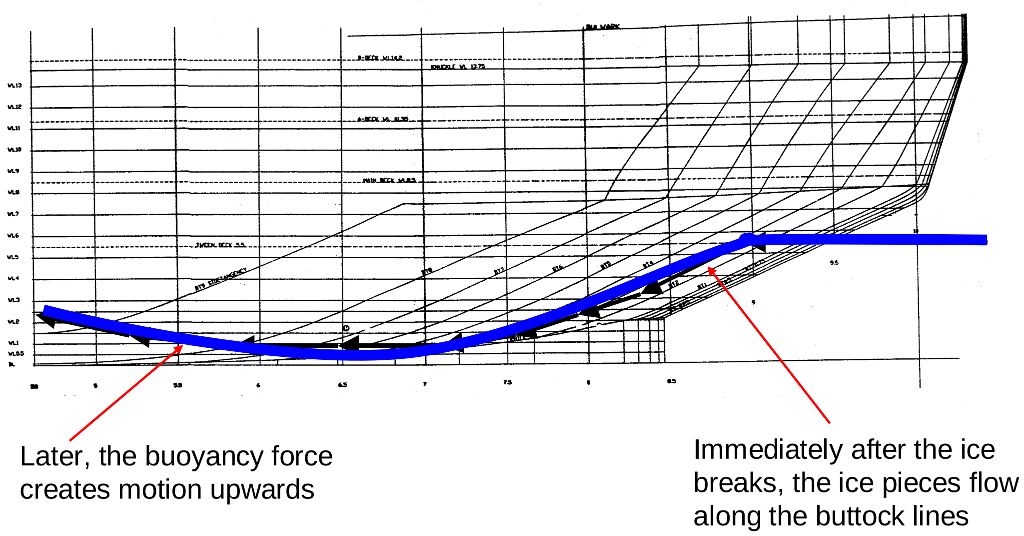

Fig. 14. The motion of the ice floes down along the ship hull.

If the ship is going astern in level ice, the ice is broken in a similar fashion by bending downwards. Floes broken in this fashion may encounter rudder or propeller. When the ship sails astern in ice, the propeller wash lubricates the ship hull as water gets between the ice floes and the ship hull and thus the ice resistance is reduced when going astern. Thus in thicker ice, ships with azimuthing propulsion (i.e. no rudders) may go better astern than forward. The actual ratio of the forward and astern speed in thicker ice depends also on the hull lines at the bow and stern. For icebreakers the capability to go astern is important as these ships must repeatedly break merchant ships they are escorting loose from ice. This takes place often by going astern by the side of the merchant ship. Thus capability to maneuver in going astern is important.

Turning in level ice

When a ship is turning in level ice, the ice breaking sequence at the bow is similar to that when going straight ahead. The main difference is that the rudder (or the azimuthing thrusters) creates a force that is pushing the ship stern sideways into the ice. Thus, if the frame angles are too close to vertical at the stern shoulder, then ice is not broken by bending at the shoulder and the ship is prevented making an efficient turn. This is illustrated in the Fig. 11 where the ship (icebreaker Tor Viking II) breaks ice in bending at the stern shoulder as the cusp formation shows.

Fig. 15. A ship turning in level ice.

<u>Ice floes</u>

When a ship is sailing in a pack ice field consisting of distinct ice floes, the floes are pushed in front of the ship and at the same time bent downwards. When the floe coverage is almost 100 % this case is quite similar to that of proceeding in level ice. The difference is that smaller floes are not broken in bending but displaced along and around the hull. In a very open pack ice the floes may also be pushed in front of the ship.

The action of ice floes is similar to the level ice in that the ice floes are being pushed down following the buttock lines, especially when the ice concentration is larger i.e. more than, say 80 %; in lower concentrations the floes might be pushed just sideways but not down. The difference in the dominating forces in the pack ice case as compared with level ice is that the inertial forces related to rigid body motion are very pronounced in ship-ice interaction. These inertial forces are further emphasized as the ship speeds in pack ice are often high, close to open water speeds. This causes a hazard for shipping in late seasons when the ice cover breaks and lower ice concentration makes it possible for ships to maintain high speeds. Collision with individual floes causes high loads and has led to ice damages in several cases.

Fig. 16. Ships in open pack ice – ice floes of concentration about 30 – 50 % - in the Pechora Sea, closest is the Lukoil icebreaker Toboy.

Forces from ice floes

The problems in determining the ice load caused by ice floes in pack ice can be clearly illustrated in the case of a ship impacting an individual ice floe – it is difficult to determine the contact force even if the bending of the ice floe is ignored and the floe is assumed to move as a rigid body. This case is treated here as it also illustrates the difficulty in determining the ice loads in a case where there is a real interaction i.e. the ship or structure motion influences the load. In this case the contact forces and also the motions are unknown and the equations of motions for the ship (and ice) are the readily available equations for the case. As there are as many equations of motion as there are degrees of freedom, clearly one more equation is needed in order to determine also the (unknown) contact force.

The case is illustrated below in the situation where a landing craft bow is colliding with a rectangular ice floe of side length 2*R*. The displacement components (degrees of freedom) are:

u_x	Longitudinal motion of the center of gravity of the ice floe
u_z	Vertical motion of the center of gravity of the ice floe
ϕ	Tilting (pitch) angle of the ice floe
u_{cr}	Crushing depth at the edge of the ice floe

Now the equations of motion for the ice floe are (ignoring hydrodynamic forces and assuming the frictional force to be described by a coefficient of friction μ) and the $F_n(t)$ being time dependent normal contact force:

x - direction: $$m_x \ddot{u}_x(t) = F_n(t)(\cos\beta + \mu\sin\beta)$$

z,φ - directions: $$M\begin{pmatrix} \ddot{u}_z(t) \\ \ddot{\varphi}(t) \end{pmatrix} + K\begin{pmatrix} u_z(t) \\ \varphi(t) \end{pmatrix} = \begin{pmatrix} F_n(t)(\sin\beta - \mu\cos\beta) \\ F_n(t)(\sin\beta - \mu\cos\beta)R \end{pmatrix},$$

where the matrices ***M*** and ***K*** are (2x2) mass and stiffness matrices for the heave and pitch motions of the ice floe. The crushing deformation can be assumed to be static and follow the commonly used pressure – area relationship for structure – ice contact viz. the average contact pressure is assumed to vary with the total contact area $A(u_{cr})$, which is a function of the crushing depth. Thus in the present edge geometry the contact force depends on the crushing depth as

$$F_n(t) = p_{av}(A)\cdot A = p_{av}\left[u_{cr}(t)\right]\cdot 2R\cdot\frac{u_{cr}(t)}{\sin\beta\cos\beta}.$$

Now there are four equations but five variables: $u_x(t)$, $u_z(t)$, $\varphi(t)$, $u_{cr}(t)$ and $F_n(t)$). The final equation comes from a requirement that the ship is in contact with ice (if there is no contact, the contact force is zero, $F_n(t) = 0$). The contact requirement is stated based on the ship's and ice floe's relative motion at the contact point along the hull outward normal; when a contact exists, the ship and ice floes motions must be the same. This requirement is often called the kinematic condition and for the case investigated here this condition is

$$\begin{aligned} v_s t\cdot\cos\beta = &\left(u_z(t) + R\sin\varphi(t) - \frac{h_i}{2}\cos\varphi(t)\right)\cos\beta + \\ &+\left[u_x(t) + R\left(1-\cos\varphi(t)\right) - \frac{h_i}{2}\sin\varphi\right]\sin\beta + u_{cr}(t) \end{aligned}.$$

If the right hand term (ship motion) becomes smaller than the left hand term (ice motion), the contact is lost and the $F_n(t) = 0$. The ship motion cannot be larger than the ice motion as the ice displacement terms must take care of this (e.g. by increasing the crushing depth).

Now there are five equations for five variables and thus the problem can, in principle, be solved. However, only approximate solutions using quite strong simplifications in geometry have been presented so far. One of these solutions is based on the method developed in the 1950's by Kheisin & Popov (1973).

Actually the equations presented are valid only in thick ice where the bending can be ignored compared to other motion components. When the floes are larger (larger R) and ice is thinner, then the bending component must also be taken into account. This complicates the equations further. It should also be remembered that the mass matrix ***M*** should include the hydrodynamic force components which can be described by the added mass.

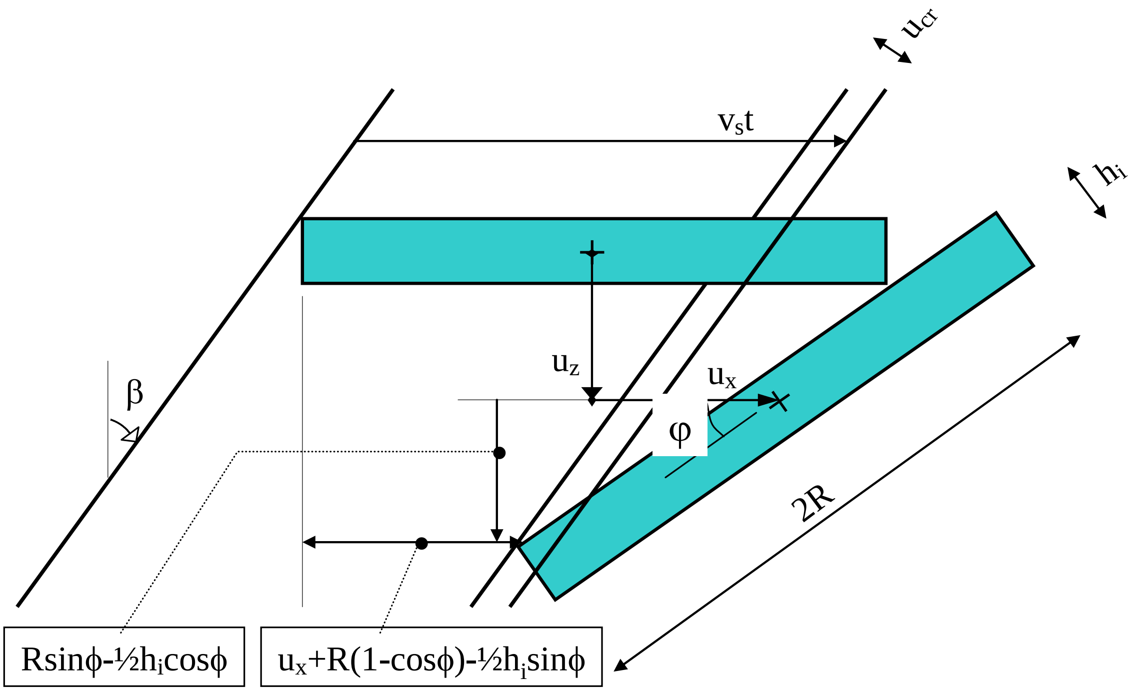

Fig. 17. Collision of a landing craft bow with an ice floe.

The collision with individual ice floes have been investigated in ice model tests, Fig. 18. Here the side of the bow collided with the edge of an ice floe; this is called an oblique impact. The contact force shows two peaks and this is due mostly to ship heeling motion - at first impact the ship heel away from the floe but when the contact force decreases the ship heels back causing the other peak. The oblique impact is indeed the most complicated case of ship – level ice interaction as the ship motion as well as the ice floe motions – and in thinner ice also the floe bending - should be accounted for.

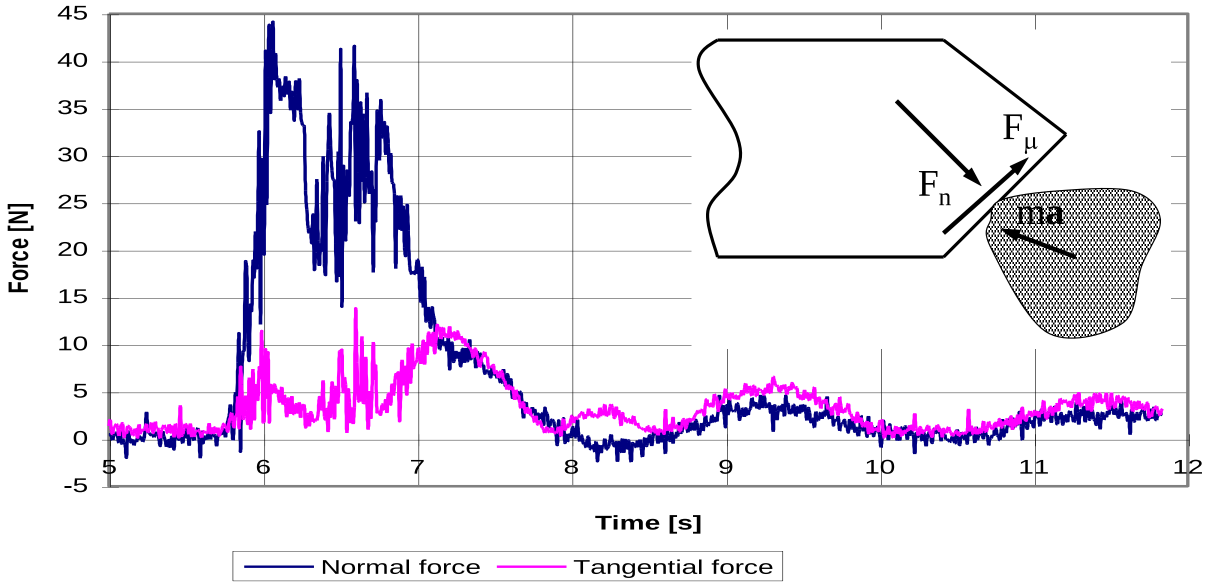

Fig. 18. The contact forces when colliding with an ice edge (Leiviskä et al 1999).

In the oblique impact all the twelwe degrees of freedom of the ice floe and the ship are active. If the ice floe is massive like a multi-year ice ridge, and the ship rams this floe perpendicular to the ice edge, only three ship motion components (heave, pitch and surge) are to be accounted for. The magnitude of the ship rigid body motions in a ramming case is illustrated in Fig. 19. This ramming case illustrating the ship degrees of freedom is shown in the photograph below. Ramming multi-year ridges which do not fail in bending causes naturally high loads on the hull girder and in some cases the design wave bending moment is exceeded. The ramming situation is highly dynamic as a result from a model test series with the ship MV Arctic shows, see Fig. 20.

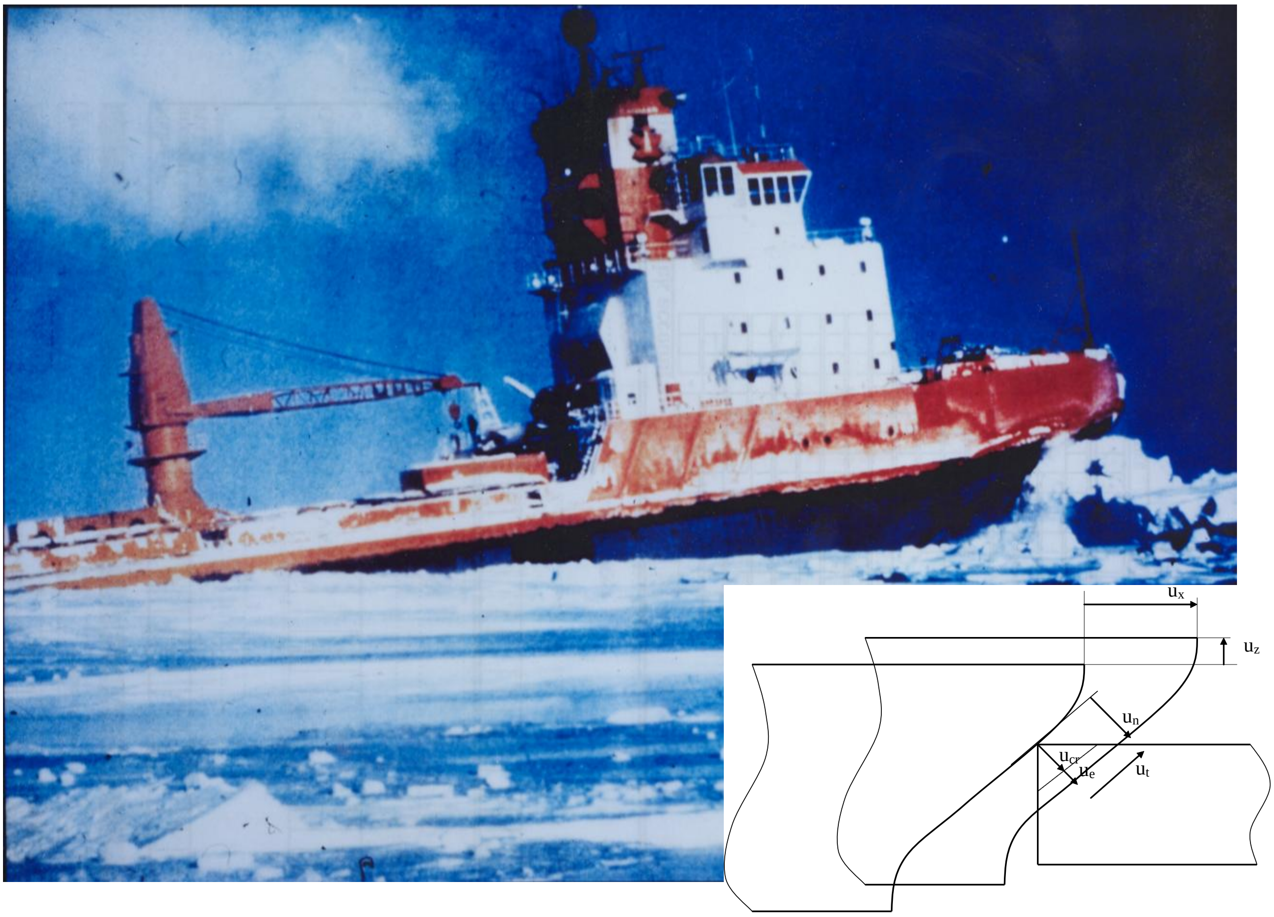

Fig. 19. CANMAR Kigoriak ramming multi-year ice ridges in the Beaufort Sea.

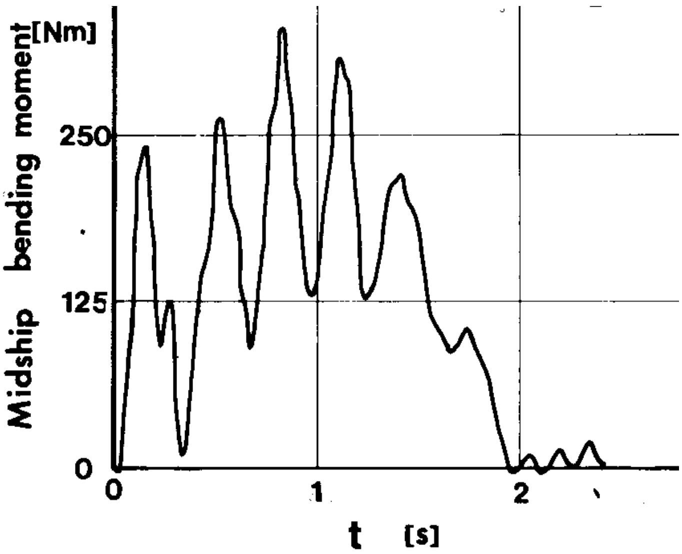

Fig. 20. Measured time history of the midship bending moment from a ram on a massive ice floe from model tests with MV Arctic, note that model scale units are used (Riska 1987).

Ice ridges

Ice ridges form the largest common obstacle the ships encounter in ice covered waters. The ridges are often that large that the ice resistance they cause is larger than the ship thrust. The ship then slows down entering the ridge and eventually may stop at the ridge. In order to continue the progress, the ship must extricate herself from the ridge. Turning of azimuthing thrusters from side to side or heeling assists in making progress in ridges.

The ice loads caused by ice ridges can be divided into two parts; load from the consolidated layer (estimated similarly as forces from level ice) and from the loose ice fragments in the ridge sail and keel. The keel loads can be either treated as loads from individual floes, in which case these loads resemble the pack ice case, or as a total load from the ridge. In designing the ship hull shell structure, individual floes must be considered and the total load is used in ship performance calculations where only the total load causing the resistance is important. Several methods have been developed to calculate the ridge global loads have been developed. Most of these methods use some kind of material behavior in analyzing the ridges. For ship applications the calculation using the methods for estimating the ridge loading on offshore structures give too high values and thus must be modified for ship-ice ridge interactions.

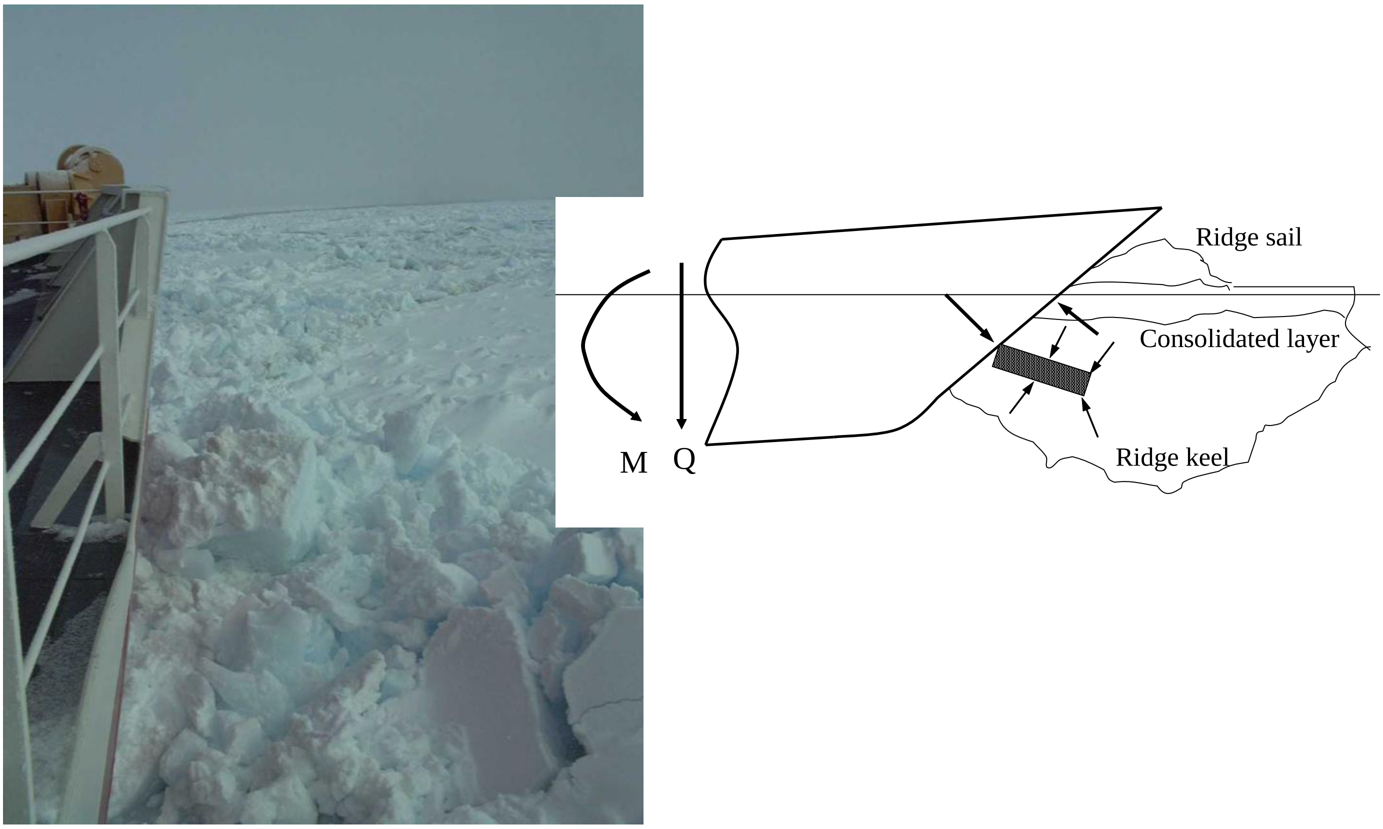

Fig. 21. A ship penetrating an ice ridge and a sketch of the loads from individual floes in the penetration process.

For ship designers the loads and ice resistance from ridges are important but as important is the knowledge where on the ship hull these loads act. A first assumption on the coverage along the hull of ridge ice loads can be obtained by assuming the ridge fragments to be submerged down and sideways to a pile resting on the ship side in a fashion that the ridge cross sectional area remains the same. The ice movement depends on the shape of the forebody. The ridge mass can be assumed to reach an equilibrium so that the angle of repose is maintained, Fig. 22. This angle of repose is often stated to be about 45°. In large ice ridges with keel depth in the range of the draught of the vessel and larger, ice can not be cleared much sideways. The ridge fragments submerge and the hull of the vessel becomes entirely surrounded by ice. In this case propeller-ice interaction can not be avoided. Thus once the ridge is thick enough, ice will get under the ship bottom and when the ship is moving forward, these ice floes under the ship bottom will eventually hit the propeller(s) and rudder(s).

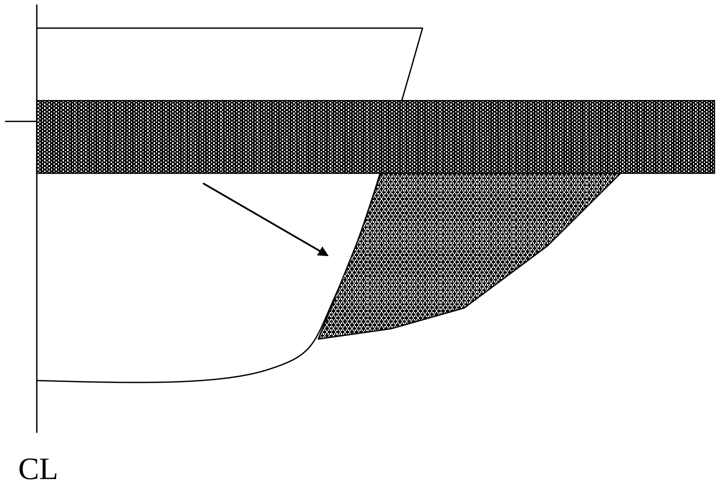

Fig. 22. The displacement of ice ridge material when a ship penetrates a small ridge. When penetrating larger ridges, sideways motions is much restrained and ice will be submerged under the ship bottom.

Compressive ice

Ice cover is always dynamic. The driving forces for ice motion are caused by the drag from currents and winds. When the driving force pushes ice against an obstacle, e.g. a coastline, ice cover converges and when the ice coverage is getting close to 100 %, ridging starts to occur. When the course of a ship is normal to the driving force, the channel the ship is making closes and ice cover may also contact with the parallel midbody of the ship. This induces large additional resistance and often ships get stopped in converging ice fields – this kind of situation is called compressive or pressured ice, Fig. 23.

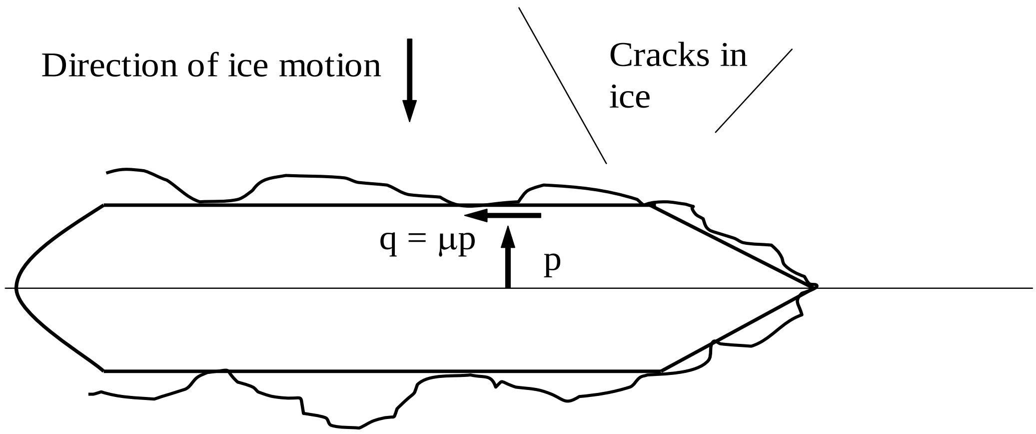

Fig. 23. Ship experiencing ice compression in a converging ice field.

The ice loads from compressive ice can be large as the Fig. 24 suggests. The ice forces on the side of the ship act as long as the level ice contacts directly the ship side. When the ice pile at the ship side has grown large, ice starts to fail at the pile and as level ice does not reach the ship side, this reduces the loading on the ship. The ice load from compressive ice acts on a narrow longitudinal load patch. The longitudinal and narrow load patch means that longitudinal frames experience much larger load (total load is $p \cdot h_c \cdot l$) than the transverse frames (total load is $p \cdot h_c \cdot s$ – h_c is the load height, l frame span and s frame spacing).

Fig. 24. A ship stuck in compressive ice and the damages that resulted from the compressive ice.

The loading caused by compressive ice can be analyzed in terms of a line load (q, unit e.g. kN/m) acting on the ship side. Measurements along different lengths have shown that the average line load depends on the load length L. The results of all the measurements can be presented as

$$q = aL^b ,$$

Where the multiplicative constant a varies a lot depending on the ice type and strength (and presumably also on the interaction type). The exponent b obtained from different measurement campaigns is quite consistently close to -0.6, see Fig. 25. Using this form of load in design means that all different load lengths must be checked when calculating the response of any single structural member. Assuming uniform pressure distribution, the line load is $p_{av} \cdot h$ where h is the load height. Load height is unknown but some measurements have suggested that the ice load is conveyed through a narrow contact and this means that quite small contact height can be used in design calculations, say, less than 10 cm.

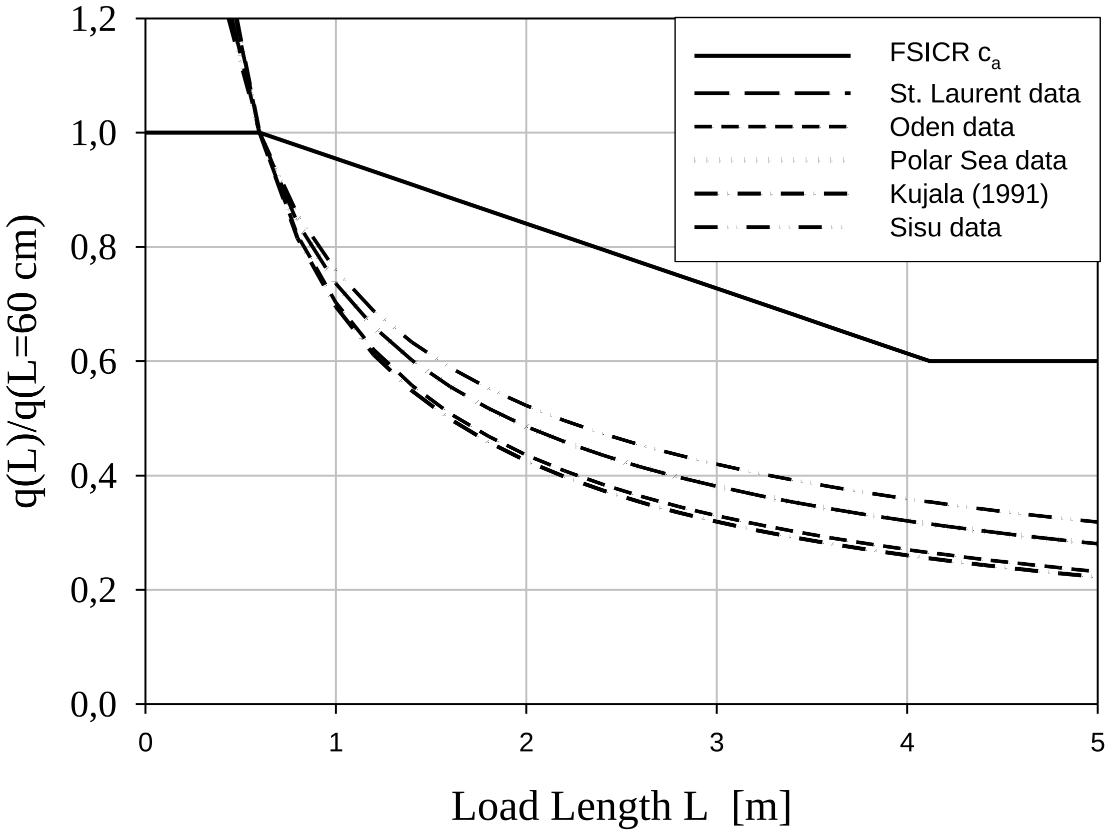

Fig. 25. Results from ice line load measurements from different measurement campaigns, normalized with the load value at load length 60 cm (Riska 2007). FSICR stands for the load versus load length dependency used in the Finnish-Swedish Ice Class Rules.

5. Conclusion

Ship design for cold regions begins by categorizing the ice action into a few different types – which often are called scenarios of ice action. These simplified ice action descriptions make it possible to get an overview on how ice is acting on the ship structures. A caveat in this somewhat dogmatic approach is that ice often finds unexpected ways of action causing losses in performance, malfunctions or damage of the ship. Better understanding of the physical processes involved in ship-ice interaction will improve this situation. Factors that influence ice actions are discussed briefly. These factors include both ship and ice characteristics. The ice loading on ship is characterized by force, pressure, load patch size and frequency. Each of these factors needs to be considered.

Finally, the intended operations of a ship influence her design. A methodical way to take into account the operations in the strength design is not apparent. Factors such as the intended operational time (exposure time) in ice, ways the ship is sailed in ice and encountered ice formations within the general ice conditions will influence the loading. Some understanding on how to tackle these questions may be obtained in looking at the different roles ships with some ice breaking capability can have.

This chapter of description of ice action is to be followed by a chapter describing the main ship design aspects. Thus the present chapter serves as an introduction to ship design aspects.

Acknowledgements

The infinite patience of Prof. Hayley Shen in putting together this chapter cannot be praised enough. During the time of writing, the author was heavily pushed by other work and the completion of the chapter took very much longer than anticipated.

Glossary

Ship conceptual design: Determining the ship main parameters so that the ship fulfills the functional requirements.
Ice load: The load acting on a ship when the ship collides with ice.
Ice pressure: The local ice force divided by the area the load is acting on.
Ice resistance: The time average of the longitudinal force from ice.
Ship propulsion: The means to move the ship forward (or astern).
Ship-ice interaction: When a ship and an ice feature are in contact, the response (motions) influence the contact force.
Level ice: Ice of uniform thickness.
Ice ridge: A triangular or trapezoidal (in cross section) pile of broken ice.
Ice conditions: All the parameters describing the existence of ice features in some sea area.
Bending strength: The maximum stress that the outer fibres of level ice can sustain when the ice is pushed down.
Ship ice performance: The speed that the ship can reach in ice of different type, the way the ship can maneuver in ice.

Bibliography

HANNIKAINEN, T. 2004: Ship's Passage through Ridged Ice Field. M.Sc. thesis, Helsinki University of Technology, Ship Laboratory, 80 p. [A description of various definitions for the equivalent ice thickness with their validations]

ICEX 1979: Ice and Climate Experiment. Report of Science and Application Working Group. Goddard Space Flight Center, Greenbelt, Maryland, USA, 90 p. [A description of various ice zones]

KENNEDY, R. & PATEY, M. 1997: Polar Vessel Design Temperature: Analysis of Russian Temperature Data. Ship Laboratory, Helsinki University of Technology, Rpt. M-224, 9 p. [Data about temperatures in the Russian Arctic]

KUJALA, P. 1991: Damage Statistics of Ice-Strengthened Ships in the Baltic Sea. Winter Navigation Research Board, Research Report No. 50, Helsinki, 66 p. [Definition of the line load versus load length]

LEIVISKÄ, T. 1999. Model Tests of Maximum Ice Impact Forces at the Bow of a Vessel. Ship Laboratory, Helsinki University of Technology, Rpt D-53, 105 p. [Tests performed to clarify the forces in an glancing impact situation]

LEPPÄRANTA, Matti 2005: The Drift of Sea Ice. Springer and Paraxis Publishing, Chichester, UK, 266 p. [A general textbook on ice conditions]

MAYKUT, G. & UNTERSTEINER, N. 1971:Some Results from a Time-Dependent, Thermodynamical Model of Sea Ice. Journal of Geophysical Research, 76, pp. 1550-1575. [Definition of the equilibrium thickness of multi-year level ice]

McCALLUM, J. 1997: Ship-Ice Interaction Scenarios. Transport Canada, Prairie & Northern Region, Marine, TP12992, Canada, 88 p. [A collection of all the major scenarios that are important in ship design, more than 100 different ones!]

POPOV, Yu. & FADDEEV, O. & KHEISIN, D. & YAKOVLEV, A. 1967: Strength of Ships Sailing in Ice. Sudostroyeniye Publishing House, Leningrad, 223 p. [Technical Translation by U.S. Army Foreign Science and Technology Center, FSTC-HT-23-96-68]. [This compendium gives the Russian theories about ice pressure and ice loads on ships]

RISKA, K. & RANTALA, H. & JOENSUU, A. 1990. Full Scale Observations of Ship-Ice Contact. Espoo, Helsinki University of Technology, Ship Laboratory, Report M-97, 54 p. [The first observation about line-like nature of the ice load on ships]

RISKA, K. & WILHELMSON, M. & ENGLUND, K. & LEIVISKÄ, T. 1997: Performance of Merchant Vessels in Ice in the Baltic. Finnish Maritime Administration, Winter Navigation Research Board, Rpt. No. 52, Helsinki, 73 p. [Definition of ice resistance and ship performance in level and broken ice]

RISKA, K. 2007: Application of the SAFEICE Project's Results in Developing the Finnish-Swedish Ice Class Rules. In: Increasing the Safety of Icebound Shipping, Final Scientific Report, Vol. 2. Ship Laboratory, Helsinki University of Technology, Rpt. M-302, 347 p. [Analysis of various factors influencing the design ice loading on ships]

VALANTO, P. 2001: The Resistance of Ships in Level Ice. Transactions of SNAME, Vol. 109, pp. 53 – 83. [Calculation of ice bending process caused by ship hull]

VARSTA, P. 1983: On the Mechanics of Ice Load on Ships in Level Ice in the Baltic Sea. Thesis for D.Sc., Espoo, Technical Research Centre of Finland, Publications No. 11, 91 p. [Calculation of ice bending process caused by ship hull]

WADHAMS, Peter 2000: Ice in the Ocean. Gordon and Breach Science Publishers, London, UK, 339 p. [A text book describing various processes in ice cover]

ZUBOV, N. 1945: Ledy Arktiki, in Russian [Arctic Ice], Izdatelstvo Glavsermorputi, Moscow. English translation 1963 by the US Naval Oceanographical Office and American Meteorological Society, San Diego, California, US. [A first comprehensive treatise of ice cover and the various processes causing ice cover to deform and/or move]

Biographical Sketch

Kaj A. Riska graduated from the Helsinki University of Technology in Naval Architecture as MSc. in 1978 and DSc. in 1988. He worked at the Technical Research Centre of Finland 1977 – 1988 as the group leader for Arctic Marine Technology. 1989-1991 he was a senior researcher for the Academy of Finland. 1992-1995 he was the director of Arctic Offshore Research Centre and 1995-2005 professor of Arctic Marine Technology at the Helsinki University of Technology. Since 2005 he has been the partner of the company ILS Oy and since 2006 Professor at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. He and his PhD students are investigating the models to describe the ice action on ships and their application in various ship design aspects.