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# LONGITUDINAL STRENGTH CONSIDERATIONS FOR ICEBREAKING TANKERS OPERATING IN SHALLOW WATERS

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## ABSTRACT

Since 1994, Germanischer Lloyd has been participating in a joint-industry research project aimed at the development of icebreaking tankers that operate largely independently in polar waters. This paper presents a recent aspect of this research involving longitudinal strength considerations for two shallow water ship/ice interaction scenarios. The first scenario is that in which the tanker beaches on submerged ice or on broken ice that has become wedged between the seabed and the ship's bottom. The second scenario is that of the tanker ramming a grounded ice ridge, and is examined for both independent operation and when assisted by a pushing icebreaker. The numerical simulation of the ridge ramming scenario is also discussed.

## 1. INTRODUCTION

Enormous reserves of oil and gas are hidden under metres of ice in the Russian Arctic regions. In order to develop them, leading international oil firms, acting in co-operation with Russian partners, have been undertaking drill soundings for some years now – mainly in the Pechora Sea, but also in the Kara Sea. These tests indicate that 30 to 35 million tonnes of oil can be produced annually in the well-explored Arctic-Tieman-Pechora field alone. Due to the massive problems with pipelines in these regions, sea transport is considered to be the preferred option to develop these resources. The sailing distance from the eastern Pechora Sea to Western Europe amounts to 1.900 nautical miles, and from the south-western Kara Sea some 2.070 nautical miles. Of these, about 350 to 500 nautical miles may be covered by ice, and these stretches are only ice-free for three or four months a year.

For this reason, Germanischer Lloyd – acting together with the Bremen shipping company Rigel and the Hamburg Ship Model Basin (HSVA) – has been participating within the scope of an R&D project to develop concepts of icebreaking tankers for Arctic service. Under the management of AKER MTW Shipyard in Wismar, and with the support of the German Ministry of Education, Science, Research and Technology (BMBF), the aim is to offer shipping companies and oil firms a modern design for the economical, safe and ecological transport of oil and gas from areas covered by ice. Two vessels of 17.200 $m^3$ capacity, built for Lukoil Arctic Tankers of Murmansk, represent the first newbuilding results of the research project, with another three units expected to follow in the near future.

In the first phase of the project, concepts for sea transport of oil from the Pechora and Kara Seas with specially designed tankers were developed. Here theoretical ship aspects, comprehensive economical studies and model tests played a significant role. In the model tests, tankers with various bow shapes were tested and optimised for their resistance, manoeuvrability and seakeeping behaviour in still water, waves and ice. The results of the initial study indicated that it was possible to achieve the transport of oil from the Pechora and Kara Seas with icebreaking tankers that are able to operate largely independently. However, economically viable transport can only be realised if the ship size is increased significantly compared to those presently in operation.

The largest tanker units presently operating in the Arctic have a deadweight of less than 20.000 tonnes. The spectrum of tankers developed in the initial study range from 20.000 to 120.000 tonnes deadweight. The main particulars of these tankers are listed in Table 1. Technical and economical considerations lead to an optimum deadweight of 50.000 tonnes to enter the new market. The reasonable technical risk and greater manoeuvring compared to larger units contributed to this assessment, which contradicts the open water trend of

**Table 1 Main Particulars of Crude Oil Carriers for the ARCtic (COC ARC)**

| Type | COC ARC 20 | COC ARC 50 | COC ARC 80 | COC ARC 120 |
|---|---|---|---|---|
| Ice class (GL) | ARC 1 | ARC 2 | ARC 2 | ARC 2 |
| Length (overall) | 156,6 m | 231,7 m | 260,4 m | 289,0 m |
| Breadth | 24,5 m | 31,0 m | 36,0 m | 43,5 m |
| Depth | 12,9 m | 18,5 m | 20,5 m | 24,5 m |
| Draught | 9,5 m | 13,0 m | 14,4 m | 16,6 m |
| Displacement | 28.100 t | 67.710 t | 100.330 t | 147.140 t |
| Cargo capacity | 24.200 m³ | 59.300 m³ | 90.500 m³ | 138.500 m³ |
| Deadweight | 20.850 t | 50.000 t | 80.000 t | 120.000 t |

decreasing required freight rate with increasing ship size. A profile view of the COC ARC 50 is shown in Figure 1. Of course, some technical risks are associated with the step to larger units. Subsequent phases of research are aimed at lessening these risks. Since primarily shallow water is to be expected in the planned operational area, Germanischer Lloyd has recently been investigating special longitudinal strength considerations arising from shallow water ship/ice interactions. The following are the results of this investigation for the

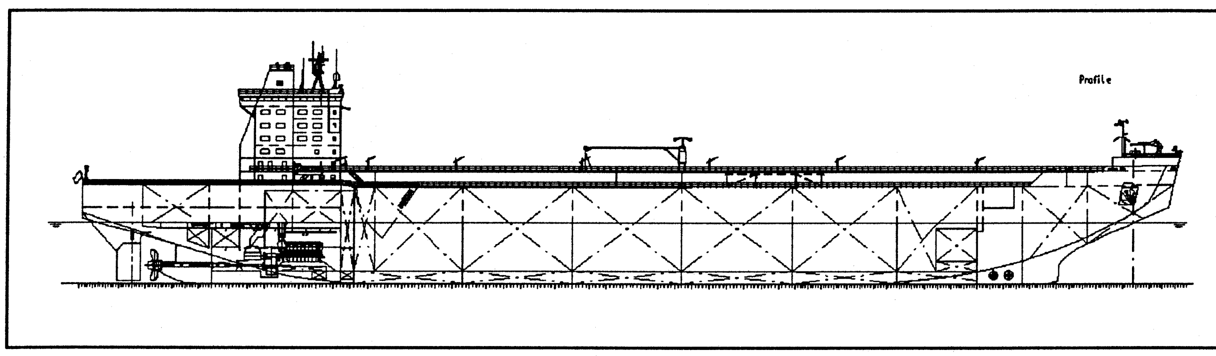


**Figure 1** **Profile of COC ARC 50**

COC ARC 50 vessel when beached on broken/submerged ice and when ramming a grounded ice ridge. Other vessel sizes may be investigated at a later date.

## 2. SHALLOW WATER SHIP/ICE INTERACTION SCENARIOS

### 2.1 Beaching on Broken/Submerged Ice

The situation of a ship becoming beached on broken ice can occur in a number of ways in shallow water. For instance, such a scenario can occur when large pieces of ice wedge between the ship's hull and the seabed. The wedging may be due to vessel trim or squat. This scenario is thought to have been the cause of bottom damage to vessels entering Tuktoyatuk NWT, Canada in the 1980's, and also occurs when icebreakers are breaking up grounded ridges or ridges in shallow water (McCallum, Lapp, and Gorman, 1997).

Furthermore, ships can beach on submerged ice when fresh water ice forms and attaches to the seabed at river estuaries. As well, icebreakers may have to break through a grounded shear zone to allow ships to take cargo inshore. Pieces of the ridges may remain attached to the seabed and are struck by ships (McCallum, Lapp, and Gorman, 1997).

### 2.2 Ramming Grounded Ice Ridge

Ramming grounded ice ridges is a special case in which the loads are higher than ramming non-grounded ridges. Because a grounded ridge will not translate or fail in flexure, the vessel response will tend to be greater than for rams into a floating ridge. In the case of the COC ARC vessels, there is an additional consideration with respect to this scenario.

The COC ARC vessels are designed to be independent 95% of the operation time. Absolute independence demands a significant increase in installed power, which cannot be economically justified. Accordingly, in severe ice conditions, the vessel will require some form of assistance. Traditionally, such assistance would take the form of a leading icebreaker. Of course, to allow the escorted vessel to manage turns without damaging the shoulders and parallel mid-body, the icebreaker should ideally break a channel that is significantly wider than the beam of the escorted vessel. However, as can be seen from Table 1, the COC ARC vessels have beams ranging from 24,5 to 43,5 metres. The icebreaker "Kapitan Sorokin" has the greatest beam of the world icebreaker fleet at 30,5 metres. Accordingly, the traditional form of icebreaker assistance would not be practical for the COC ARC 50 vessel and larger units, since these vessels are simply too wide for the relatively narrow channel of the icebreaker. Converting existing icebreakers by adapting the beam, or constructing icebreakers with greater beams, would require considerable effort and expense.

One solution is to attach the icebreaker's ice strengthened part of the stem to a specially developed stern notch of the tanker. This enables the icebreaker to push the tanker through extreme ice conditions in a so-called *Pushing Icebreaker Mode*. Naturally, the tanker bow would need to be strengthened for the more severe ice conditions. The model tests to verify the feasibility of such icebreaker support will take place in the Hamburg Ship Model Basin, but the advantages are obvious. For example, the designer can optimise the tanker's bow shape without focussing on the icebreaking performance of the fore shoulders or the compatibility of the bow with icebreaker notches designed for much smaller vessels. As well, the risk of damage is lowered since the tanker negotiates turns using its own manoeuvring abilities. This technique would also enable the cargo vessel to use its full power.

## 3. METHODS OF ANALYSIS

### 3.1 Beaching on Broken/Submerged Ice

Calculations with respect to beaching on broken/submerged ice were done with the vessel in the design and ballast conditions. Calculations were carried out for the fully loaded vessel when beached by the bow (0,85L), and the ballasted vessel when beached amidships. The calculations were carried out with the NAPA program used by the GL Emergency Response

Services Department. Once the hull geometry, lightship and deadweight distributions are supplied to the program, it is then able to calculate the change in draught, heel and trim, as well as the bending moment and shear force distribution, for a beaching force at any location.

### 3.2 Ramming Grounded Ice Ridge

The scenario of the fully loaded tanker ramming a grounded ice ridge was analysed numerically on the basis of an equivalent mass-spring system as shown in Figure 2. Once the response characteristics of the ship were determined, the equations of motion were solved for

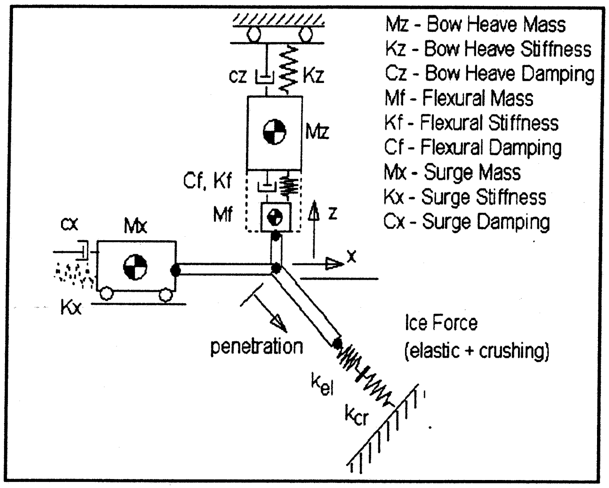


Figure 2 Equivalent Mass-Spring System

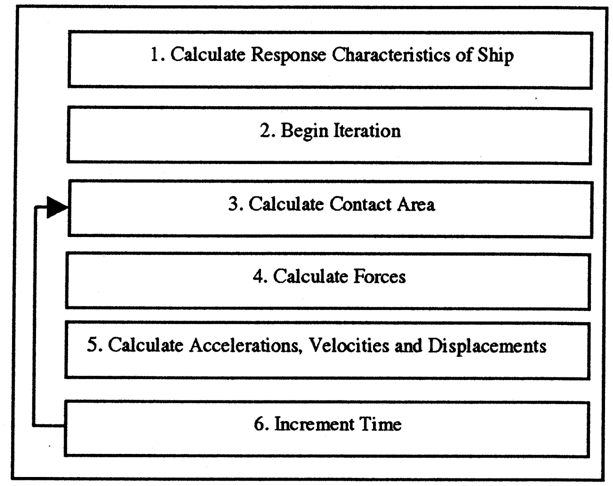


Figure 3 Algorithm of Numerical Simulation

the system throughout the interaction. Such analyses have been previously well documented and shown to compare well with analytical and full-scale results (Daley and Riska, 1994; Daley, Hayward and Riska, 1996; Daley, Smith and Riska, 1997). The numerical simulation is performed using a spreadsheet application. An algorithm of the simulation is shown in Figure 3. Damping and surge stiffness values were set equal to zero and the effects of friction were not included.

#### 3.2.1 Calculating the Response Characteristics of the Ship

To calculate the hull girder response to vertical ice loads on the bow (0,95L), it was necessary to determine the stiffness of the bow heave (Kz) and hull deflection (Kf) springs. In previous work, the former had been calculated from hydrostatic calculations based on the design waterplane, while the component of bow stiffness attributable to hull deflection had been based on the generalised stiffness of 1$^{st}$ mode hull girder bending, or some combination of modes to achieve the assumed shape of deflection. Because of its regulatory nature, such generalisations were a necessity of the referenced works.

In the present work, however, quite specific values have been calculated with GLFRAME using a lumped mass-beam idealisation of the COC ARC 50 hull girder and the associated masses of equipment and cargo. GLFRAME is a linear FE program for the calculation of two- and three-dimensional structures. The hull girder was modelled with a total of 21 nodes, each having three degrees of freedom; translation in the x- and z-directions as well as rotation about the y-axis. By using the beam model to determine the combined stiffness of the bow heave and flexural springs, assumptions regarding hydrostatic responses and hull girder deflection shapes were not required.

Once the vertical bow displacement was calculated, the magnitudes of bending moments and shear forces over the length of the vessel were obtained from the beam model of the hull girder. Figure 4 shows the distributions of bending moments and shear forces for a bow displacement resulting from a 100 MN vertical bow force. Since the responses to the ice loads

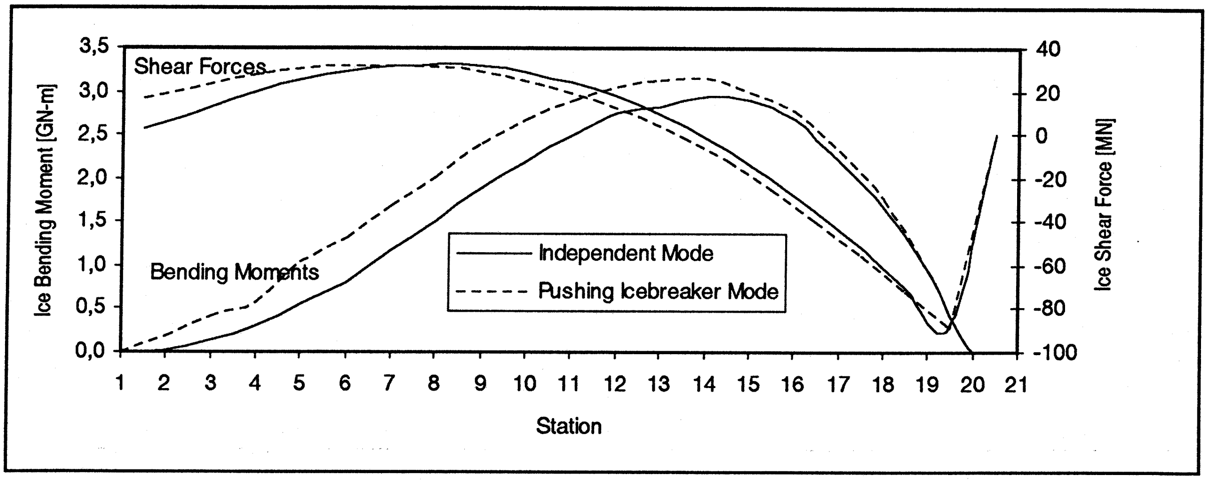


**Figure 4 Bending Moments and Shear Forces for 100 MN Vertical Bow Force (0,95L)**

were obtained by subtracting the still water component from the total response, the responses attributed to the ice loads incorporate those changes in bending moments and shear forces due to the deviation in buoyancy forces from still water values.

### 3.2.2 Calculation of Contact Area

In order to determine the total area of contact, a matrix was derived from the lines plan of the COC ARC 50 that defined this quantity throughout the interaction in 0,5m increments of heave and surge. Both the vertical and horizontal projections of the contact area of contact were similarly calculated. The ice edge was assumed to be rectangular and pitch angles were assumed to be small. It was necessary to track the penetration of the bow into the ice in order to determine when the ice was being crushed, when it was only compressed elastically, and when the bow was not in contact with the ice. An elastic ice layer of 0,5 metres was used in the simulation, although the results are quite insensitive to this value.

### 3.2.3 Calculation of Contact Forces

The prediction of the ship/ice interaction force is a complex process. Based on previous research studies and empirical data, the contact pressure was calculated using the relationship

$$P = C_1 A^{C_2} \qquad (1)$$

where $P$ is the contact pressure, $A$ is the total contact area, and the factors $C_1$ and $C_2$ are determined empirically. With a nominal pressure value of $C_1$ = 1,0 MPa, area exponents of $C_2$ = 0 and $C_2$ = -0,4 were used. The former is a conservative assumption for the predominantly first-year ice of the Pechora and Kara Seas, while the latter is useful to illustrate the influence of the pressure-area effect on the resulting global loads.

Having determined the contact areas and pressure, the horizontal and vertical force components were obtained simply:

$$Fx = PAx \qquad (2)$$

$$Fz = PAz \qquad (3)$$

where $Ax$ and $Az$ are the projections of the contact area on the vertical and horizontal planes.

3.2.4 Calculation of Accelerations, Velocities and Displacements

Having obtained the magnitude of the horizontal and resultant vertical forces, the bow accelerations could then be obtained by applying them to the effective masses in the horizontal and vertical directions. The velocities and displacements of the bow could subsequently be determined.

The effective vertical mass of the bow was established by combining the influences of the ship's inertial mass and mass moment. Regarding the latter, the beam model of the hull girder showed that a force on the bow resulted in rotation about a point located one third of the vessel's length from the aft perpendicular. Rectangular Lewis forms were used to estimate added vertical mass effects, adjusted for underwater shapes and shallow water effects (water depth below keel was assumed to be comparable with the design draught of the vessel). A nominal added mass of 5% of displacement was applied in the horizontal direction.

3.2.5 Influence of the Pushing Icebreaker

As noted in 2.2, it was necessary to analyse the ramming scenario for both the independent and pushing icebreaker modes of navigation. To assess the influence of a pushing icebreaker on the maximum bending moments and shear forces of the tanker, calculations were performed based on the particulars of a Taymyr class Russian icebreaker; a shallow-draught icebreaker of 23.500 tonnes (34,7% of COC ARC 50 displacement). Most importantly, the icebreaker adds to the effective mass of the tanker in the horizontal direction. The additional momentum at all speeds means that the vessel penetrates further into the ice before it loses its kinetic energy. Greater penetration leads to greater contact area, which results in greater bow loads, associated bending moments and shear forces. Since the details of the coupling between the icebreaker and the tanker have not yet been examined in detail, a pinned connection was assumed when determining the response characteristics of the tanker. This is a conservative assumption and had the effect of increasing the vertical bow mass by about 4,9 percent, while increasing the stiffness of the bow heave spring by about 8,0 percent.

## 4. RESULTS AND DISCUSSION

### 4.1 Beaching on Broken/Submerged Ice

4.1.1 Vessel in Design Condition

The maximum ice bending moments and ice shear forces for the vessel in the design condition are shown in Figures 5 and 6, respectively. The maximum ice bending moment occurred close to amidships, while the location of the maximum shear force was at the point of application on the bow (0,85L). Also shown in Figures 5 and 6 are the wave-induced bending moments and shear forces used by major classification societies in longitudinal

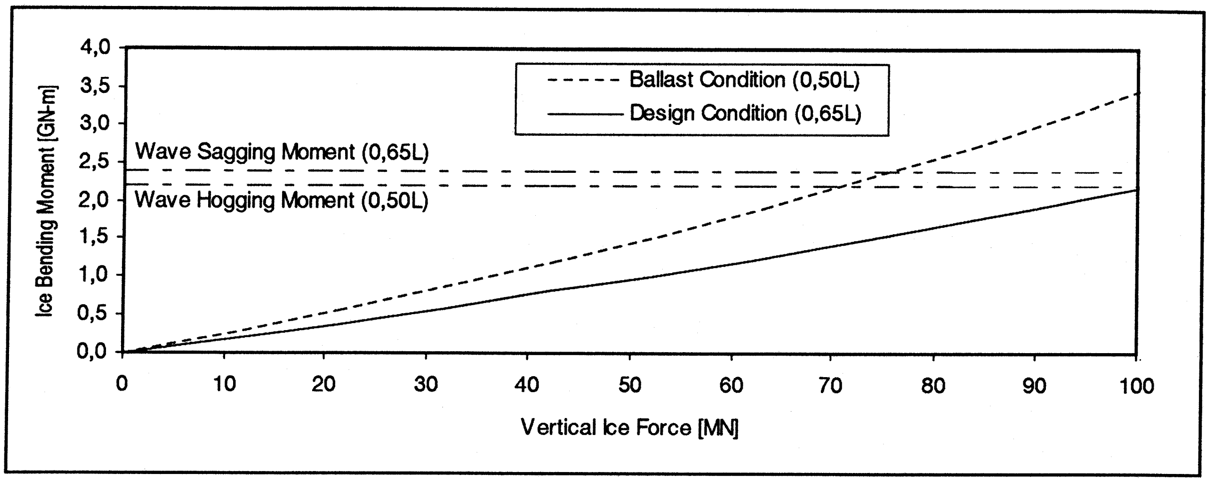


**Figure 5 Maximum Ice Bending Moments - Beaching on Broken/Submerged Ice Scenario**

strength assessments. As can be seen, a vertical bow force of about 42 MN is required before the vessel's open water shear forces are exceeded in the design condition. A plot showing the combinations of contact pressure and area required to produce this force is shown in Figure 7. Since the bottom structure of the vessel is designed to withstand local pressures up to

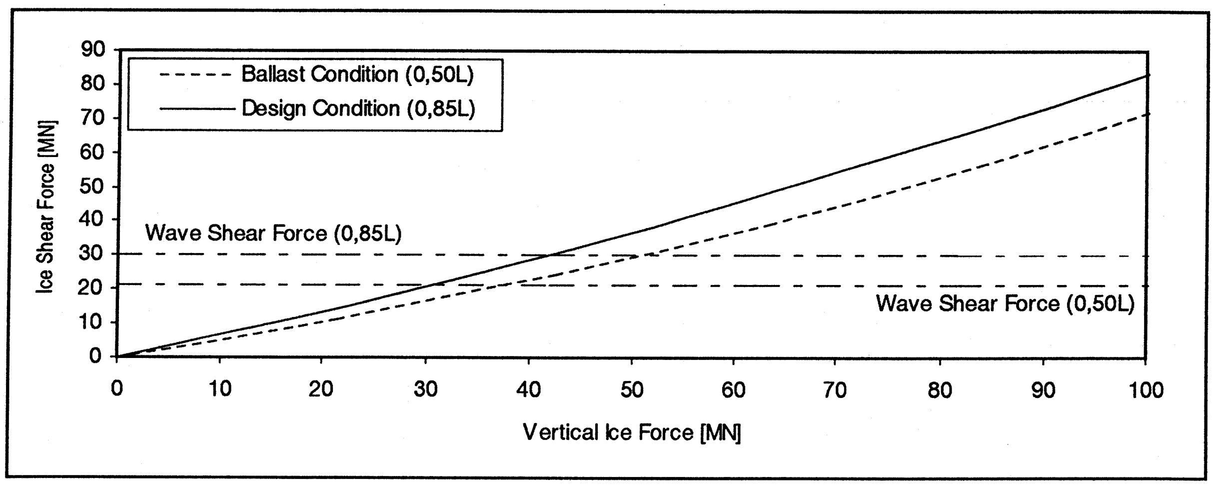


**Figure 6 Maximum Ice Shear Forces - Beaching on Broken/Submerged Ice Scenario**

0,65 MPa, this pressure is plotted to delineate the extent of damage for various pressure-area combinations. Because the design draught of the vessel is 13,0 m, and the lifting force required to raise the vessel at 0,85L is 21MN/m, the intact ice thickness is critical when it is about 11,0 m less than the prevailing depth of water i.e. (2,0m)(21MN/m) = 42MN. In the design condition, the vessel's GM was reduced by 24,6 percent when the maximum shear force induced by ice was equal to that due to waves.

### 4.1.2 Vessel in Ballast Condition

The maximum ice bending moments and ice shear forces for the vessel in the ballast condition are also shown in Figures 5 and 6. Both the maximum ice bending moment and shear force occurred at the point of load application (0,5L). A vertical amidships force of about 37 MN was required before the vessel's open water shear forces were exceeded. With a

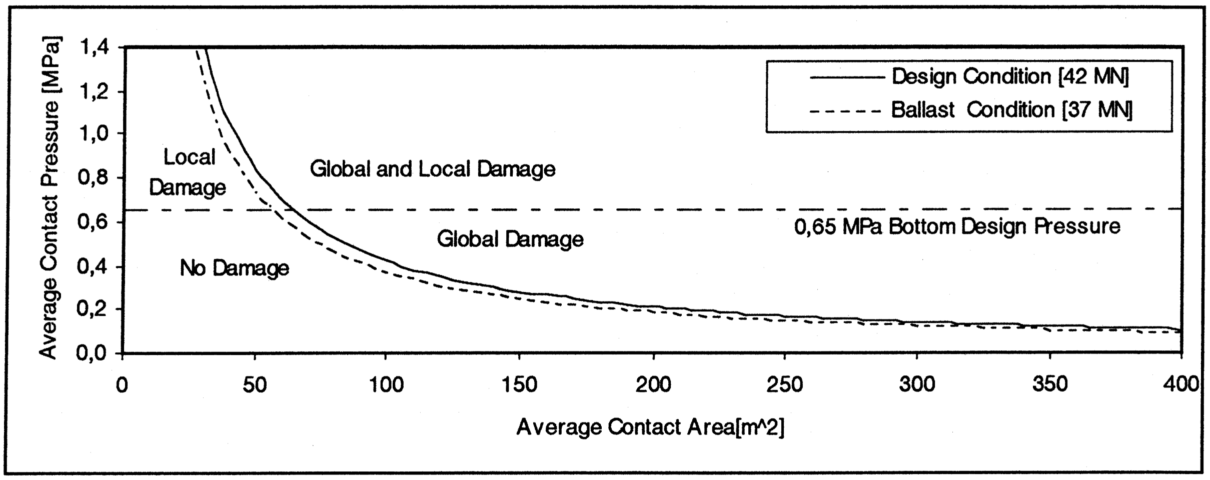


**Figure 7 Damage Scenarios for Pressure-Area Combinations**

mean ballast draught of 7,3m and a required lifting force of 53MN/m at 0,5L, the critical intact ice thickness is about 6,6 m less than the prevailing water depth i.e. (0,7m)(53MN/m) = 37MN. When the maximum shear force induced by ice was equal to that due to waves, the vessel's GM in the ballast condition was reduced by 7,4 percent.

## 4.2 Ramming Grounded Ice Ridge

### 4.2.1 Independent Mode

Typical vertical force-time histories for the COC ARC 50 ramming a grounded ice ridge in independent mode are shown in Figure 8. Plots are shown for three different ice strengths at a speed of 3,0 m/s. The effects of the area exponent in the pressure-area relationship are

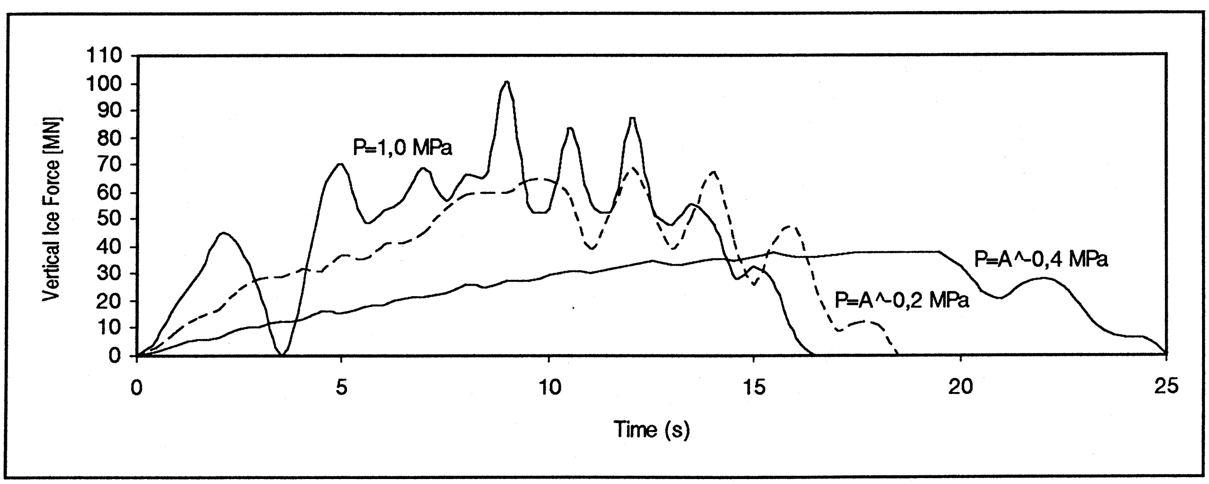


**Figure 8 Vertical Force-Time Histories - Ramming Grounded Ice Ridge Scenario (3 m/s)**

clearly visible. The ice pressures based on the -0,4 and -0,2 area exponents result in much 'softer' rams than those for which the pressure is independent of the contact area. The vessel's first mode bending frequency of about 0,7 Hz. was compared with the duration of the impulse-like loads for rams up to 5 m/s, to verify that such loads would not induce a dynamic response in the hull girder.

The maximum bending moments and shear forces for two ice strengths in the independent mode are shown in Figures 9 and 10, respectively. For comparison, the open water values used by classification societies are again shown, in addition to those values of

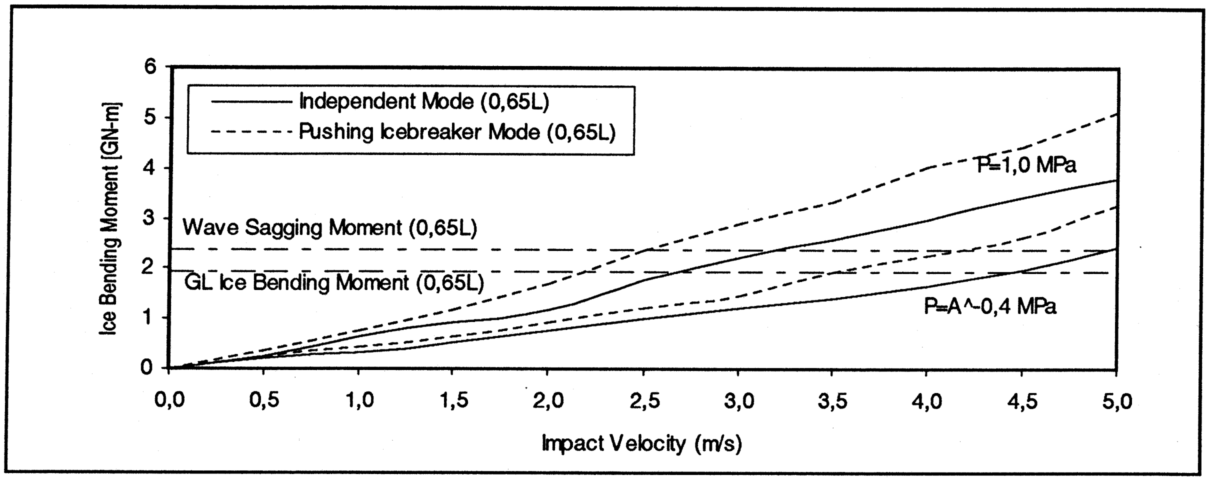


**Figure 9 Maximum Ice Bending Moments - Ramming Grounded Ice Ridge Scenario**

ice bending moments and shear forces according to GL construction rules for Arctic Class vessels. The latter are obtained by placing a load equal to 10% of the still water displacement on the stem post. It can be seen that the wave sagging moment of 2,37 GN-m is greater than the GL ice bending moment of 1,95 GN-m. Since the wave bending moment used by classification societies is proportional to length squared, while the GL ice bending moment is directly proportional to displacement, this situation would be reversed for vessels of lesser

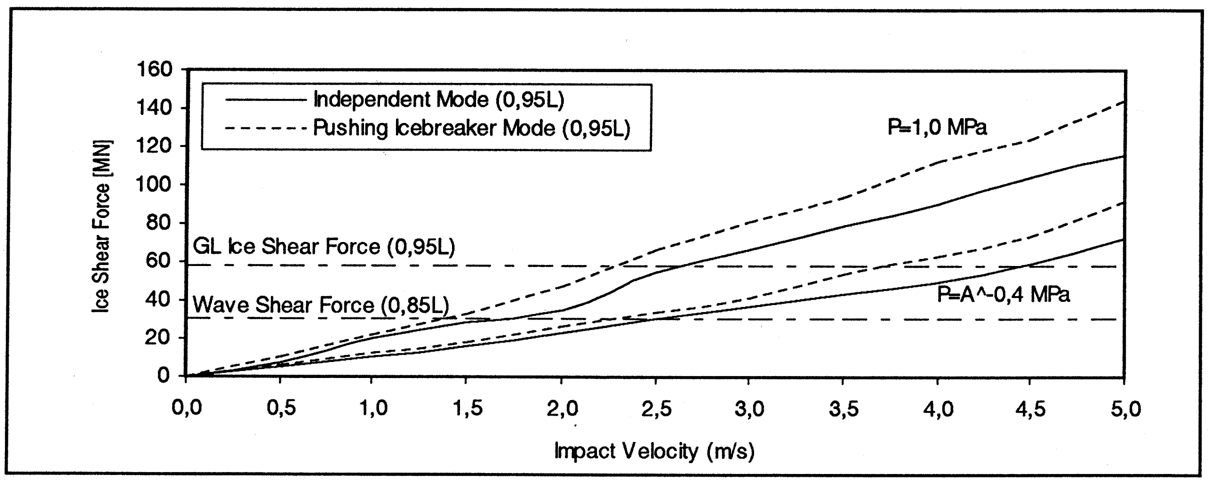


**Figure 10 Maximum Ice Shear Forces - Ramming Grounded Ice Ridge Scenario**

length. The speeds required for the ice ramming bending moments to exceed those of open water are about 3,2 m/s for P = 1,0 MPa, and about 5,0 m/s for $P = A^{-0.4}$ MPa. The speeds required before the open water shear forces are exceeded are about 2,4 m/s and 4,1 m/s for P = 1,0 MPa and $P = A^{-0.4}$ MPa, respectively (ice shear forces calculated for 0,85L are about 60% of those shown in Figure 10 for 0,95L).

### 4.2.2 Pushing Icebreaker Mode

The results of bending moments and shear forces for the two ice strengths in the pushing icebreaker mode are also shown in Figures 9 and 10. The speeds required for the ice ramming bending moment to exceed those of open water are about 2,5 m/s for P = 1,0 MPa, and about 4,1 m/s for $P = A^{-0.4}$ MPa. The speeds required before the open water shear forces are exceeded are about 2,1 m/s for P = 1,0 MPa, and about 3,4 m/s for $P = A^{-0.4}$ MPa (again calculated at 0,85L).

Over the range of speeds investigated, the effect of the pushing icebreaker was to increase the maximum bending moments by about 28 percent and maximum shear forces by about 19 percent. When the influence of the pinned connection is removed i.e. only additional horizontal mass considered, both the maximum bending moment and shear force values only increase by about 15 percent.

## 5. CONCLUSIONS

For the scenario of the COC ARC 50 beached on broken/submerged ice, the combination of contact areas and pressure required to generate sufficient forces causing global strength problems are not unlikely. However, it is evident that local strength problems would probably accompany such scenarios.

For the case of the vessel ramming a grounded ice ridge, a constant ice strength of 1,0 MPa is considered to be a conservative assumption for the Pechora and Kara Seas (especially since the contact area grows quite rapidly during the interaction). Nevertheless, the analysis shows that bending moments in excess of open water requirements can be avoided with prudent operation when navigating independently. Similarly, although the additional influence of a pushing icebreaker can be significant, such operations are possible if safe operating speeds are observed in shallow ice-covered waters.

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