Ice Impact Capability of DRDC Notional Destroyer

Prepared for

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Acknowledgements

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A parallel study is underway for the US Coast Guard, in which ABS is leading the investigation. This study has made use of many of the same approaches and software that is being employed for the USCG study. Mr. John Dolny of the ABS Harsh Environment Technology Center has provided valuable input, software and computer resources for this project. The provision of the LS-Dyna software by ABS to execute the finite element analyses is gratefully acknowledged. The updated DDePS software was developed by Mr. Dolny.

Finally Ms. Katherine Daley is thanked for preparing the LS-Dyna .k files for the extensive structural assessment and for preparing the response results.

1. Introduction

DRDC has an interest in understanding the structural capability of its vessels when deployed in high latitude environments with potential for ice impact loading on the hull structure in the marginal ice zone. The vessel being considered here is a concept referred to as the Notional Destroyer, and has characteristics similar to many naval patrol/frigate/destroyer class vessels with a hull structure that is not strengthened for ice impact. This report, while building on prior techniques, includes new approaches for the direct analysis of structural capability under ice loads. These new analysis approaches have been tailored for application to non-ice strengthened vessels such as naval vessels.

The objectives of this project are to exercise the state-of-the-art of available technologies to estimate operational capabilities and limitations for non-ice strengthened (and light ice-strengthened) RCN assets operating in ice conditions. The hope is that this work will aid in the development of knowledge needed to support operations in high latitude environments.

The assessment of the structural capability of the Notional Destroyer to operate in ice is based on methods developed by the author and colleagues to assess ice class ships. In the present case the vessel has no ice class and so naturally its capability will be substantially less than an ice class ship. Nevertheless, all vessels will have some capacity to interact with ice, and this assessment is an attempt to determine the extent of the capability that a warship might have. The Notional Destroyer is not a real vessel. The design is of a generic vessel, with initial estimates of various structural and vessel particulars. The assessment therefore requires that some assumptions be made to permit the calculations to proceed. There are also a number of assumptions inherent in the assessment approach. The strict validity of some of the assumptions to non-ice class ships are somewhat uncertain. For example, the methods to determine forces are based on rigid body interaction mechanics. The elasticity of the ice and ship are normally ignored. In this assessment, the baseline assessment also ignores the structural compliance. In an extended analysis, the compliance of the structure (elastic and plastic) is considered. Nevertheless, it must be understood that assessment is merely an estimate, where the author has made assumptions that are believed to be reasonable given the currently available knowledge.

This report includes the technical background behind a new version of the software assessment tool called “Direct Design for Polar Ships” (DDePS), which is now called **DDePS_2a_Safe_Check** (latest version v3.1). This updated software tool allows a user to explore damage estimates and develop guidance for speed limitations based on deterministic impact scenarios for a specific ship.

2. Vessel Description

General Description

The Notional Destroyer is a concept warship which is about 150m in length and weighs from 7700 tonnes to 9100 tonnes, depending on age and ice accretion. A sketch of the vessel layout is given in Figure 1. Figure 2 shows the lines of the vessel. The operating waterlines are shown for reference. The main particulars are given in Table 1.

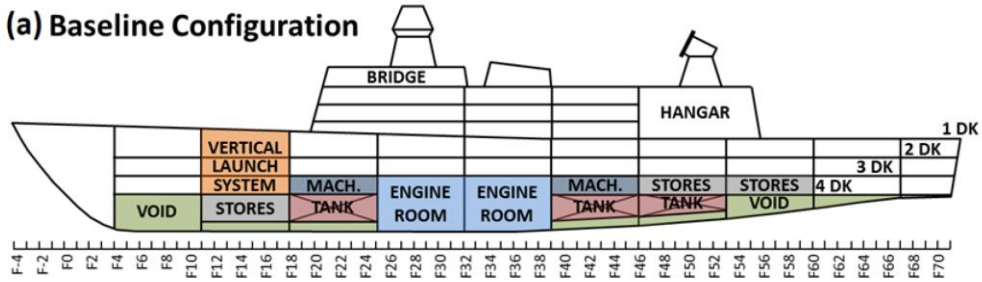

Figure 1: Notional Destroyer – Concept of General Layout

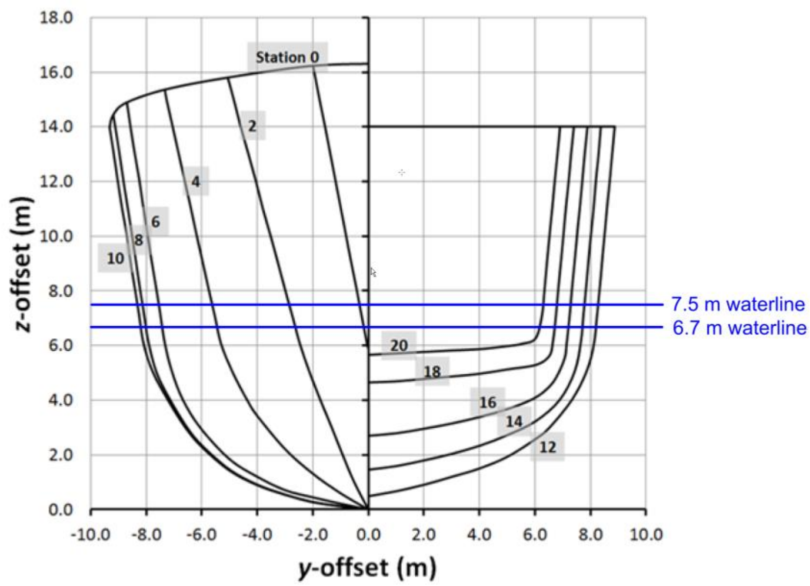

Figure 2: Notional Destroyer – Body Lines

Table 1 Notional Destroyer – Main Particulars

Particular	***Beginning of Life (no ice accretion)***	***End of Life (with max ice accretion)***
Length overall	151.4 m	
Overall depth	16.5 m	
Amidships depth	14.0 m	
Maximum breadth	18.7 m	
Displacement	7673 t	9095 t
Length along waterline	142.8 m	143.5 m
Length between perpendiculars	137.8 m	138.5 m
Amidships location [a]	68.9 m	69.2 m
Longitudinal center of gravity [a]	72.0 m	73.8 m
Waterline breadth	16.8 m	17.0 m
Draft	6.7 m	7.5 m
Block Coefficient	0.48	0.51

[a.] Distance aft from forward perpendicular (FP). The FP is 0.80 m and 1.48 m forward of frame 0 (F0 at x=0) for the beginning and end of life, respectively.

Hull Form Parameters

In order to conduct an ice impact assessment, the 3D angles and coordinates of impact locations must be known. The body lines from Figure 2 were imported into Rhinoceros (2010) to create a full 3D representation of the hull (Figure 3). The angles at various stations (to be used as impact locations) were extracted (Figure 4) and are listed in Table 2 for the 7.5 m draft (end of life) and in Table 3 for the 6.7 m draft (beginning of life).

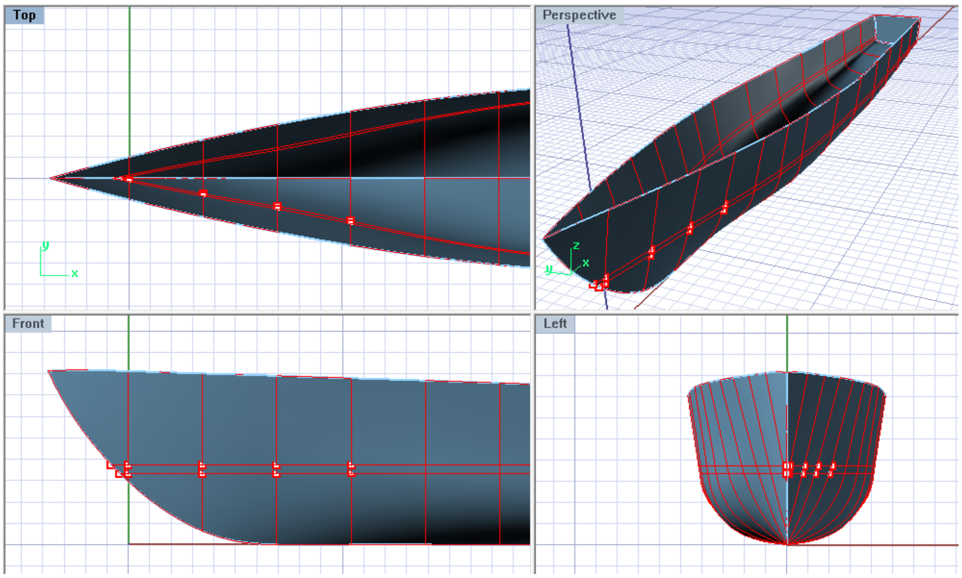

Figure 3: Notional Destroyer – Rhino 3D Model

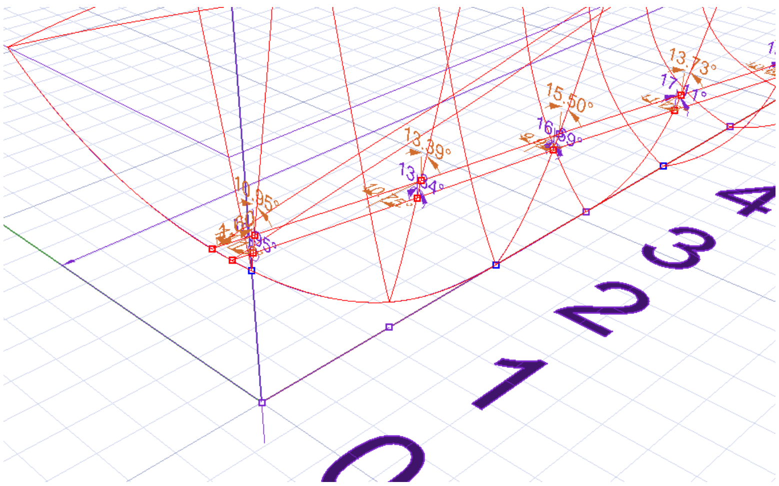

Figure 4: Extraction of hull angles from Rhino 3D Model

Table 2 Coordinates and angles for 7.5 m waterline

station	$x_{station}$	x_{fp}	z_{keel}	x_{cg}	y_{cg}	z_{cg}	α	β	fr.no.[1]
0	0	1.6	7.5	72.2	0.3	0	11.1	11.0	0
1 [2]	6.9	8.5	7.5	65.3	1.7	0	10.8	13.4	4
2	13.9	15.5	7.5	58.3	2.9	0	9.9	15.5	7
3	20.8	22.4	7.5	51.4	4.3	0	11.8	13.7	11
4	27.7	29.3	7.5	44.5	5.7	0	10.8	10.5	14
5	34.7	36.3	7.5	37.5	6.8	0	8.4	9.8	18
6	41.6	43.2	7.5	30.6	7.5	0	5.2	7.9	21
7	48.5	50.1	7.5	23.7	8.0	0	2.4	7.8	25
8	55.5	57.1	7.5	16.7	8.2	0	1.3	8.2	28
9	62.4	64.0	7.5	9.8	8.3	0	0.9	8.5	32
10	69.4	71.0	7.5	2.8	8.3	0	0.5	8.5	36

[1]approximate frame numbers [2]4 locations for ice impact analysis are highlighted

Table 3 Coordinates and angles for 6.7 m waterline

station	$x_{station}$	x_{fp}	z_{keel}	x_{cg}	y_{cg}	z_{cg}	α	β	fr.no.*
0	0	0.8	6.7	71.2	0.2	0	10.7	11.0	0
1	6.9	7.7	6.7	64.3	1.5	0	10.2	13.3	4
2	13.9	14.7	6.7	57.3	2.6	0	9.9	16.7	7
3	20.8	21.6	6.7	50.4	4	0	12.1	17.1	11
4	27.7	28.5	6.7	43.5	5.5	0	10.1	13.3	14
5	34.7	35.5	6.7	36.5	6.7	0	8.3	9.8	18
6	41.6	42.4	6.7	29.6	7.5	0	5.0	7.9	21
7	48.5	49.3	6.7	22.7	7.9	0	2.3	7.9	25
8	55.5	56.3	6.7	15.7	8	0	1.0	8.6	28
9	62.4	63.2	6.7	8.8	8.1	0	0.8	9.5	32
10	69.4	70.2	6.7	1.8	8.2	0	0.5	9.5	36

*approximate frame numbers

Structural Information

The structure of the Notional Destroyer is representative of a warship, and is intentionally very light in comparison to an ice class ship. The information given below describes the structural characteristics of the outer hull structure, which is the structure that would be involved in an ice impact. Ice impact loads are highly localized, and so the structure of the outer hull determines the ice capacity in an impact. There are no significant global strength issues for any conceivable ice interaction for this type of vessel. The global strength would only be an issue in a heavy ram with a massive ice feature. Such operations would cause extensive local damage and are thus not considered. The material parameters are listed in Table 4. The structural layout parameters are listed in Table 5. Additional framing parameters are shown in Figure 5 and Table 6. Figure 5 shows the midship cross section with plating and framing information given. The scantlings shown on Figure 5 are assumed to carry forward into the bow region where the ice impacts would likely take place.

Table 4 Notional Destroyer – Material Properties

Parameter	***Value***
Young's modulus [a]	207 GPa
Poisson's ratio [a]	0.3
Yield strength [a]	355 MPa
Density [a]	7850 kg/m^3
Post Yield behavior [b]	Bi-linear kinematic hardening
Post Yield modulus [b]	1.5 GPa

a. these values were provided by DRDC
b. assumed by author

Table 5 Notional Destroyer – Structural Arrangement Particulars

Structural Parameter	***Value***
Web Frame spacing [a]	2.0 m
Hull longitudinal stiffener spacing [a]	550 mm
Vertical spacing between decks [a]	2.75 m
Deck longitudinal stiffener spacing [a]	575 mm
Vertical stiffener spacing on watertight bulkheads [a]	575 mm
Transverse offset of longitudinal bulkheads from centerline [a]	3.45 m
Vertical stiffener spacing on longitudinal bulkheads and girders [a]	575 mm
Brackets connecting longitudinal hull frames and web frames [b]	none

a. these values were provided by DRDC
b. assumed by author

Table 6 Notional Destroyer – Transverse Framing Particulars

Primary Member [a]	**Location**	**Typical Scantling**	**Deep Scantling**
Transverse web frame	Between Nos. 1 and 2 decks	191x7W 40x9F	N/A
Transverse web frame	Between Nos. 2 and 3 decks	210x7W 45x10F	N/A
Transverse web frame	Between Nos. 4 and 4 decks	230x7W 50x10F	560x10W 120x25F
Transverse web frame	Between Nos. 4 and inner bottom	273x7W 60x12F	608x11W 130x27F
Transverse web frame	Between inner bottom and keel	364x8W 80x16F	651x11W 140x29F
Deck beam	No. 1 deck	220x7W 50x10F	N/A
Deck beam	Internal decks	225x8W 120x15F	N/A
Plate floor	Engine rooms	1355x7W 165x14F	N/A
Plate floor	Beneath inner bottom in stores compartments and tanks	10 mm web	N/A

a. all values were provided by DRDC

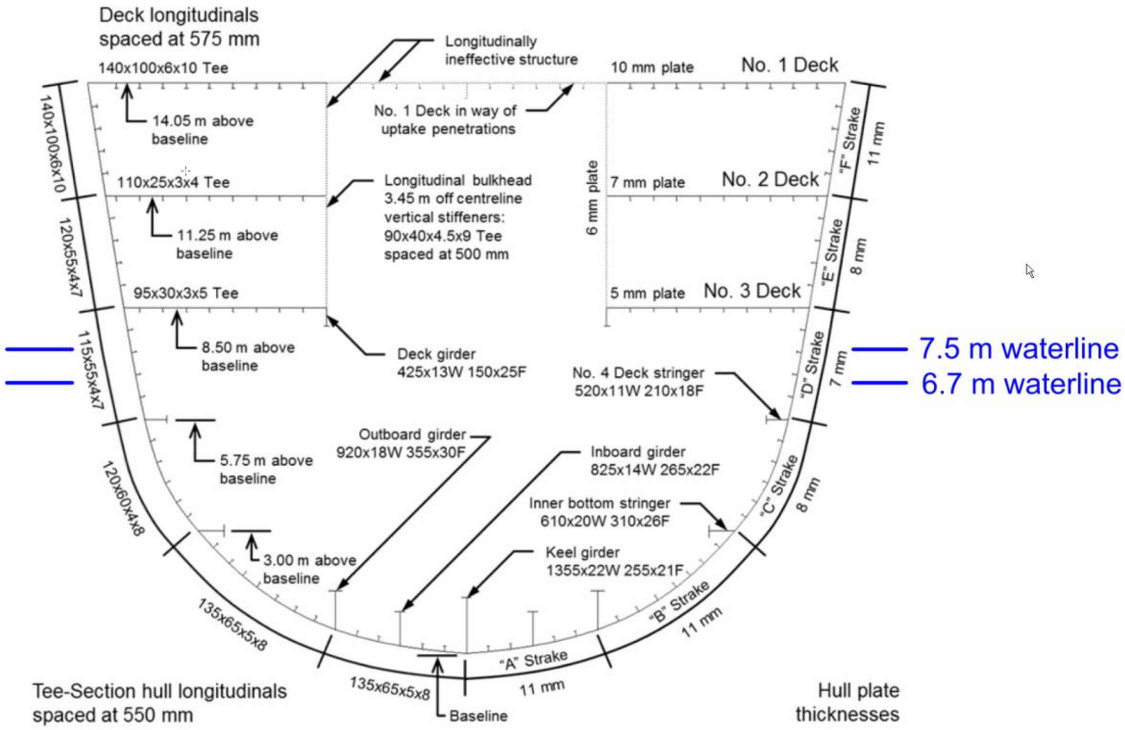

Figure 5: Notional Destroyer – Midship Structure

3. Finite Element Model Development

The finite element model of the structure only needs to exhibit the local structural response to the ice impact. Therefore a relatively small model is sufficient. One larger model, extending from 3m AB to the No. 2 Deck was developed. Figure 6 illustrates the region of the large finite element model. Also shown is the region of the smaller model, which only spans between 5.75m AB to the 3rd deck.

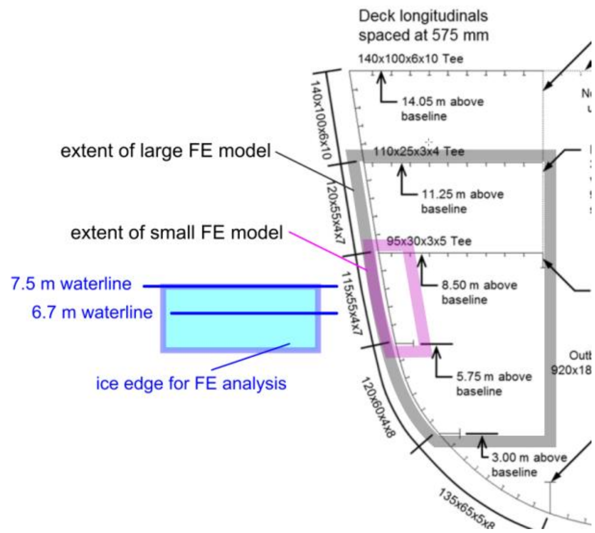

Figure 6: Midship Structure showing location of finite element models

Figure 7 shows the Rhino model of the area covered by the larger finite element model. The model is 6m in longitudinal extent, covering three web frames spacings. Figure 8 shows the extent of the small finite element model. The ice edge was modeled as a vertical prism, approximately 2 x 2 x 2 meters, with a 150 degree wedge arranged normal to the hull. This is only meant to represent the ice edge, not the whole ice mass. Because the hull was approximately 10 degrees from vertical, the ice contacts at a point and the nominal contact becomes a triangle as it indents.

The models developed in Rhino were exported as .iges files for import into the finite element program. Figure 9 illustrates the approach taken to the finite element modeling. The steel structure was all modelled with shell elements on the mid-plane of the plating, webs and flanges.

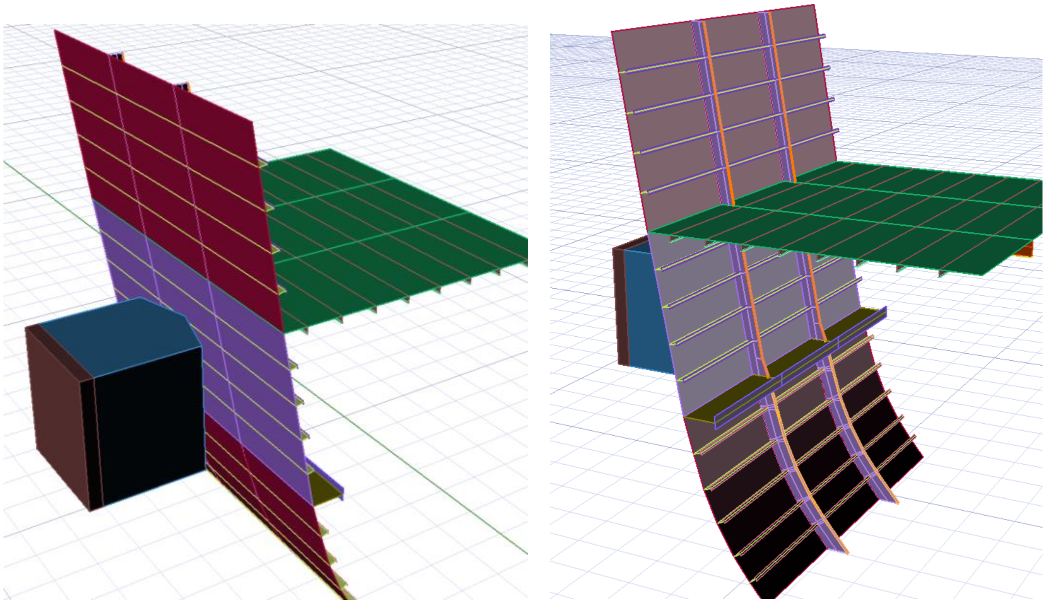

Figure 7: Hull structure as modeled in Rhino covering extent of large finite element model

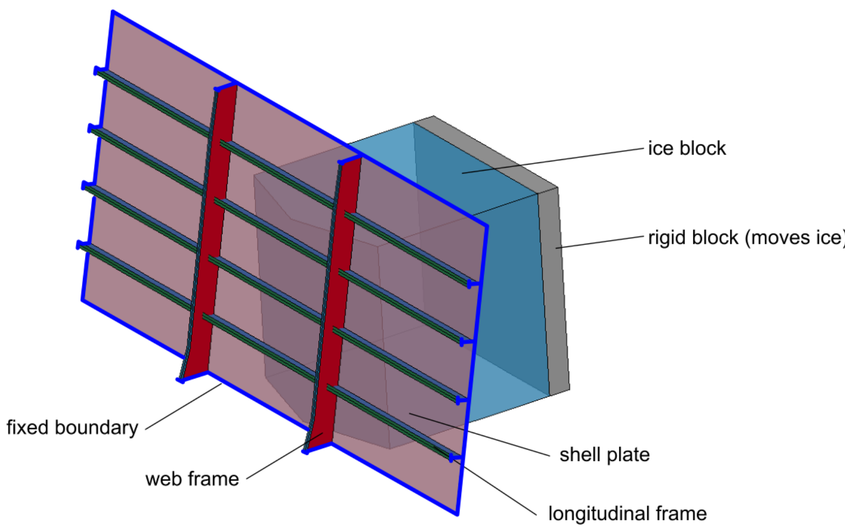

Figure 8: Hull structure as modeled in Rhino covering extent of small finite element model

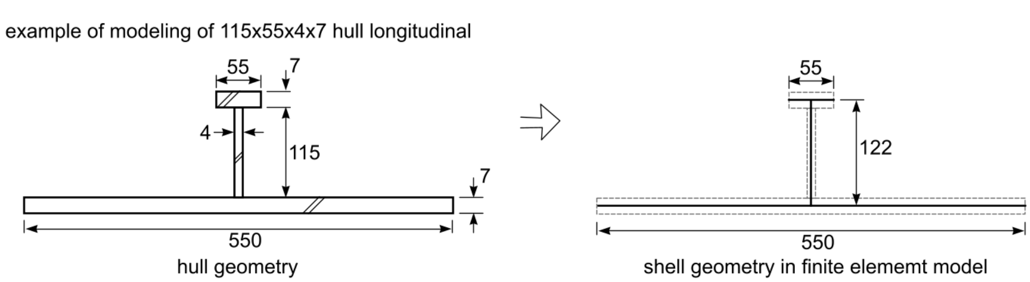

Figure 9: Example of shell element geometry in finite element model

Structural Finite Element Model Description

Figure 10 shows a typical case of the large model in LSDyna, with the mesh shown on the right. The mesh was as uniform in sizing as possible with a typical element of 5cm x 5cm. Figure 11 shows a typical LSDyna shell section definition window. A "Belytschko-Tsay" element formulation with 5 though thickness integration points was used. The authors have used these assumptions with good success in the past. Figure 12 shows the steel material model. A yield stress of 355 MPa with a post-yield tangent modulus of 1.5 GPa, was used for the steel.

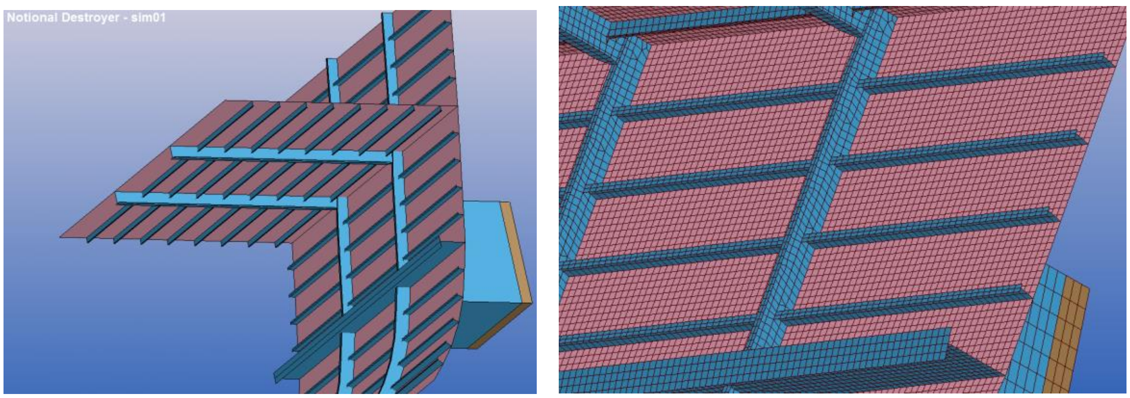

Figure 10: Hull structure as modeled in the LS Dyna finite element model.

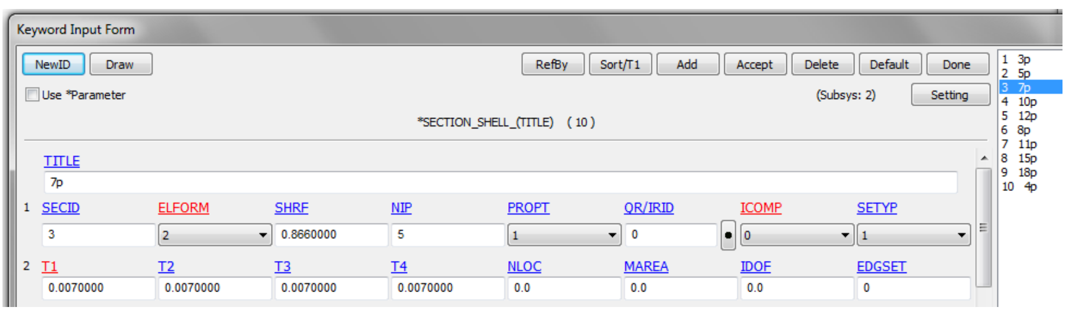

Figure 11: Example LS-Dyna Shell Section definition.

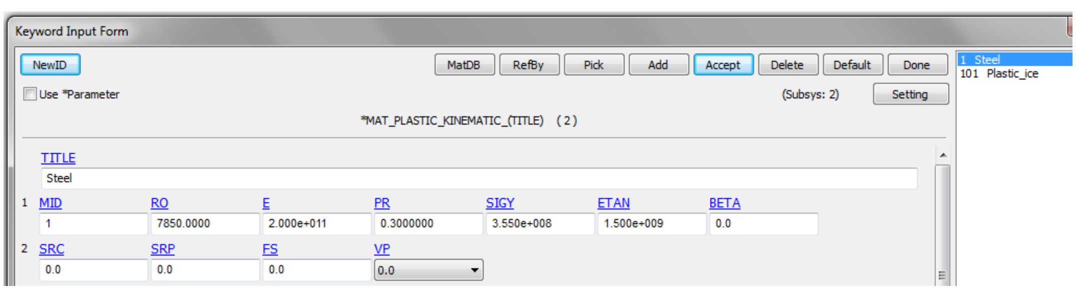

Figure 12: Example LS-Dyna Steel Material definition.

FE Model Runs

Figure 13 shows the locations where the ice impacted the structure in various runs listed in Table 7. In all cases (except run 14 and 15) the ice was moved horizontally, normal to the hull, and moved a distance of 185 mm after contact. The ice normal velocity was 1 m/s, which is neither slow nor especially fast for normal speed. No material rate effects were included, and only minor dynamic effects (inertial forces) would be expected. While not truly quasi static, this would be close to quasi static in structural terms. One might wish to explore this further. In the case of run 14, the ice was moved laterally 1m as it moved 185 mm inwards (see Figure 24). This would represent an impact with a vessel speed of 5 m/s. Again, from a structural perspective, this is not truly quasi-static, but close to being so. In the case of run 15, the ice only moved 58mm inward and then was withdrawn. In cases 1 to 15 the ice was modeled to be very hard winter ice. The material model in LS Dyna was called EP6 because the nominal yield strength was 6 MPa, although this produced ice pressures at around 12 MPa as shown in Figure 15. This is a conservative assessment, but is not much above actual ice contact pressures measured in the laboratory (see Figure 14). For cases 4-26, 8-26 and 14-26, three cases were re-run with local ice crushing strength equal to the strongest ice in the IACS Polar Rules. This was accomplished by setting the LSDyna material yield strength to 2.6 MPa (which resulted in crushing pressures at around 6 MPa). Thus, while the final assessment will be based on moderately conservative values of ice strength, the analysis has shown that the response is not strongly dependent on ice strength, nor on the location of impact.

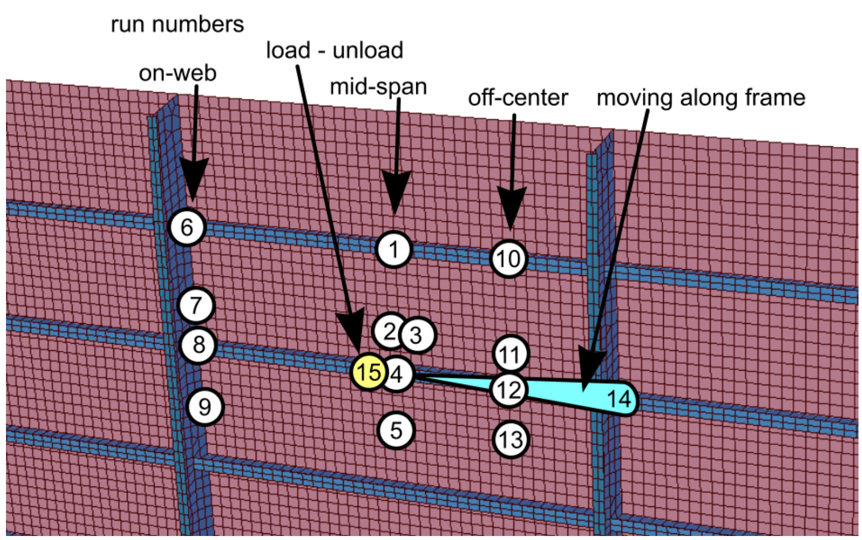

Figure 13: Sketch showing Run #s, with locations of first ice contact.

Table 7 List of Structural Response Runs

Run Number	Description	Ice Model
1	mid-span on longitudinal	EP6*
2	on plate near mid-span of longitudinal	EP6
3	on plate near mid-span of longitudinal (repeat with smaller ice block)	EP6
4	mid-span on longitudinal	EP6
5	on plate near mid-span of longitudinal	EP6
6	on web frame at join	EP6
7	on web frame	EP6
8	on web frame at join	EP6
9	on web frame	EP6
10	quarter-span on longitudinal	EP6
11	on plate near quarter-span of longitudinal	EP6
12	quarter-span on longitudinal	EP6
13	on plate near quarter-span of longitudinal	EP6
14	moving from mid-span of longitudinal to web while indenting steadily (1m lateral movement)	EP6
15	Repeat of run 4 with loading and unloading	EP6
4_26	Repeat of run 4 with EP26 ice model (PC1 target ice strength)	EP26
8_26	Repeat of run 8 with EP26 ice model (PC1 target ice strength)	EP26
15_26	Repeat of run 14 with EP26 ice model (PC1 target ice strength)	EP26

*EP6 and EP26 refer to the modeling approach for the ice material, discussed below.

Ice Model Development

The loads on a ship depend on many factors, including the ice edge crushing strength. Selection of the appropriate ice load model is a challenge. Figure 14 shows pressures measured in a lab setting and indicated contact pressures in the 10 MPa range. Design local pressures in the IACS polar rules range from a few MPa up to 6 MPa for the highest ice class. Ice edge strength is only one of many factors that affect the loads, especially in the case of the Notional Destroyer in marginal ice. Ice mass is far more crucial, but ice edge strength should be carefully selected.

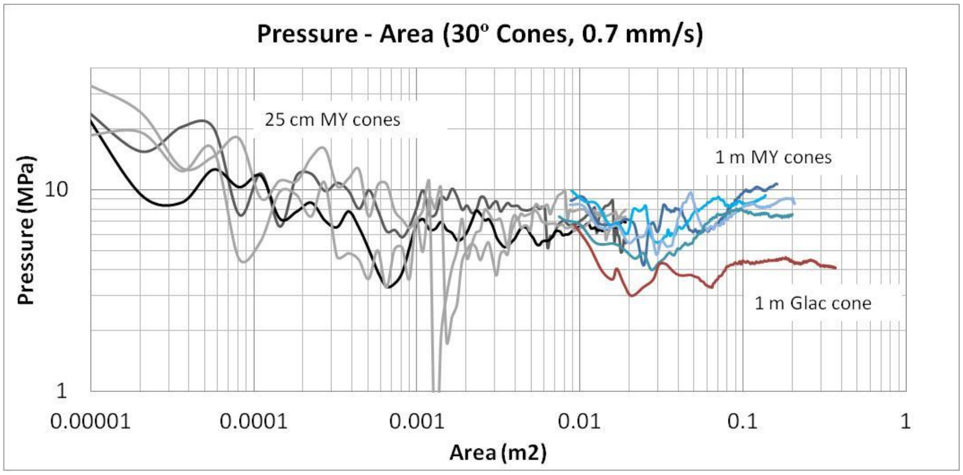

Figure 14: Measured Pressures in STePS2 lab tests.

Two models of ice pressure were developed for the LS-Dyna runs to assess the Notional Destroyer. To develop the ice material model in LS-Dyna, models were run in which a crushable ice was indented onto a rigid plate. The setup was similar to that pictured in Figure 8, but with the shell plate modelled as rigid. Two material models were developed, and are termed EP_6 and EP_26. EP_6 produced local contact pressures of about 12MPa, certainly conservative values. EP_26 produces local pressures around 6 MPa, very close to the PC1 design pressures, though lower than the lab measured pressures in Figure 14. Both model made use of material Material Type 3 in LSDyna, which is an elasto-plastic strain hardening material. Both models would represent very hard ice, whether thick first year or multi-year. EP_26 happens to reflect the Polar Rules for multi-year ice and EP_6 happens to represent very conservative values as measured in laboratory tests. Neither are definitive values.

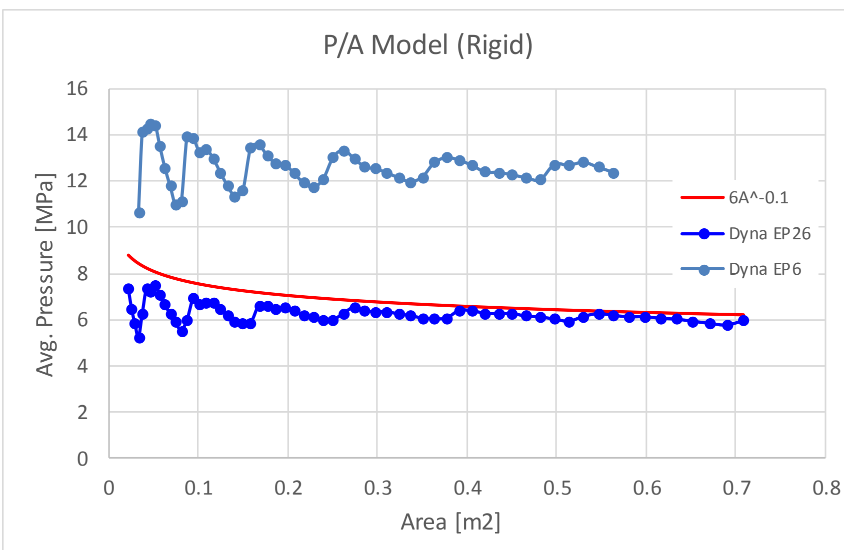

Figure 15: Measured Pressures in STePS2 lab tests.

FE Model Results

The plots below show the various load-deflection plots for the load cases listed in Table 7 for locations sketched in Figure 13. For these cases the load is plotted against the ice movement. This movement is equal to the sum of the ice indentation and the structural deformation. The data is plotted this way so that it can be used in a collision analysis. The area under theses curves represents all the ice and structure deformation energies (elastic and plastic). Figure 16 shows all the 15 cases which used the EP6 ice load model. Figure 17 shows just those case on the mid-span of the longitudinal frames. Figure 18 shows just those cases where the load was on the web frame. Figure 19 shows just the off-center case. It is clear that the location does not have a strong effect on the response. The initial capacity of the web frames is considerable greater than the longitudinal frames, but only initially. At large ice penetrations the load capacity is only weakly influenced by location. Run 15, shown in Figure 20 shows the result of unloading after 0.22 MN at location 4. It is clear that the structural deformation is only about half of the total ice movement, indicating that both ice and structure deform a similar amount. It also clear that at these load level the elastic component (the rebound) is about half the total structural deformation. Therefor the size of the dent would be only 19mm even though the ice mass had moved 58mm into the structure.

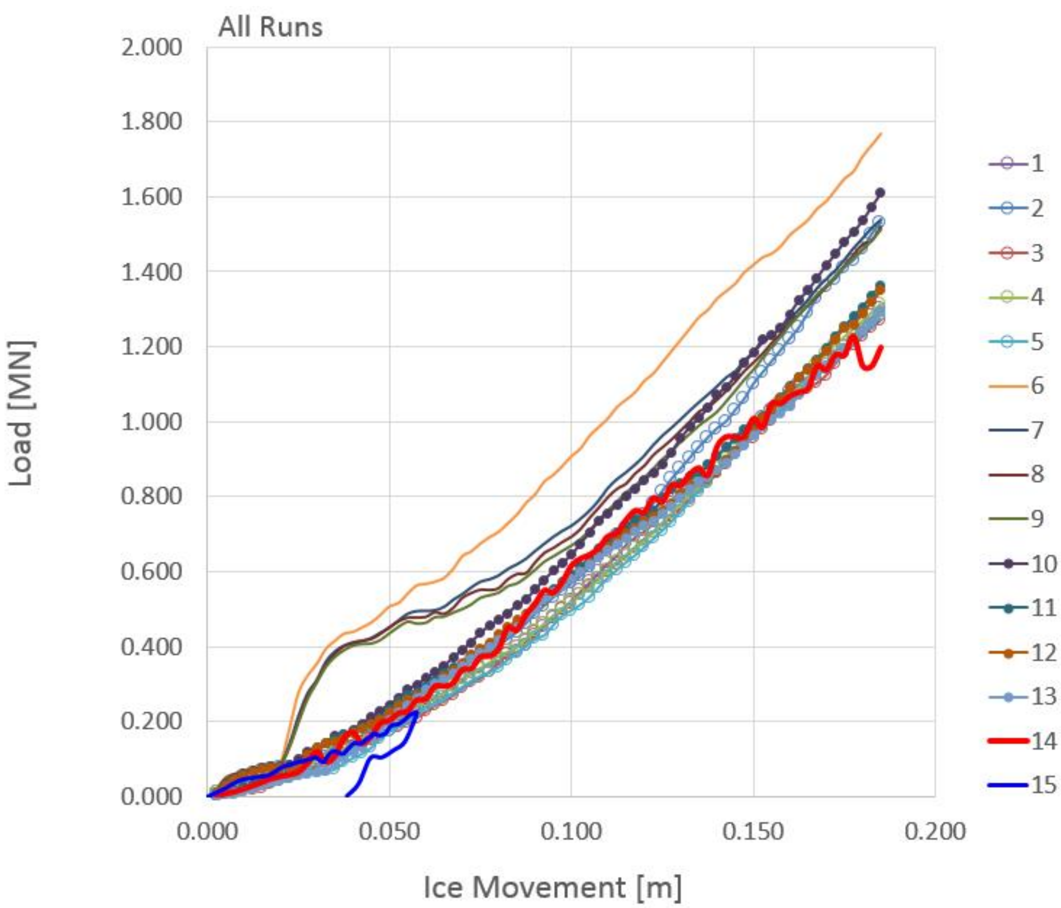

Figure 16: LS-Dyna Force vs Ice Displacement (all cases).

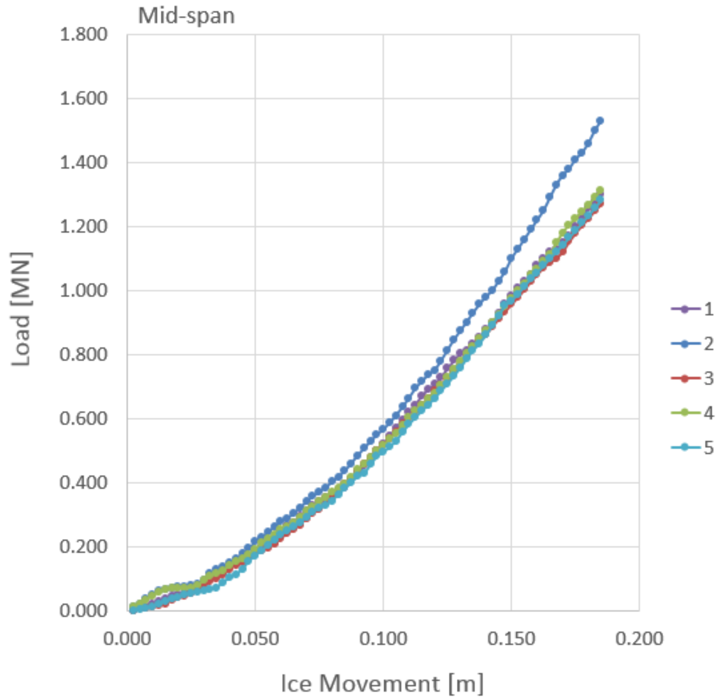

Figure 17: LS-Dyna Force vs Ice Displacement (load on longitudinal mid-span).

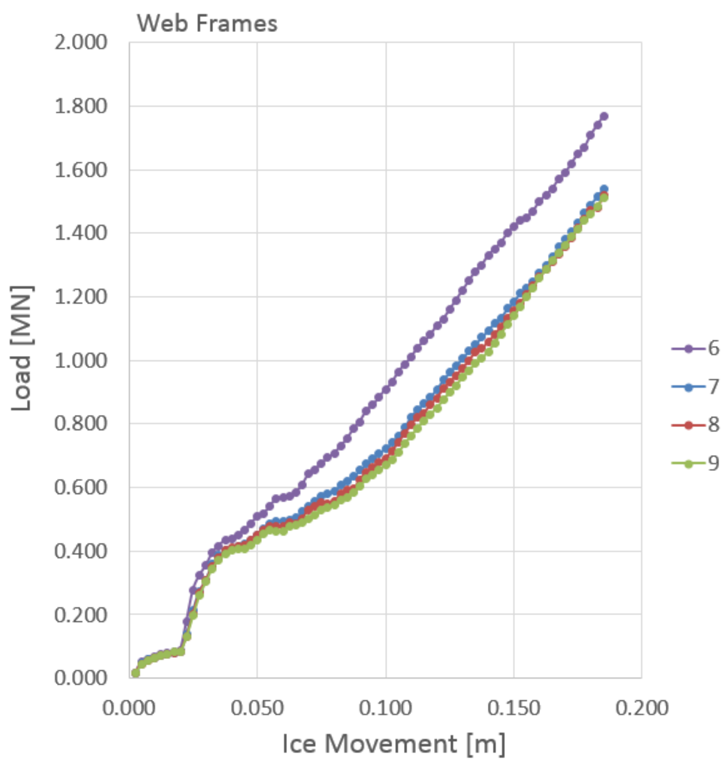

Figure 18: LS-Dyna Force vs Ice Displacement (load on web frame).

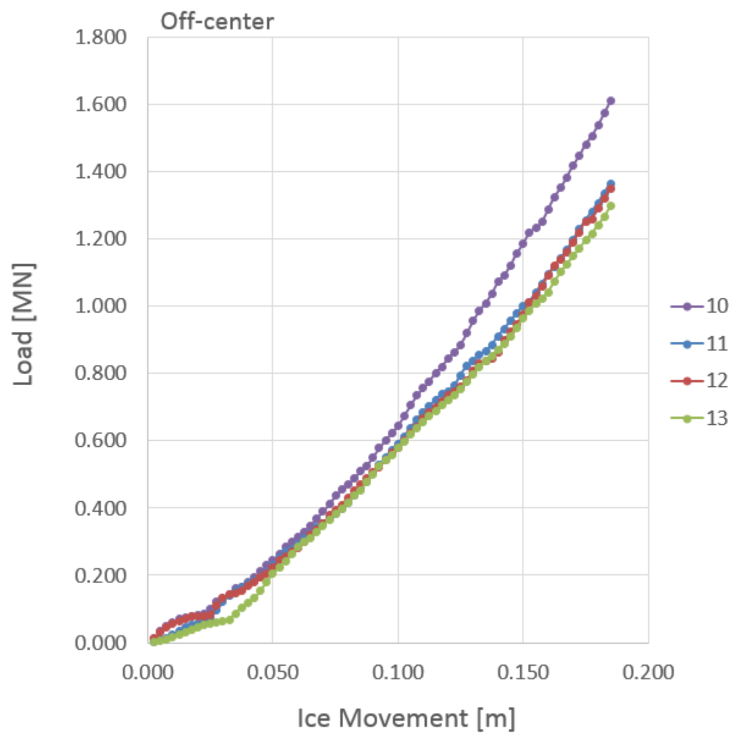

Figure 19: LS-Dyna Force vs Ice Displacement (load on longitudinal off-center).

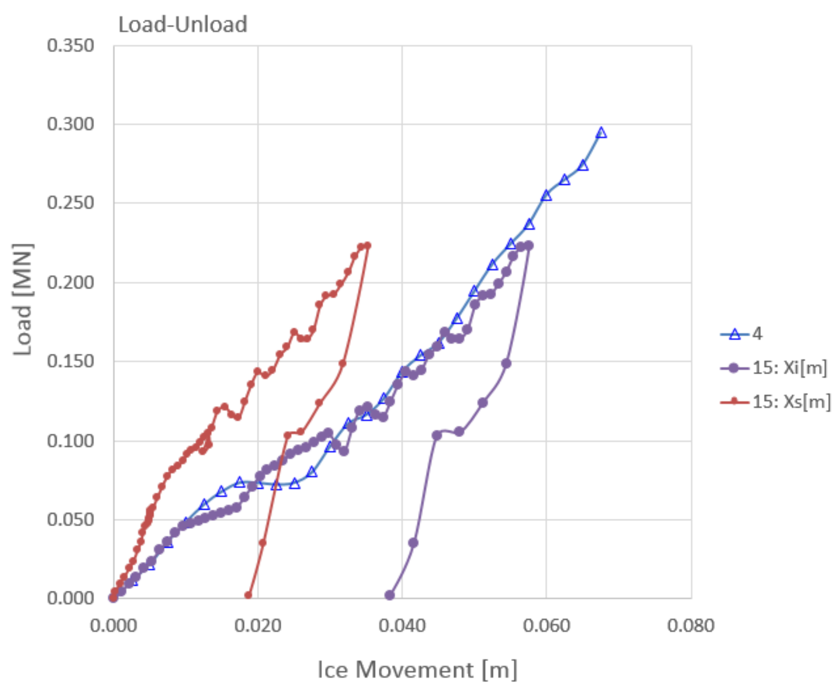

Figure 20: LS-Dyna Force vs Ice Displacement (Xi) and structural Displacement (Xs), at mid-span.

Figure 21 shows the analysis for case 4 and 4_26, in which the force is plotted against both the ice displacement and the structural deflection. This makes the structural capacity clearer and allows cross checking with the calculated plastic capacity. For the longitudinal frame, the load capacity for a central load patch at plastic hinge formation (from the Polar Rules limit states, see equation 57) is 111 kN, which does not seem inconsistent with the LS-Dyna results. Figure 22 shows case 8 with the load on the web frame. Once again the calculated plastic capacity, 400 kN in this case (see equation 66), seems to match quite well with the LS-Dyna results.

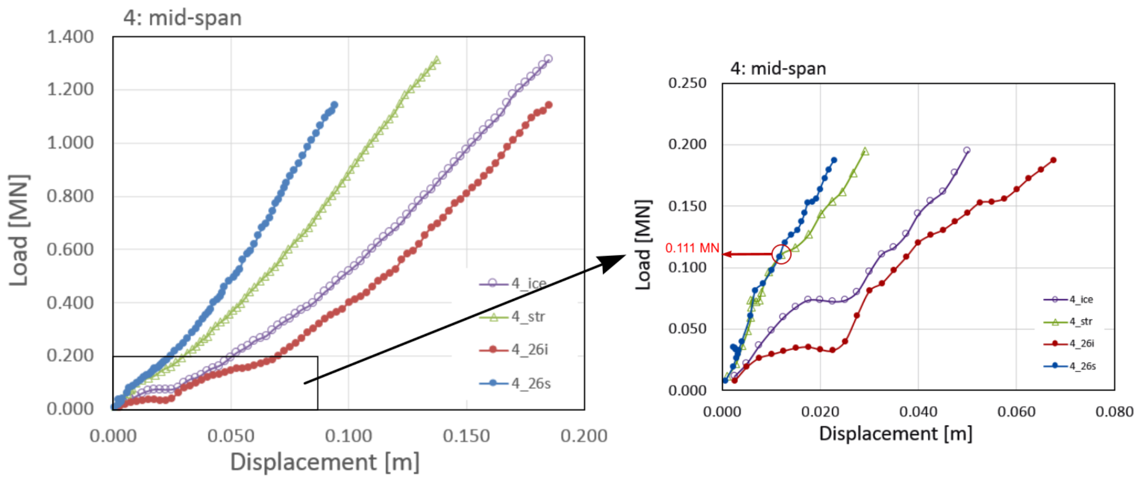

Figure 21: LS-Dyna Force vs ice displacement (i) and structural displacement (s), for case 4 with the EP6 and EP_26 ice models.

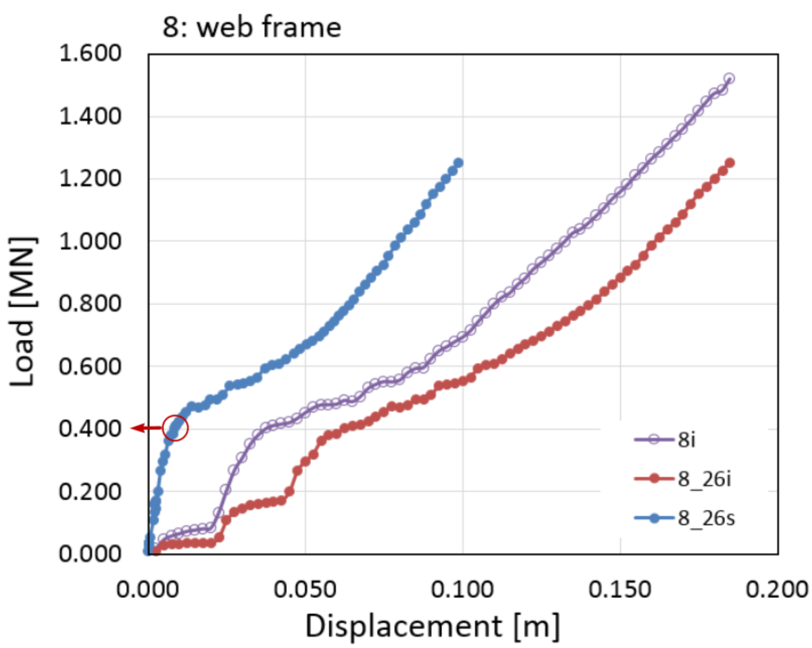

Figure 22: LS-Dyna Force vs ice displacement (i) and structural displacement (s), for case 8 with the EP6 and EP_26 ice models.

The final step in the analysis is to find an equation that can be used to assess the total energy absorption in a collision, taking ice and structural response into account. Run 4_26 was selected to be conservatively representative of the energy absorbing capacity of the ice and structure. The curve somewhat underestimates the capacity at the lower end, but adequately represents the rest. A rough estimate of the associated permanent deformation at these load levels is about 67% of the ice movement above 30mm, (for loads above 110 kN). So for example an ice load of 400 kN would cause about 46mm of permanent dent. The load equation (units MN, m) is;

$$F = 25\,x^{1.8} \tag{1}$$

$$d_{perm} = 0.67 * (x - .03) \tag{2}$$

Where F is the maximum force, x is the maximum ice-structure relative movement and d_{perm} is the size of the resulting dent.

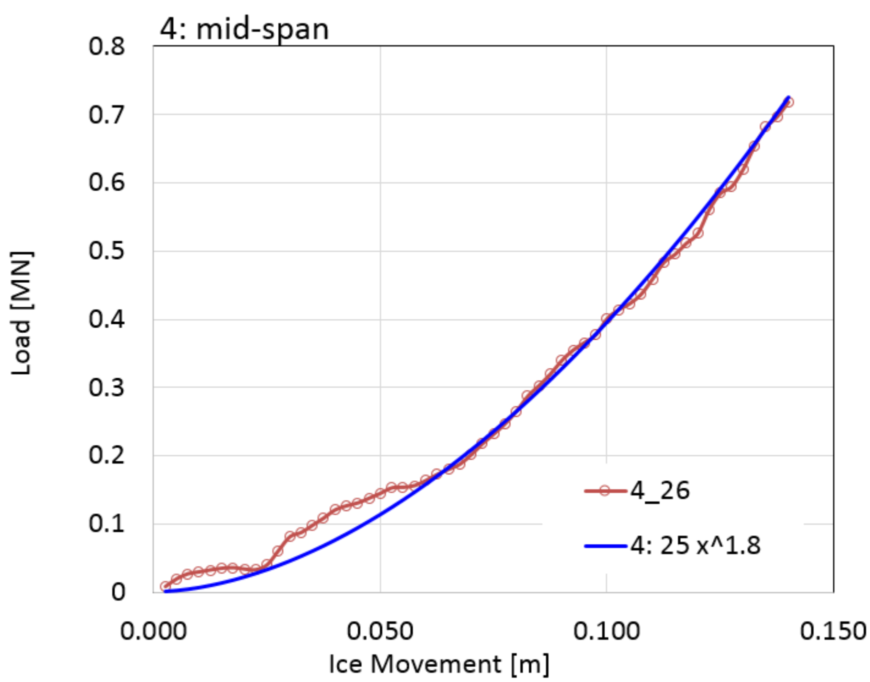

Figure 23: LS-Dyna Force vs ice displacement for case 4 with EP_26 ice model, and fitted curve.

Moving Load Analysis

Additional finite element runs were used to explore the effect of ice movement along the hull. This analysis was performed to get an initial sense of the importance of this issue to this design. Figure 24 shows the developing von Mises stresses as the load moves along the hull and inward. Figure 25 shows a view looking down the side of the hull, with the ice moving in. Figure 26 compares the response to a load directly on a web frame (case 8) to a load moving on to a web frame (case 14). The two cases are similar but the movement does cause some loss of capacity as is to be expected.

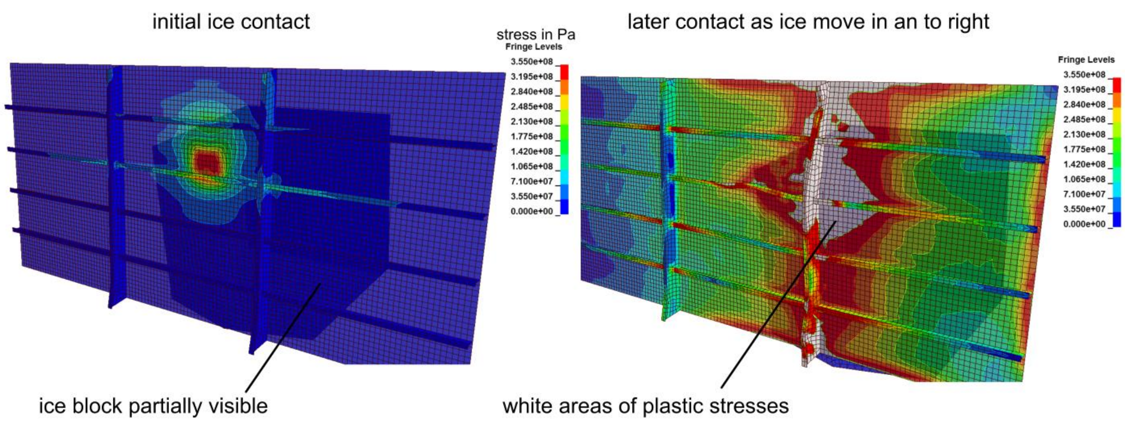

Figure 24: LS-Dyna moving load simulation images (Case 14).

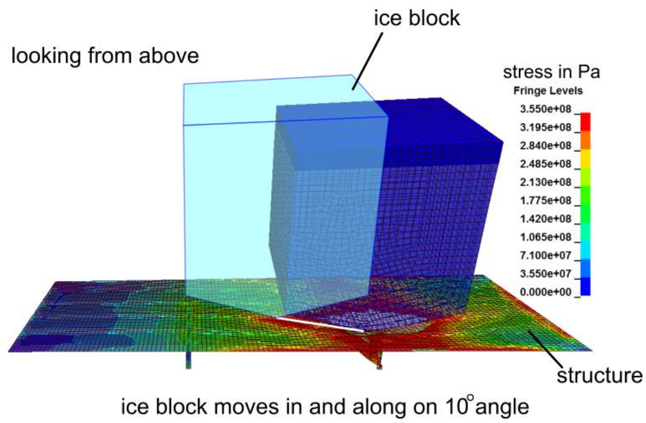

Figure 25: Sketch showing view from above showing the ice movement path at 10 degrees.

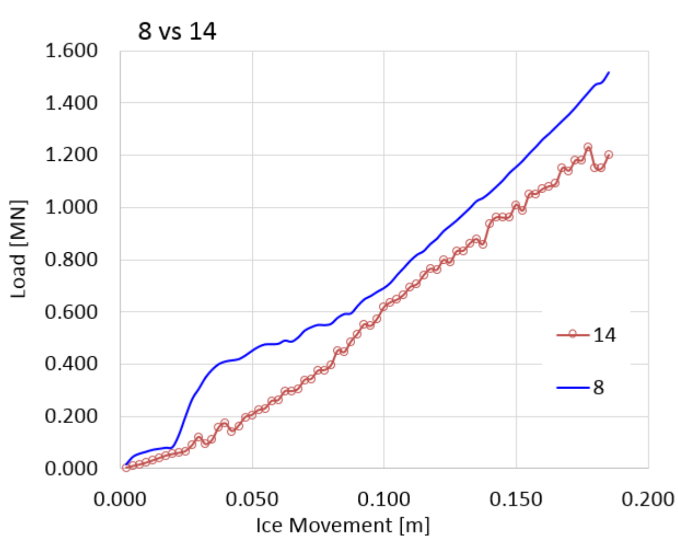

Figure 26: Load on web (8) vs moving load (14) moving on to web.

4. DDePS Ice Loads Assessment Tool

Direct Design for Polar Ships (DDePS) is a Microsoft Excel based spreadsheet tool capable of modeling a large set interaction scenarios between a ship and ice. The impact models, described in several technical reports by BMT Fleet Technology and ABS (Kendrick & Daley, 2006a, 2006b, 2009; Daley & Liu, 2009) are based on the same overall methodology found in the IACS Polar Class Unified Requirements but consider a wide range of scenarios, including infinite and finite ice floes. 25 total cases are available, each with as many as 25 user input variables. A complete list of available interaction scenarios are provided below.

1ai: Head On Ram (Wedge Bow) (initial Impact)
1ab: Head On Ram (Wedge Bow) Beaching (full solution)
1abs: Head On Ram (Wedge Bow) Beaching (simplified solution)
1bi: Head On Ram (Spoon Bow) (initial Impact)
1bb: Head On Ram (Spoon Bow) Beaching (full solution)
2a: Glancing Collision with sheet (Wedge Edge)
2b: Glancing Collision with sheet (Round Edge)
2c: Glancing Collision with mass (Spherical Edge)
2d: Glancing Collision with mass (Pyramidal Normal Edge)
3a: Reflected Collision with sheet (Wedge Edge)
3b: Reflected Collision with sheet (Round Edge)
4ai: Wedging Ram (square ice) (initial Impact)
5a Glancing Impact on the Midbody (Vertical Side Wedge Edge)
5b Glancing Impact on the Midbody (Vertical Side Round Edge)
6a Close Pack Pressure on the Midbody (Vertical Side Wedge Edge)
6b Ice Floe Impact Pressure on the Midbody (Vertical Side Wedge Edge)
7a_1 Stern hull collision (convex)
7a_2 Stern hull collision (convex)
7b_1 Pod collision (Side Wedge)
7b_2 Pod collision (End Wedge)
7b_3 Pod collision (End Cylinder)

The collisions are solved using an analysis of energy. From an external point of view, the interaction between the ship and ice floe is treated as a rigid body interaction in 3-dimensional space. In most impact cases, the collision is assumed to occur quickly, as if the ice-hull contact is fixed at a single point. From the internal dynamic point of the view, the ice crushing is modeled as a 'process' pressure-area model. The momentary ship-ice impact force can be analytically calculated in terms of energy and momentum balance.

For the purposes of this project, only the 2a – Glancing Impact scenario is used. An enhanced version of DDePS has been recently developed and is used here. It builds upon the original DDePS Case 2a (glancing impact with a wedge edge) by incorporating a number of new technical elements/user features and combines various structural limit checks. A list of new developments is provided below:

i. Input deck to save and load ship data files
ii. Updated flexural failure models (dynamic, friction, and horizontal stress effects)
iii. IACS Polar UR structural limit states (3 hinge collapse, shear capacity, plating)
iv. Large deflection limit states ("X" cm of allowable structural deformation)

v. Parametric analysis tool for rapid calculation of impact parameters (varying speed and thickness or floe size)
vi. Speed Check analysis tool for calculation of technical limit speeds for different structural limit states
vii. Database of bulb flats
viii. Grillage plotting tool (for visualization purposes)

Case 2a Interaction Scenario

For the purposes of evaluating technical safe limit speeds for ships in ice, DDePS Case 2a - glancing collision on the bow shoulder - is a reasonable impact scenario to form the core model. A simplified version of this interaction scenario, a glancing collision on the edge of a thick level ice sheet, was adopted for the IACS Polar Class Unified Requirements design ice load model (Daley, 2000). Figure 27 is a sketch of the assumed scenario for the safe speed evaluation.

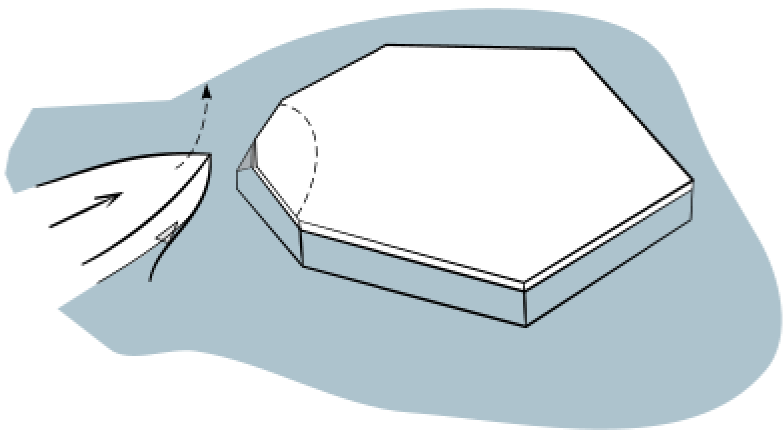

Figure 27: Safe Speed Collision Scenario

The total force during the impact event is limited by one of two limit conditions. When the ship impacts an ice feature, the force increases as the hull penetrates. This penetration will cease if either the ship runs out of energy (in other words - normal speed becomes zero) or the downward component of the force causes the ice to fail in flexure. The maximum structural impact force is determined either by a 'momentum limit' or by a 'flexural failure limit'. Therefore two models are required to determine the impact force: a crushing impact force model and a flexural force limit model. The following sections describe the detailed derivation of the ice impact model, ice crushing parameters, and a basic static flexural failure model.

Impact Model

The DDePS 2a model computes ice forces and ship responses for a glancing collision with an ice edge. Both finite sized and infinite floes (level ice sheet) can be modeled. The core method originates with Popov (1967) with an update by Daley (1999). Most earlier applications of the Popov model adopted the Kurdyumov-Khesin hydrodynamic ice crushing model to resolve the local contact pressure (Kurdyumov & Kheisin, 1976). That model is rate sensitive and can only be solved by numerical integration. The updated model by Daley uses a simple pressure-area relationship to resolve the local contact pressure and has an analytical solution (an equation). The update makes it possible and fairly simple to implement the calculation in a spreadsheet. The model assumes that all motions are the result of an impulse along the normal to the shell at the collision point. Currently, no sliding friction, hull curvature, or buoyancy forces are considered in the collision mechanics solution[1]. The only hydrodynamic effect considered is the added mass of the surrounding water. These assumptions are reasonable for single quick transient ship-ice impact situations.

The six motion equations for a general rigid body in 3D space can be converted into one motion equation (3) along the normal of the contact surface;

$$F_n = M_e \cdot \ddot{\zeta} \tag{3}$$

Where

ζ is the ice indentation from the initial contact point along the normal of the shell

$\ddot{\zeta}$ is normal acceleration of the impact point

M_e is the effective (or reduced) mass of the ship-ice impact system.

$$M_e = \frac{1}{\frac{1}{M_{e_{ship}}} + \frac{1}{M_{e_{ice}}}} \tag{4}$$

M_{e_ship} and M_{e_ice} are the effective mass of the ship and ice respectively at the contact point and can be obtained from equations (5) and (6);

$$M_{e_{ship}} = \frac{1}{\frac{l^2}{M_{sx}} + \frac{m^2}{M_{sy}} + \frac{n^2}{M_{sz}} + \frac{\lambda^2}{I_{sx}} + \frac{\mu^2}{I_{sy}} + \frac{\nu^2}{I_{sz}}} \tag{5}$$

$$M_{e\_ice} = \frac{1}{\frac{li^2}{M_{ix}} + \frac{mi^2}{M_{iy}} + \frac{ni^2}{M_{iz}} + \frac{\lambda i^2}{I_{ix}} + \frac{\mu i^2}{I_{iy}} + \frac{\nu i^2}{I_{iz}}} \tag{6}$$

The various mass terms refer to the various degrees of freedom. For example M_{sx} is the ship's mass plus added mass in surge, and I_{iy} is the mass moment of inertia of the ice floe in pitch. The ice floe is assumed to be oriented normal to the point of contact, somewhat simplifying the analysis.

$\ddot{\zeta}$ is the net acceleration at the point of contact (i.e., the second time derivative of the ice penetration). The situation is reduced to one in which one body is initially moving (the impacting body) and the other is at rest (the impacted body). The solution is found by equating the available (effective) kinetic energy with the energy expended in ice crushing:

$$KE_e = IE_i \tag{7}$$

Where, KE_e can be calculated using the following equation.

---

[1] Some new developments have been made to include frictional components in the Popov collision terms. This results of these developments will be included in future versions of DDePS presented in the associated documentation.

$$KE_e = \frac{1}{2} M_e V_n^2 \tag{8}$$

The available kinetic energy is the difference between the initial kinetic energy of the impacting body and the total kinetic energy of both bodies at the point of maximum force. If the impacted body has finite mass it will gain kinetic energy. Only in the case of a direct (normal) collision involving one infinite (or very large) mass will the effective kinetic energy be the same as the total kinetic energy. In such a case all normal motion will cease at the time of maximum force.

The indentation energy is the integral of the indentation force F_n on the crushing indentation displacement ζ_n;

$$IE = \int_0^{\zeta_c} F_n \, d\zeta_n \tag{9}$$

Ice Crushing Forces

The solution of the energy equations requires that force is described as a function of indentation. By using an ice 'process' pressure-area relationship, it is possible to derive a force-indentation relationship. This assumption means that ice force will depend only on indentation, and the maximum force occurs at the time of maximum penetration. The collision geometry is the ice/structure overlap geometry. The average pressure P_{av} in the nominal contact area A is related to the nominal contact area as;

$$P_{av} = P_o A^{ex} \tag{10}$$

P_o is the average pressure when the contact area is 1m^2 and *ex* is a constant (typically ex = -0.1). The above equation is a 'process' pressure area model (in contrast to a 'spatial' pressure area model). The 'process' pressure area model describes the development of the average contact pressure (and its nominal contract area) throughout the ice penetration process. A 'spatial' pressure area model describes the spatial variation of pressure in the contact area at a moment in time.

The ice force is related to the nominal contact area. The relationship between the normal indentation and normal contact area can be found for each specific contact situation. For the case of a general wedge edge ice geometry, as shown in Figure 28, the contact area can be expressed as;

$$A = \zeta_n^2 \left(\frac{\tan(\phi/2 - \theta) + \tan(\phi/2 + \theta)}{2\sin(\beta')\cos^2(\beta')} \right) \tag{11}$$

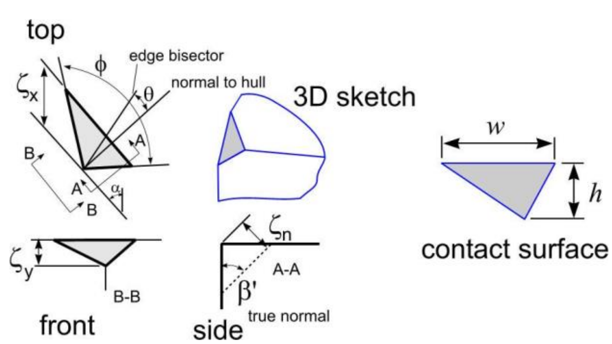

Figure 28: General wedge edge interaction geometry

For simplicity if we assume the wedge angle is normal to the hull, i.e. θ = 0, areas can be expressed as;

$$A = \zeta_n^2 \left(\frac{\tan(\phi/2)}{\sin\beta' \cos^2\beta'} \right) \tag{12}$$

The total normal force can then be expressed as;

$$F_n = P_{av}\, A = P_o\, A^{1+ex} \tag{13}$$

Combining equations (12) and (13), the impact force can be stated as;

$$F_n = P_o\, \zeta_n^{2+2ex} \left(\frac{\tan(\phi/2)}{\sin\beta' \cos^2\beta'} \right)^{1+ex} \tag{14}$$

After grouping shape terms;

$$F_n = P_o\ fa\ \ {\zeta_n}^{fx-1} \tag{15}$$

The ice indentation energy can be obtained by integrating the force over the depth of normal penetration;

$$IE_i = \int_0^{\zeta_c} F_n d\delta_n = \frac{P_o}{3+2ex} \left(\frac{\tan(\phi/2)}{\sin\beta' \cos^2\beta'} \right)^{1+ex} \zeta_n^{3+2ex} \tag{16}$$

Finally, the indentation energy can be stated as;

$$IE_i = \frac{P_o}{fx} fa\, {\zeta_n}^{fx} \tag{17}$$

Where the shape parameters are as follows;

$$fx = (3 + 2\ ex) \tag{18}$$

$$fa = \left(\frac{\tan(\phi/2)}{\sin(\beta') \cos^2(\beta')} \right)^{1+ex} \tag{19}$$

These indentation parameters are only valid for the ice contact shape shown in Figure 28 (see Daley, 1999).

By equating the ice indentation energy to the effective kinetic energy, the normal penetration ζ_n (or ice penetration ζ_c) can be expressed as;

$$\zeta_n = \zeta_c = \left(\frac{KE_e \cdot fx}{P_o \cdot fa} \right)^{1/fx} \tag{20}$$

The height and width of the true (albeit idealized) contact area can be represented as functions of ice crushing penetrations as shown in equations (21) and (22):

$$W_z = \frac{2\,\zeta_c \tan(\phi/2)}{\cos(\beta')} \tag{21}$$

$$H_z = \frac{\zeta_c}{\sin(\beta')\cos(\beta')} \tag{22}$$

In DDePS and the Polar Rules design ice load model, a simple patch translation is performed to convert the triangular load patch (caused by the geometric ship-ice overlap) to a rectangular load patch that is more applicable for direct structural analysis. The rectangular patch is then further reduced, maintaining a constant aspect ratio, to account for load concentration as ice edges spall off. This is illustrated in Figure 29 and dimensions for the final load patch width w and height b are derived in equations (23) through (26).

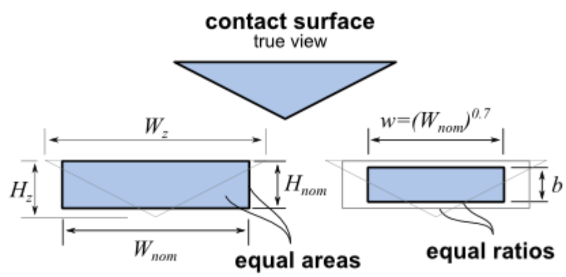

Figure 29: Translation and reduction of true contact surface to rectangular patch load

$$AR = W_z/H_z = 2\tan(\phi/2)\sin(\beta') \tag{23}$$

$$W_{nom} = W_z\sqrt{2} \tag{24}$$

$$w = W_{nom}{}^{0.7} \tag{25}$$

$$b = w/AR \tag{26}$$

Finally the remaining load patch dimensions – pressure P and line load Q can be expressed as:

$$P = F_n/A = F_n/(w \cdot b) \tag{27}$$

$$Q = F_n/w \tag{28}$$

Static Flexural Limit Model

In the IACS Polar Rules (2007) there is a simple quasi-static flexural limit force. The Polar Rules were formulated this way because they only need to apply to the design cases in the rules, which is always very thick ice. In such cases the quasi-static assumptions are quite valid. The same model is available in DDePS. The force normal to the ship's hull at the point of impact with the ice feature is limited to;

$$F_{n,UR} = \frac{1.2 \cdot \sigma_{flex} \cdot h_{ice}^2}{\sin(\beta')} \tag{29}$$

Where,

1.2 is a constant (assuming a wedge angle of 150° or 2.62 radians)

σ_{flex} is the flexural strength of the ice

h_{ice} is the ice thickness

β' is the angle measured from the vertical axis of the ship's hull at the point of impact (i.e. the normal frame angle)

Since the normal force is only a function of the flexural stress of the ice, we may say that the vertical force is simply:

$$F_v = 0.46 \cdot \sigma_{flex} \cdot h_{ice}^2 \cdot \phi \tag{30}$$

The Polar Rules flexural limit is not valid for cases of thinner ice and higher speeds. As a result, a new model is needed for the purposes of safe speed evaluation. This is further explained in the following section.

5. DDePS Enhancements

The follow sections describe two major technical enhancements included in DDePS_2a_SafeCheck. The first contains a series of updates to the flexural failure limit model. The second gives consideration to energy that is expended into deforming the structure.

Flexural Failure Limit Model

For the more general cases of thinner ice and higher speeds, the Polar Rule flexural force limit model is extended as shown below to include horizontal force, friction and dynamic effects. These are necessary enhancements that are critical to a safe speed assessment.

Horizontal Stress

Horizontal impact force causes compression stress in the ice feature. This compressive stress negates (or relieves) a portion of the tensile flexural stress in the top of the ice, thereby causing an apparent increase in the flexural capacity of the ice sheet. The horizontal stress σ_{comp} is given by:

$$\sigma_{comp} = F_h / A_{ice} \tag{31}$$

Where,

F_h is the horizontal force from both the normal and friction forces

A_{ice} is the cross sectional area of the ice feature

$A_{ice} = \phi \, l \, h_{ice}$ (see Figure 30)

ϕ is the ice edge angle

$l = 10 \ h_{ice}$ is the length of the ice cusp

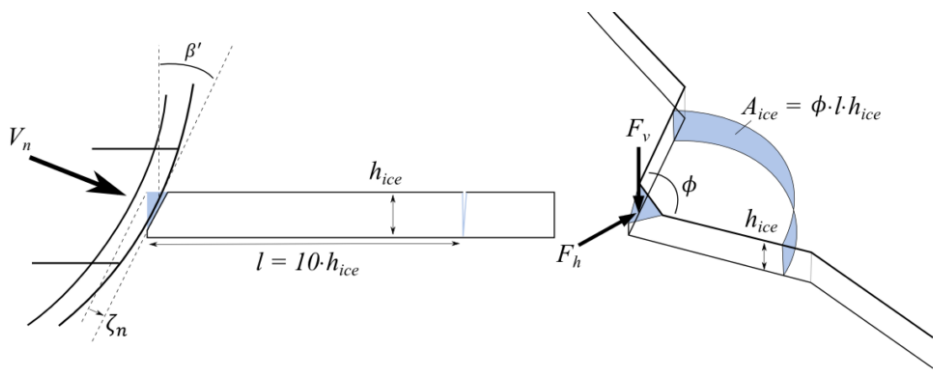

Figure 30: Geometry of flexural failure and ice cusp

Friction

Hull-ice friction is important because it affects the horizontal impact force, which influences the flexural force limit. Figure 31 shows that the horizontal component of both the normal and frictional forces are additive. The consideration of friction tends to increase the horizontal force (compressive stress) and decrease the vertical force (bending stress) in the ice during impact.

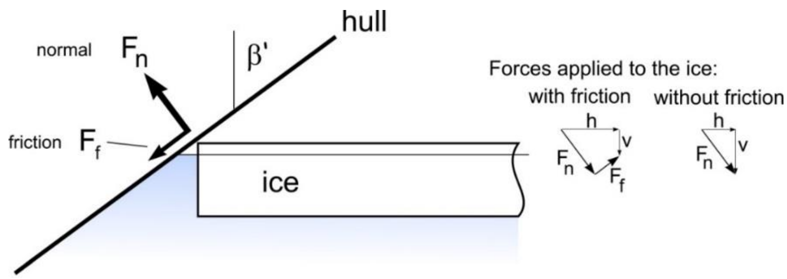

Figure 31: Hull-ice Contact showing Normal and Frictional Forces

When including friction, the horizontal force is;

$$F_h = F_n \cdot \cos(\beta') + \mu F_n \cdot \sin(\beta') \tag{32}$$

Where,

μ is the Coulomb friction factor

When including friction, the vertical force is;

$$F_v = F_n \cdot \sin(\beta') - \mu F_n \cdot \cos(\beta') \tag{33}$$

Design Normal Force

The total stress in the ice is given by:

$$\sigma_{total} = \sigma_{bend} - \sigma_{comp} \tag{34}$$

From F_v and F_h above we get:

$$\sigma_{total} = \frac{F_n \cdot (\sin(\beta') - \mu\cos(\beta'))}{C\ h_{ice}^2\ \phi} - \frac{F_n \cdot (\cos(\beta') + \mu\sin(\beta'))}{10\ h_{ice}^2\ \phi} \tag{35}$$

Solving for the normal force, and substituting σ_{flex} for σ_{total} to get the design normal force:

$$F_n = \frac{C\ \cdot \sigma_{flex} \cdot h_{ice}^2 \cdot \phi}{(\sin(\beta') - \mu\cos(\beta')) - C/10\ \cdot (\cos(\beta') + \mu\sin(\beta'))} \tag{36}$$

This design equation should be approximately equivalent to Polar Rules equation. Using a wedge angle of 150 degrees, a friction factor of 0.1 and β' of 45 degrees, the value of C needed to make the formula equivalent to the Polar Rules is 0.39. This generalizes the Polar Rules flexural model to any arbitrary ice wedge angle. So the formula for normal quasi-static force including friction effects becomes:

$$F_n = \frac{0.39\ \cdot \sigma_{flex} \cdot h_{ice}^2 \cdot \phi}{(\sin(\beta') - \mu\cos(\beta')) - 0.039\ \cdot (\cos(\beta') + \mu\sin(\beta'))} \tag{37}$$

Dynamic Effects by Daley and Kendrick

The following method was developed by Daley and Kendrick (2011) to include the dynamic support effects of water under the ice feature. Several authors (Colbourne, 1989; Valanto, 1996) have indicated a velocity dependence in the force required to break ice in bending, no analytical solutions were found to describe the phenomena. In response to the need for a practical analytical solution to this issue, a simple Froude scaling based method was developed. This method was offered as a starting point, with an understanding of the need for further improvement.

The dynamic effects of the water support arise from velocity dependent drag and acceleration dependent added mass; of which, the added mass effects are believed to dominate. Dynamic support effects are incorporated in the flexural force by scaling the design normal force (given above) with the ratio of Froude Numbers (raised to a power). A 'quasi-static' Froude Number is postulated, below which the "static" flexural case given above is used. For higher Froude numbers the flexural force is multiplied by a factor representing dynamic effects.

Previous experiments (Colbourne, 1989) suggest that the dynamic effects are related to Froude Number, a supposition that seems reasonable as Froude scaling will typically produce dynamic similitude. Further, Colbourne suggested that while the dynamic support increases with increasing Froude Number, the rate of change of this increase decreases with increasing Froude Number. Therefore linear scaling based on some static case would not be appropriate. Considering this, the following approach was adopted:

$$F_{nd} = \frac{0.39 \cdot \sigma_{flex} \cdot h_{ice}^2 \cdot \phi \cdot Kd}{(\sin(\beta') - \mu\cos(\beta')) - 0.039 \cdot (\cos(\beta') + \mu\sin(\beta'))} \tag{38}$$

Where,

$$Kd = \left(\frac{FN}{FN_s}\right)^n \text{ or } 1 \quad \text{whichever is greatest} \tag{39}$$

F_n is the quasi-static normal force as given above

F_{nd} is the dynamic normal force

FN is the Froude Number for the dynamic case

$$FN = Vn/\sqrt{g \cdot h_{ice}} \tag{40}$$

Vn is the speed in the direction normal to the plane of impact with the ice feature

$Vn = V_{ship}\sin(\alpha)\cos(\beta')$

g is acceleration due to gravity

h_{ice} is the ice thickness

$FN_s = V_{static}/\sqrt{g\, h_{ice}}$ is the Froude number for the static case (assume 0.1)

V_{static} is the maximum speed in the direction normal to the plane of impact with the ice feature at which the impact may be considered "static"

n is the scale factor modifying exponent (.33 chosen here)

Based on experience, a “static” Froude number of $FN_s = 0.1$ was chosen. This implies that the maximum speed at which an impact may be considered “static”, V_{static}, is dependent on ice thickness h_{ice} which is a reasonable assumption.

Figure 32 shows the normal crushing force (blue), the modified flexural force limit (green) and the IACS URII flexural force limit (red). Note that the horizontal portion of the green line represents the case without dynamic scaling (i.e., $V < V_{static}$).

For any given speed, the design normal force is the minimum of the crushing force and the flexural force limit. If the IACS URII flexural force model is used (red line) it would appear that the design normal force would be constant for ever increasing velocities; implying that the ship can travel ever faster through the ice feature without increasing hull loading. The modified flexural force model (green line) exhibits increasing design normal force with increasing velocity.

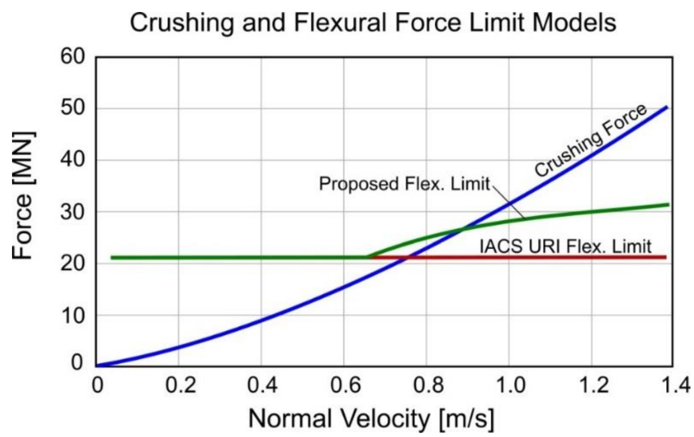

Figure 32: Illustration of Crushing and Flexural Force Models

Updated Dynamic Effects based on work by Sazidy

M.S. Sazidy (Sazidy, Daley, Colbourne, & Wang, 2014; Sazidy, Daley, & Colbourne, 2014) studied the dynamic factors involved in the contact between a ship side and ice. Figure 33 illustrates the type of analysis that was used to study dynamic effects. The ice edge was modelled using LS-Dyna, which is commercially available explicit dynamic finite element program. The program was able to model the ice edge crushing and flexural response in a time-history analysis that accounts for and can demonstrate dynamic effects.

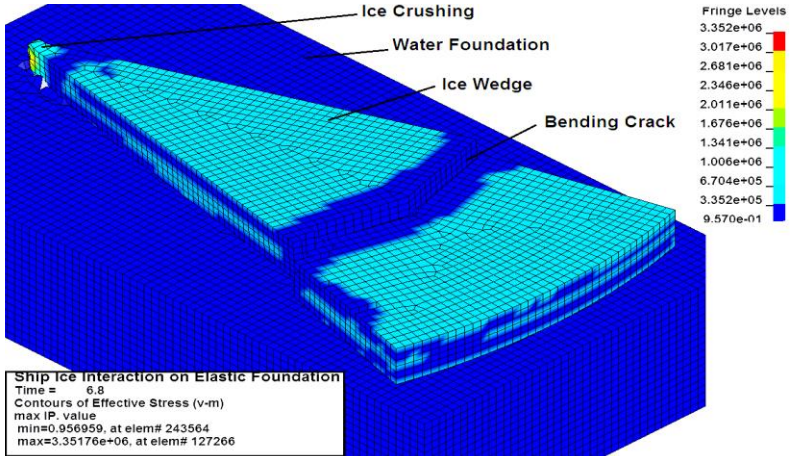

Figure 33: Simple ice wedge breaking pattern (Sazidy, Daley, Colbourne, et al., 2014)

Equation (41) is the new flexural failure model of vertical impact force for dynamic ice wedge breaking.

$$F_{vd} = 0.29\ \mathrm{n}_w^{-0.3}\ \sigma_f\ h^2\ \theta\ \ K_v \tag{41}$$

where n_w is the number of wedges. The dynamic factor K_v is defined as:

$$K_v = 1 + 2.57 \sin\alpha \cos\beta' \,(\theta/n_w)^{0.2} FN^{0.26} \tag{42}$$

where Froude Number (FN) is defined in equation (40). The normal impact force can be expressed in the following form:

$$F_{nd} = \frac{F_{vd}}{\sin\beta'} \tag{43}$$

Sazidy's analysis did not take friction into account, although it did implicitly take the effect of the horizontal stress into account. As a result equation (38) and (43) are not quite comparable. Sazidy's formulation can be adjusted to be compatible with equation (38) by making the following change.

$$F_{nd} = \frac{0.284\ \mathrm{n}_w^{-0.3}\ \sigma_f\ h^2\ \theta\ \ K_v}{(\sin(\beta') - \mu\cos(\beta')) - 0.0284\ \cdot (\cos(\beta') + \mu\sin(\beta'))} \tag{44}$$

Equation (44) as well as Equations (43) and (38) are a function of many parameters. Figure 34 shows a comparison of the various equations for a set of selected parameters (also listed in the figure). In DDePS_2a_SafeCheck several flexural failure limit options are available. The user can select from the following options:

- static – equation (29)
- dynamic1 – equation (38)
- dynamic2 – equation (44)

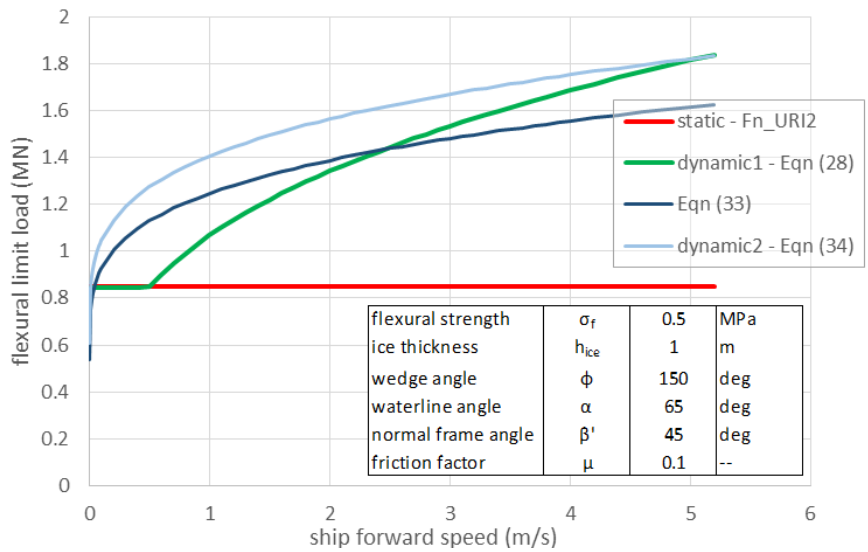

Figure 34: Comparison of Dynamic Formulae

Deformable Structure

During an ice-ship interaction event, energy may be absorbed by deforming the structure elastically and plastically in addition to crushing the ice. Most standard models of ship-ice interaction (e.g. the design ice load model in the Polar Rules) assume the ship to be a perfectly rigid body. This assumption is in general valid for stiff structures (i.e. high ice class ships). However for non-ice classed (or even light-ice classed) ships, a substantial portion of the available kinetic energy can be expended into deforming the relatively compliant structure. This concept is generalized by the following energy balance equation where IE_i and IE_s are the ice and structural indentation energies respectively.

$$KE_e = IE_i + IE_s \tag{45}$$

For complex structural arrangements, no analytical equation exists to represent the combined structural and ice indentation processes. Daley & Kim (2010) approached this problem numerically by simplifying the ice load to a point load (highly localized force) and the plastic response of the structure was represented by a linear deformation function (46).

$$F_n = k_p \zeta_n + F_o \tag{46}$$

The concept, sketched in Figure 35, was implemented into a spreadsheet tool as a practical way to evaluate ice loads with the consideration of the ship's plastic deformation. Daley and Kim applied a 'design of experiments' (DOE) method to develop regressions models for the k_p and F_o terms. The models are functions of a range of input variables which represent the structural parameters of a stiffened panel (frame spacing, span, dimensions, plate thickness, etc.). This is a very useful model that can easily be implemented into a spreadsheet tool however for large collisions that involve extensive damage, the assumption of a point load is no longer valid.

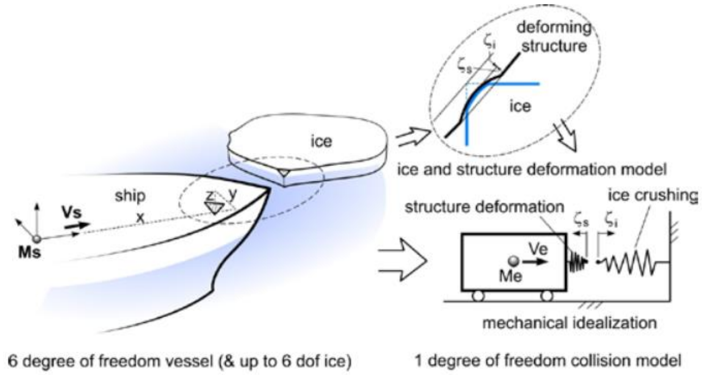

Figure 35: Concept sketch for compliant ship-ice collision model (from Daley & Kim, 2010)

In order to appropriately quantify the structural indentation energy, a more sophisticated approach has been developed in this study which takes into account a more realistic developing load patch. Consider the sketch in Figure 36. As the structure penetrates the ice edge (idealized as wedge edge) local plastic and elastic deformations develop in the structure along with ice crushing. The load patch shape is slightly altered compared to the case of a rigid structure (see in Figure 36).

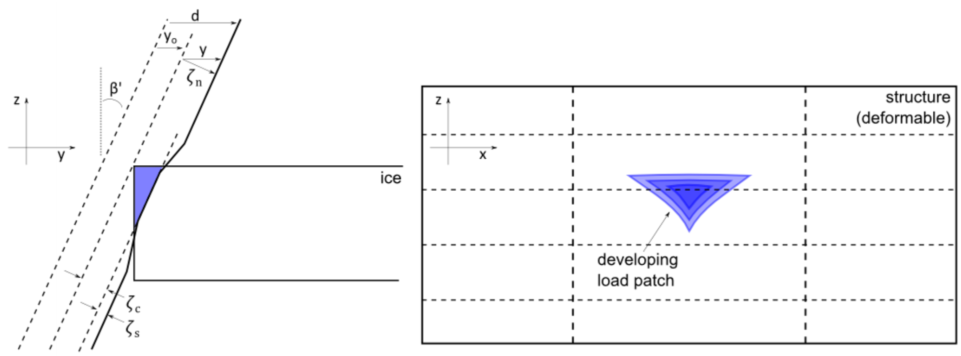

Figure 36: Sketch of interaction model considering structural deformation

The total contact force can be expressed as a power function (47) of 'total' normal displacement (i.e. 'total' normal penetration) of the structure from its initial contact point ($\zeta_n = \zeta_s + \zeta_c$). Specific values for C_s and k can be obtained from a numerical simulation of a ship grillage impacting an ice edge. This was described in detail above (see Figure 23);

$$F_n = C_s \zeta_n^k \tag{47}$$

The sum of ice and structural indentation energies can the obtained by integrating the total force over the depth of 'total' normal penetration;

$$IE_i + IE_s = \int_0^{\zeta_c} F_n d\zeta_n \tag{48}$$

By equating the sum of the ice and structural indentation energies to the effective kinetic energy as shown in equation (49),

$$KE_e = \int_0^{\zeta_c} F_n d\zeta_n = \frac{C_s \zeta_n^{k+1}}{k+1} \tag{49}$$

The ‘total’ normal penetration ζ_n can be expressed as;

$$\zeta_n = \left(\frac{KE_e(k+1)}{C_s}\right)^{\frac{1}{k+1}} \tag{50}$$

This ‘total’ normal penetration ζ_n can be used to solve for total contact force using equation (47). Then by rearranging equation (15), one can solve for the ice crushing portion of the penetration;

$$\zeta_c = \left(\frac{F_n}{P_o \cdot fa}\right)^{\frac{1}{fx-1}} \tag{51}$$

The structural indentation portion is then simply the difference;

$$\zeta_s = \zeta_n - \zeta_c \tag{52}$$

The LS-Dyna analysis was used to tune the ice model (rigid structure) and obtain the C_s and k terms for a particular bow section of the Notional Destroyer (deformable structure). The value for C_s is 25 and k is 1.8 (units of MN and m).

6. Structural Limit States

Two different criterion have been used to assess the safe speeds of the Notional Destroyer’s structural capacity (i.e. limit state) against the applied ice load for a given interaction scenario;

1. Direct Limit Load Criteria (Ice Crushing Energy)
2. Large Deflection Criteria (Ice and Structural Compliance)

These are further described in the following sections. The user can select up to two “limit checks” in the *SpeedCheck* tab (limit check A and limit check B).

Direct Limit States (Ice Crushing)

The direct line load criteria method was presented and discussed in detail in a conference paper authored by ABS (Dolny, Yu, Daley, & Kendrick, 2013). Limit speeds are established when the loading term (Q_{load}) exceeds the structural capacity (Q_{cap}) for a given interaction scenario (speed, impact location, ice thickness or floe size, strength parameters, etc.).

$$v_{lim}(h) = v_i\left(Q_{load} > Q_{cap}\right) - \Delta v \tag{53}$$

Q_{cap} is calculated from equations (53) and (54), and is based on the technical background for the plastic structural limit states adopted by the IACS Polar Class Unified Requirements. These limit states define the point where denting begins to occur. Therefore, the speeds computed by this approach are set such that there will be *no observable deformation* of the hull. Several limit states, expressed in terms of pressure and taking into account the actual structural dimensions, are considered. The capacity of the frame can be considered as the minimum of limit pressures.

$$p_{cap} = \min(p_1, p_2, \dots, p_n) \tag{54}$$

When combined with the ice load model (requires the applied load height), the frame capacity can be expressed in terms of a line load capacity as shown in equation (55).

$$Q_{cap} = \frac{F_{cap}}{s} = p_{cap} \cdot b \tag{55}$$

The structural limit states adopted by the Polar Rules provide a set of analytical expressions for the capacity of primary stiffening members (Kendrick and Daley, 2000; Daley, Kendrick and Appolonov, 2001; Daley, 2002). These models were derived on the basis of energy methods and make use of plastic limit analysis. They were validated against extensive numerical simulations and physical experiments. Conceptual sketches of the limit states are shown in Figure 37.

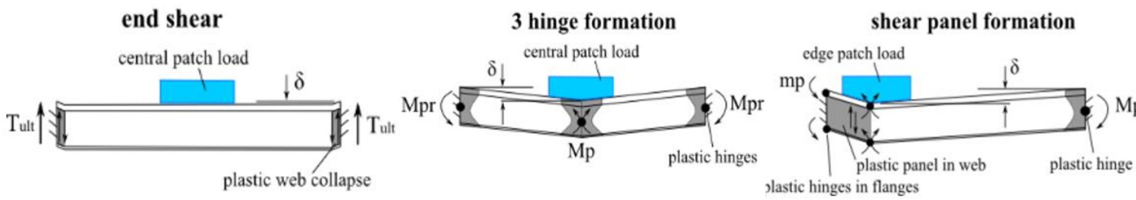

Figure 37: Structural limit states for frames subjected to lateral patch loads

The following sections present capacity equations, in terms of limit pressures, for transverse and longitudinal framing orientations. It should be understood that these notional "capacities" are in reality well below any ultimate strength due to strain hardening, membrane response and other effects. A robust structure can support 5-10 times the Polar Rules design load, as shown by extensive FE and experimental work (Daley & Hermanski, 2009; Manual, Gudimelta, Daley, & Colbourne, 2013).

The speed estimates from this approach will be quite conservative. This is because no structural compliance is considered. The Notional Destroyer has such a light hull structure that a significant amount of energy is stored elastically (see Figure 20 to illustrate).

Transverse framing

The limit state capacities used in the IACS Polar Rules are described below. The pure shear collapse limit in which a transverse frame will fail by *shear* at the supports due to a *central load* patch is shown in equation (56).

$$p_{lim,shear} = \frac{2\, A_o\, \sigma_y}{b\, s\, \sqrt{3}} \tag{56}$$

Equations (57) and (60) consider pressure applied as a *central load* patch which causes the formation of *three plastic hinges* (one central and two end hinges) under bending. The frame is considered to have two fixed supports (j = 2). For case 1 (57), the total bending capacity is reduced based on a relatively simple quadratic shear-moment interaction.

$$p_{lim,c1} = \frac{1}{12\ Z_{pns} + 1} \sigma_y Z_p \frac{4}{b\, s\, a\left(1 - \frac{b}{2\, a}\right)} \tag{57}$$

$$Z_{pns} = \left[\frac{Z_p}{A_o\, a\, \left(1 - \frac{b}{2\, a}\right)}\right]^2 \tag{58}$$

The force to cause the collapse condition can be written as;

$$F_{lim,c1} = \frac{1}{12\ Z_{pns} + 1} \sigma_y Z_p \frac{4}{a\left(1 - \frac{b}{2\,a}\right)} \tag{59}$$

Case 2 (60) includes a modification in which the bending capacity is reduced only by the loss of web capacity.

$$p_{lim,c2} = \frac{\left[2 - kw + kw\sqrt{1 - 48\,Z_{pns}\,(1 - kw)}\right]}{12\,Z_{pns}\,kw^2 + 1} \sigma_y Z_p \frac{4}{b\ s\ a\left(1 - \frac{b}{2\,a}\right)} \tag{60}$$

A fourth limit state (61) considers the case of an off-center (*end case*) or asymmetric load in which plastic hinges form in the flanges along with a shear panel in the web near the load and a large plastic hinge at the far end.

$$p_{lim,asy} = \left[\frac{A_w}{\sqrt{3}} + \frac{Z_p}{l}\ fz\right] \frac{\sigma_y}{b\ s\left(1 - \frac{b}{2\,a}\right)} \tag{61}$$

The capacity of the transverse frame can be considered as the minimum of the four limit states provided above;

$$p_{cap} = \min\left(p_{lim,c1}, p_{lim,c2}, p_{lim,asy}, p_{lim,shear}\right) \tag{62}$$

Longitudinal Framing

The longitudinal framing limit states are based on the same principles as the transverse cases however the relative orientation of the load patch is simply rotated. The pure shear collapse limit in which a longitudinal frame will fail by shear at the supports due to a central and symmetrical load patch is shown in equation (63).

$$p_{lim,shear} = \frac{2\,A_o\,\sigma_y}{w_{1L}\,b_{1L}\sqrt{3}} \tag{63}$$

For longitudinal frames, the effective load patch height is taken as:

$$b_{1L} = \min(b, s) \tag{64}$$

The effective load patch width is taken as:

$$w_{1L} = \min(w, a) \tag{65}$$

Equations (66) considers a central and symmetrical load patches which causes the formation of three plastic hinges (one central and two end hinges) under bending. The frame is considered to have two fixed supports (j = 2).

$$p_{lim,c1} = \frac{1 + \frac{j}{2}\sqrt{3\,(j^2 - 4)\,Z_{pnsL} + 1}}{3\,j^2\,Z_{pnsL} + 1}\sigma_y Z_p \frac{4}{w_{1L}\,b_{1L}\;a\left(1 - \frac{w_{1L}}{2\,a}\right)} \tag{66}$$

Where,

$$Z_{pnsL} = \left[\frac{Z_p}{A_o\,a\,\left(1 - \frac{w_{1L}}{2\,a}\right)}\right]^2 \tag{67}$$

The force on the frame required to cause collapse can be written as;

$$F_{lim,c1} = \frac{1 + \frac{j}{2}\sqrt{3\,(j^2 - 4)\,Z_{pnsL} + 1}}{3\,j^2\,Z_{pnsL} + 1}\sigma_y Z_p \frac{4}{a\left(1 - \frac{w_{1L}}{2\,a}\right)} \tag{68}$$

The capacity of the longitudinal frame can be considered as the minimum of the two limit states provided above.

$$p_{cap} = \min\left(p_{lim,c1}, p_{lim,shear}\right) \tag{69}$$

Large Deflection Limit States

When the structural indentation energy model is included in the collision model, the amount of structural deformation (plastic + elastic) can be calculated for a given interaction scenario. Limit speeds are established when the structural indentation at the given load exceeds the allowable deformation level set by the user.

$$v_{lim\_defl}(h) = v_i\left(\zeta_s > \zeta_{s\_allow}\right) - \Delta v \tag{70}$$

7. Operational Assessment of Notional Destroyer

This section presents an assessment of the ice operational limits, from a structural capacity perspective, of the Notional Destroyer. Various relationships will be presented, showing the influence of ice mass, ice strength and thickness on the technical safe speed that the Notional Destroyer can attain. Under this section, the safe speeds will be determined two ways. In the first case, called *Rigid-P/A* (Rigid Structure -Pressure/Area) it is assumed that all the vessels' effective kinetic energy is absorbed in ice crushing. This is the standard approach taken for icebreaker design, as the structures are elastically very rigid and no permanent deformation is permitted at the design point. In the second case, called *EP-P/A* (Elasto/Plastic -Pressure/Area) the kinetic energy is absorbed by ice crushing and the elasto-plastic response of the hull.

The analysis presented below contains many assumptions about the collision mechanics and parameters. Some were listed above, while others include;

- The ship is assumed to be moving **straight forward**. This could be relaxed but would greatly expand the number of parameters to be included.
- Simple added mass assumptions for both ship and ice were assumed.

Rigid P/A Direct Limits - Collison Cases

Force vs Speed, Various Diameters, One Thickness

These plots (Figure 38 through Figure 54) show how speed, ice thickness and floe size combine to create ice impact forces at station 3 on the Notional Destroyer. For small thin floes the loads are within the vessel capability at all speeds. As floe size and thickness increase, the forces at higher speeds exceed the structural capacity (for these assumptions).

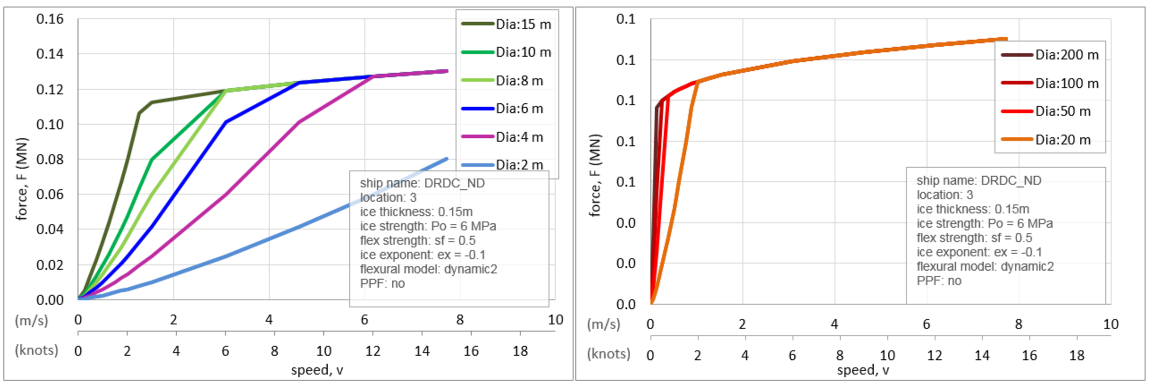

Figure 38: P/A Collision Forces vs. Speed (15cm Ice Thk., various Floe Dia.)

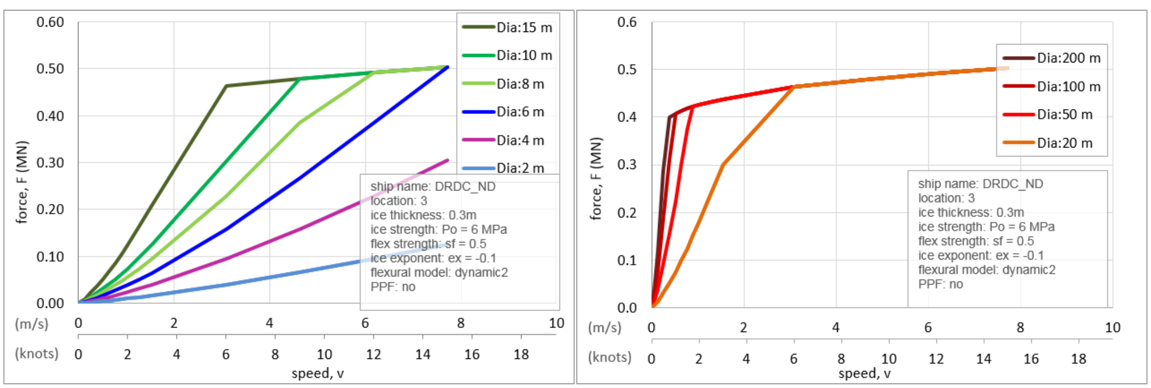

Figure 39: P/A Collision Forces vs. Speed (30 cm Ice Thk., various Floe Dia.)

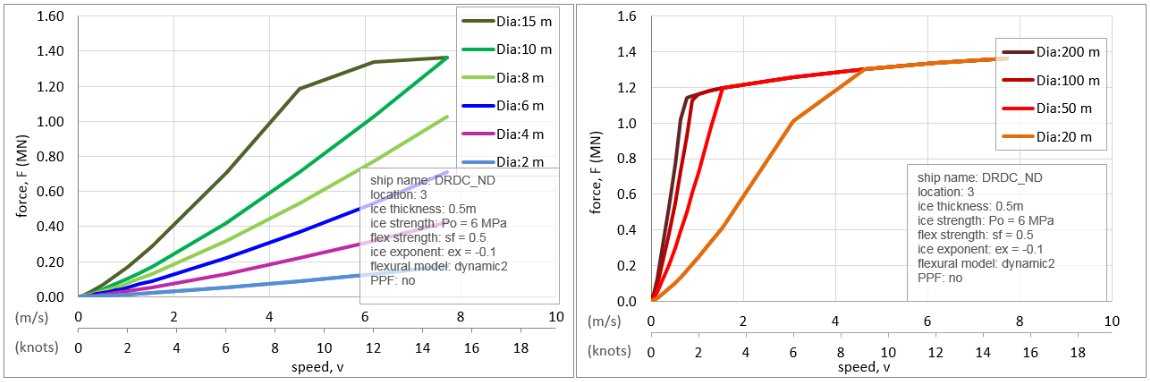

Figure 40: P/A Collision Forces vs. Speed (50 cm Ice Thk., various Floe Dia.)

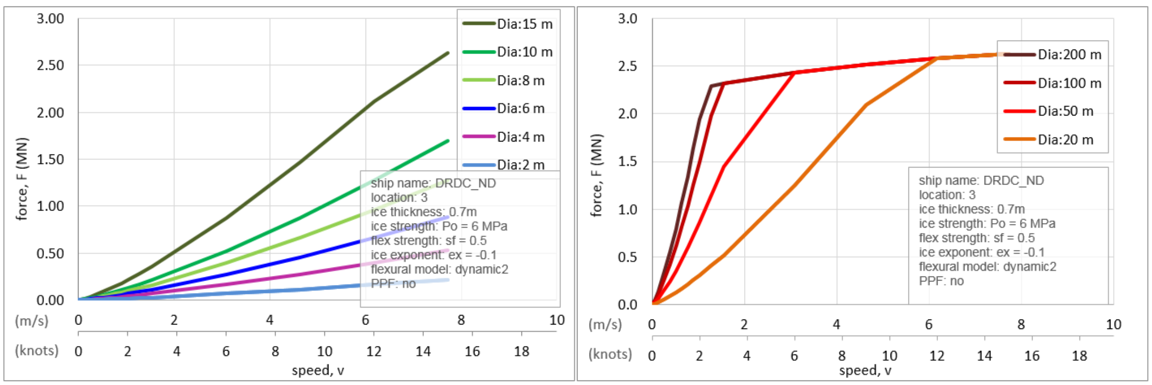

Figure 41: P/A Collision Forces vs. Speed (70 cm Ice Thk., various Floe Dia.)

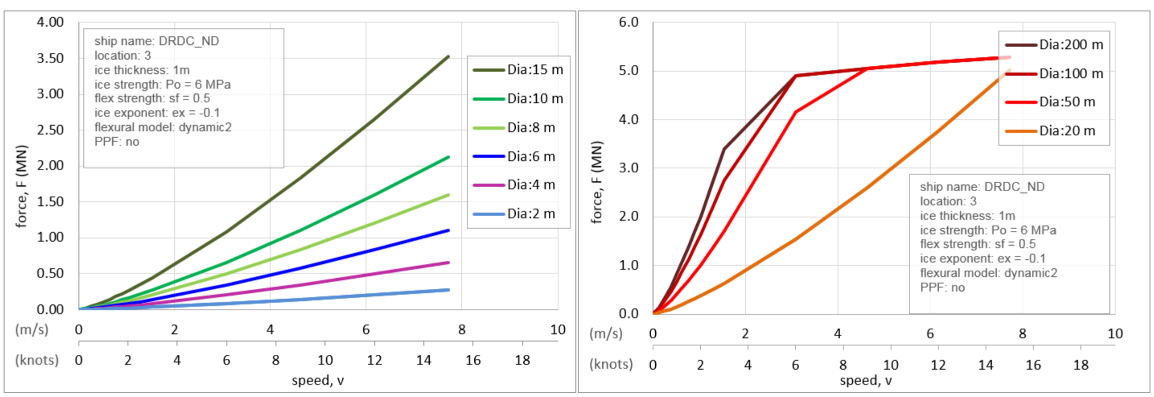

Figure 42: P/A Collision Forces vs. Speed (1.0 m Ice Thk., various Floe Dia.)

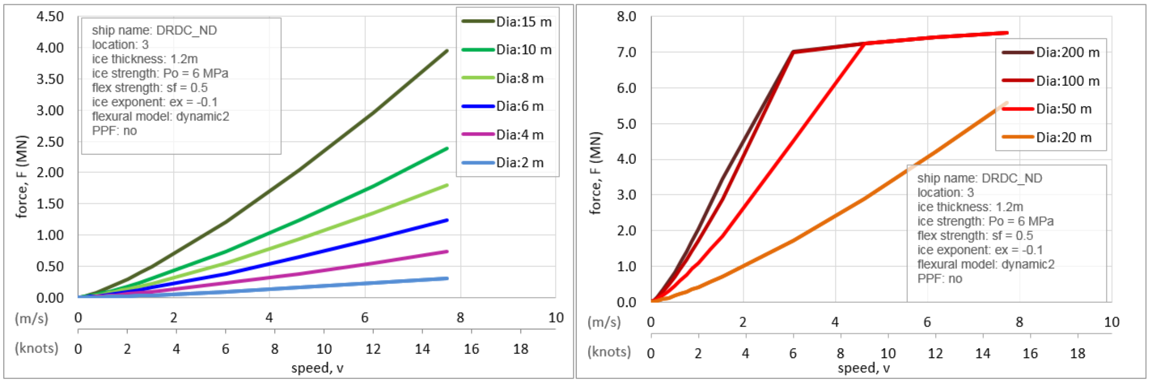

Figure 43: P/A Collision Forces vs. Speed (1.2 m Ice Thk., various Floe Dia.)

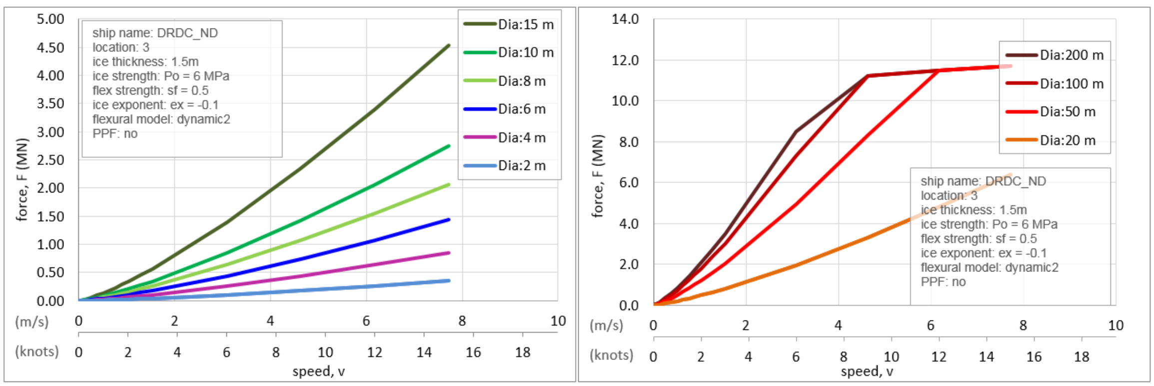

Figure 44: P/A Collision Forces vs. Speed (1.5 m Ice Thk., various Floe Dia.)

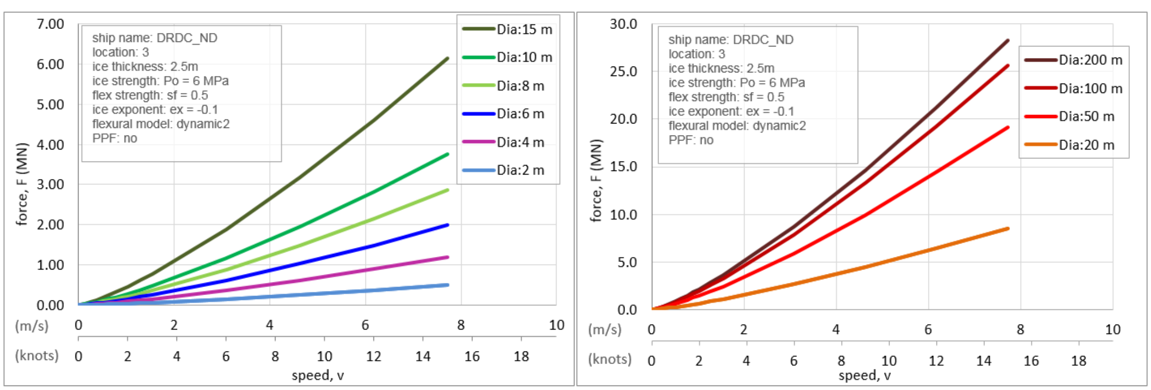

Figure 45: P/A Collision Forces vs. Speed (2.5 m Ice Thk., various Floe Dia.)

Force vs Speed, Various Thicknesses, One Diameter

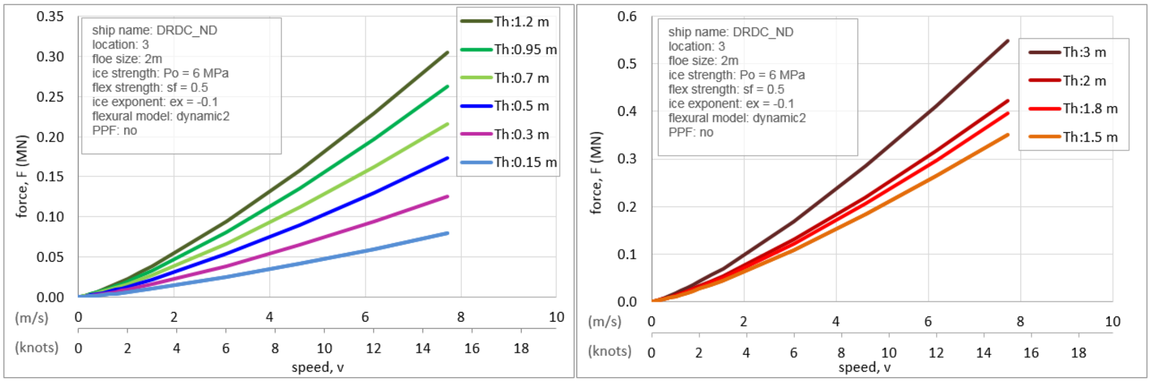

Figure 46: P/A Collision Forces vs. Speed (2 m Floe Dia., various Ice Thk.)

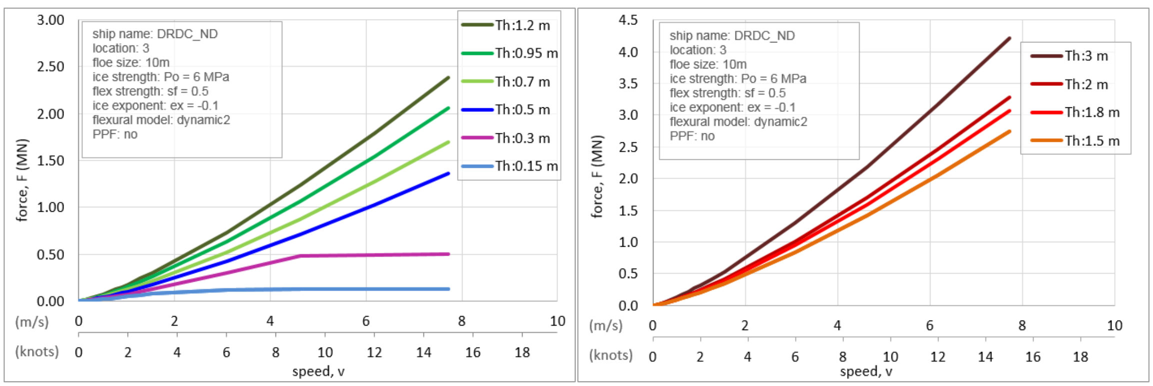

Figure 47: P/A Collision Forces vs. Speed (10 m Floe Dia., various Ice Thk.)

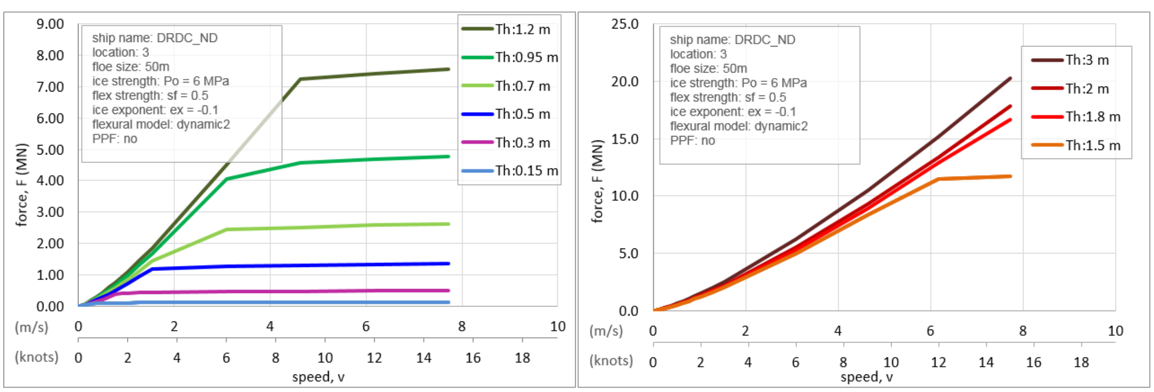

Figure 48: P/A Collision Forces vs. Speed (50 m Floe Dia., various Ice Thk.)

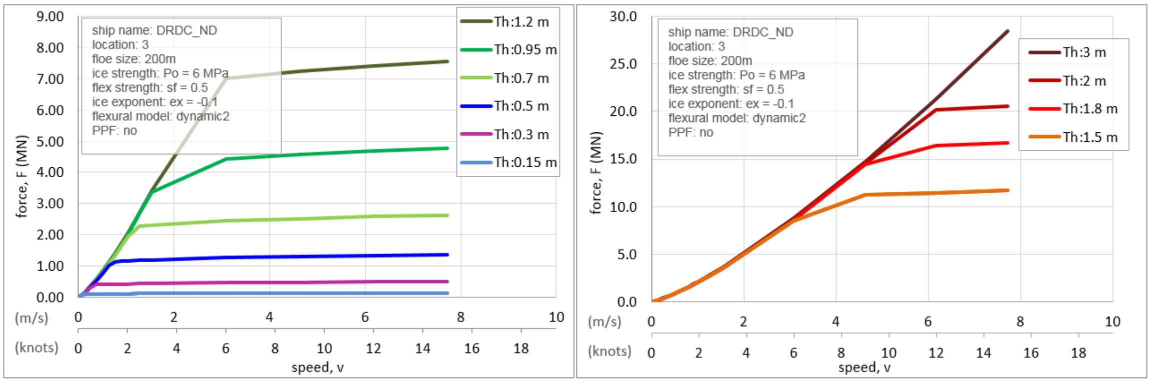

Figure 49: P/A Collision Forces vs. Speed (200 m Floe Dia., various Ice Thk.)

P/A Direct-Technical Safe Speed vs Thicknesses and Floe Size, 4 Locations

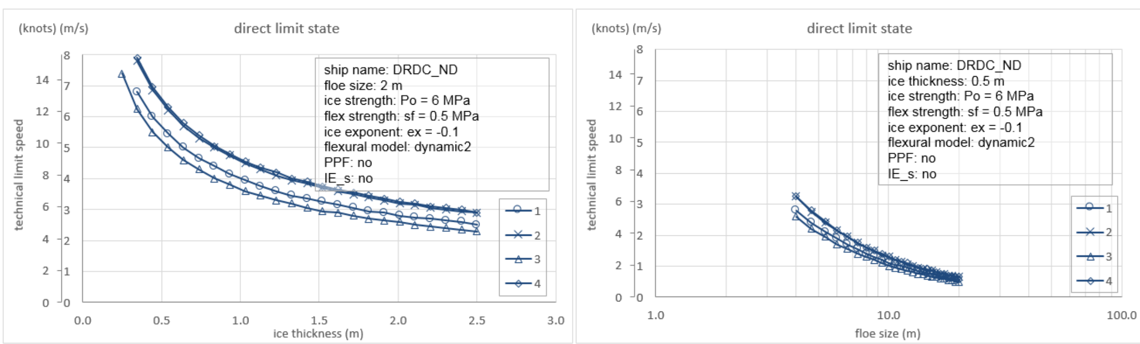

Figure 50: P/A Direct Technical Safe Speed vs Ice Thk. (2 m Floe Dia.) and vs Dia. (0.5m Thk.)

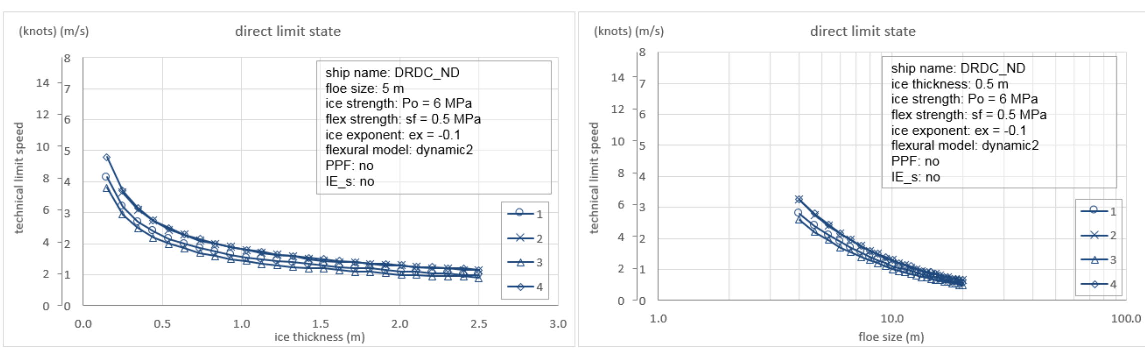

Figure 51: P/A Direct Technical Safe Speed vs Ice Thk. (5 m Floe Dia.) and vs Dia (0.5m Thk.)

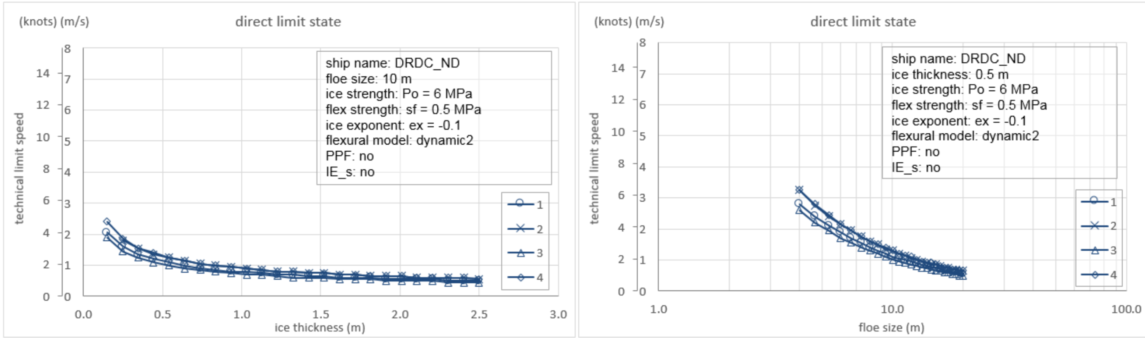

Figure 52: P/A Direct Technical Safe Speed vs Ice Thk. (10 m Floe Dia.) and vs Dia (0.5m Thk.)

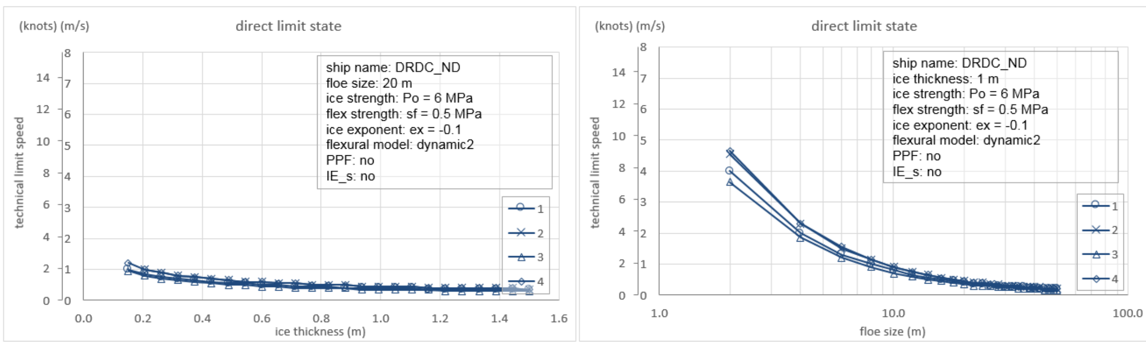

Figure 53: P/A Direct Technical Safe Speed vs Ice Thk. (20 m Floe Dia.) and vs Dia (1.0 m Thk.)

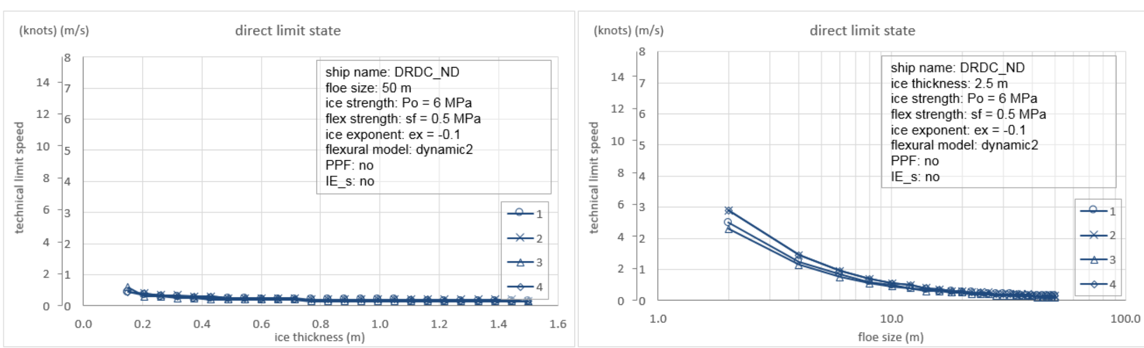

Figure 54: P/A Direct Technical Safe Speed vs Ice Thk. (50 m Floe Dia.) and vs Dia (2.5m Thk.)

EP Collison Cases

Force vs Speed, Various Diameters, One Thickness

These plots (Figure 55 through Figure 62) show the effect of impact speed on ice force for collisions modeling the ice crushing and the elasto-plastic structural compliance.

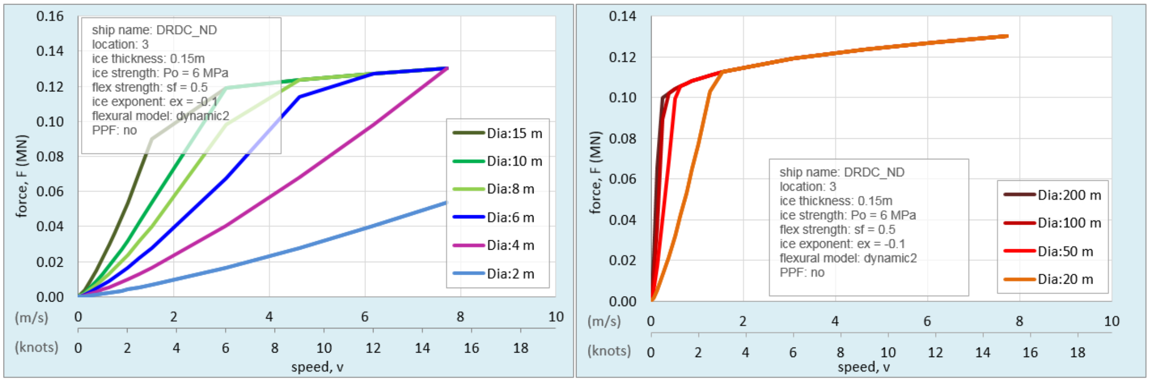

Figure 55: EP Collision Forces vs. Speed (0.15 m Ice Thk., various Floe Dia.)

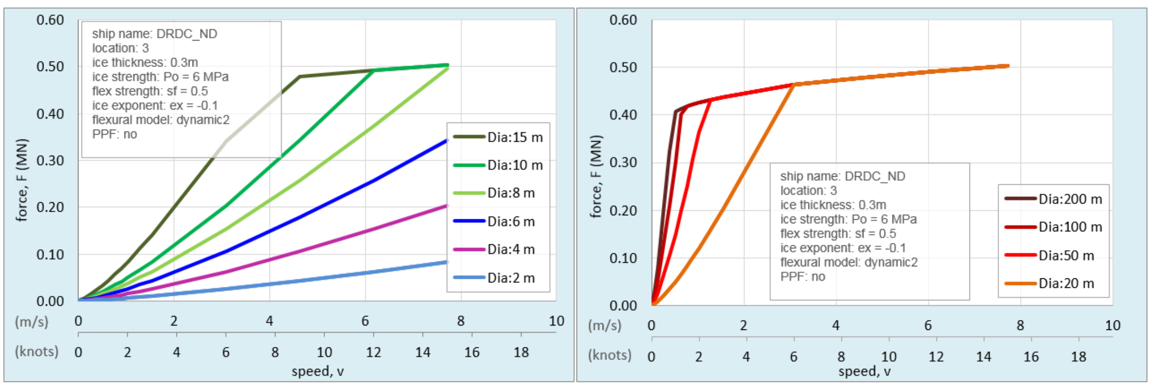

Figure 56: EP Collision Forces vs. Speed (0.30 m Ice Thk., various Floe Dia.)

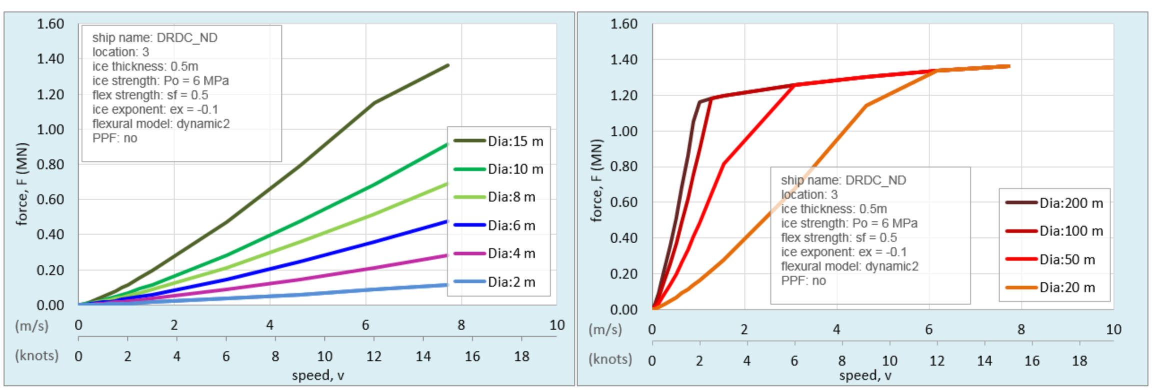

Figure 57: EP Collision Forces vs. Speed (0.50 m Ice Thk., various Floe Dia.)

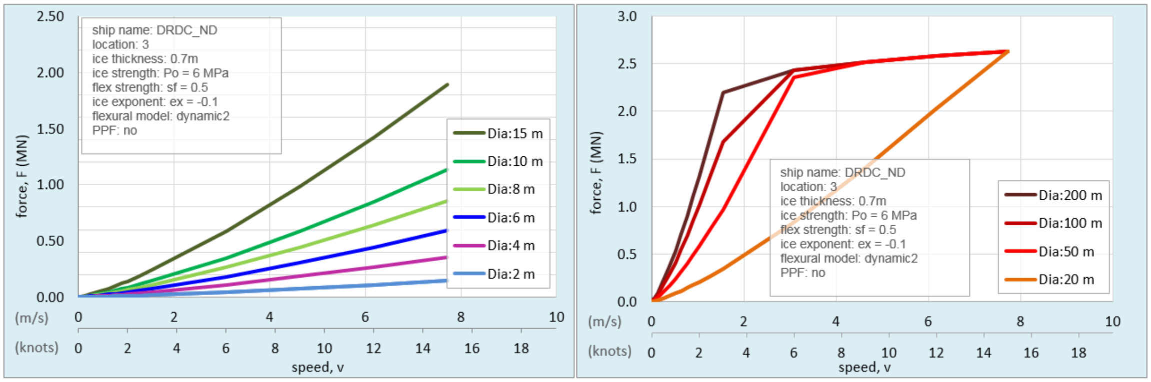

Figure 58: EP Collision Forces vs. Speed (0.70 m Ice Thk., various Floe Dia.)

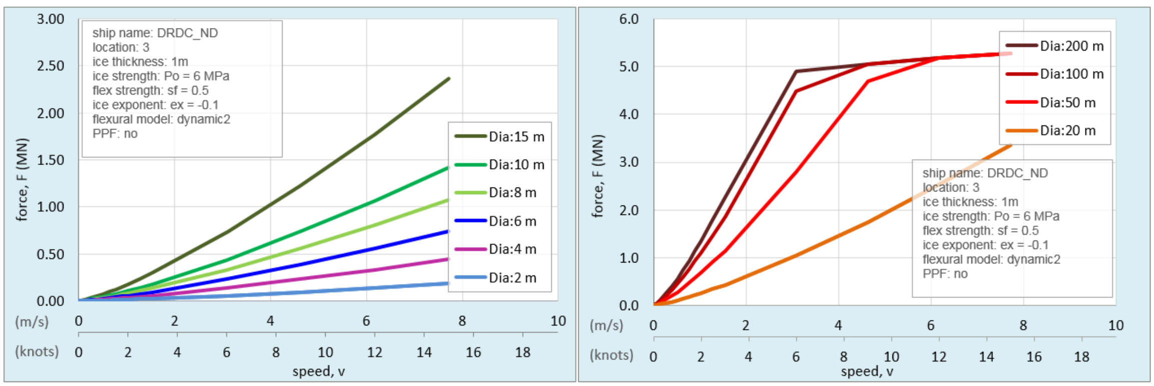

Figure 59: EP Collision Forces vs. Speed (1.0 m Ice Thk., various Floe Dia.)

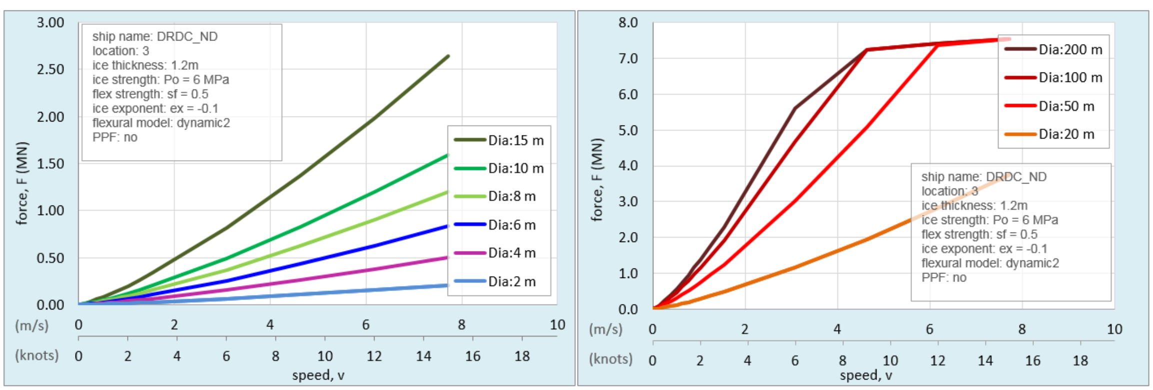

Figure 60: EP Collision Forces vs. Speed (1.2 m Ice Thk., various Floe Dia.)

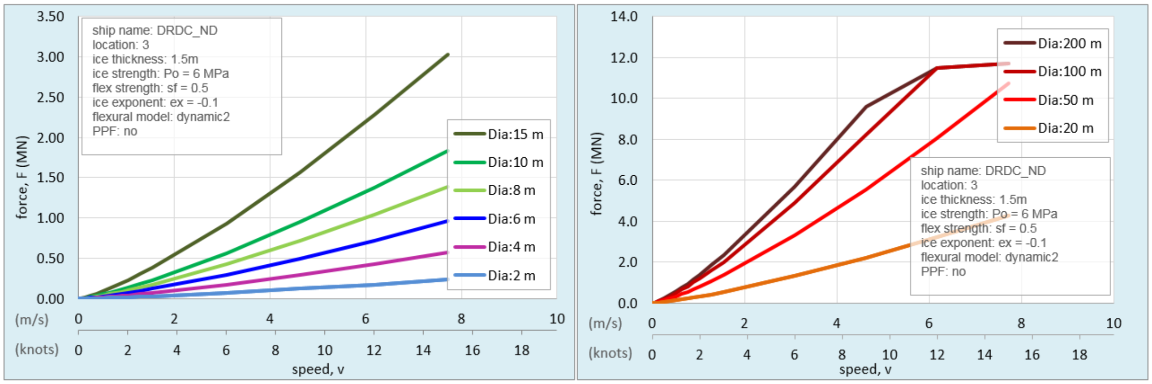

Figure 61: EP Collision Forces vs. Speed (1.5 m Ice Thk., various Floe Dia.)

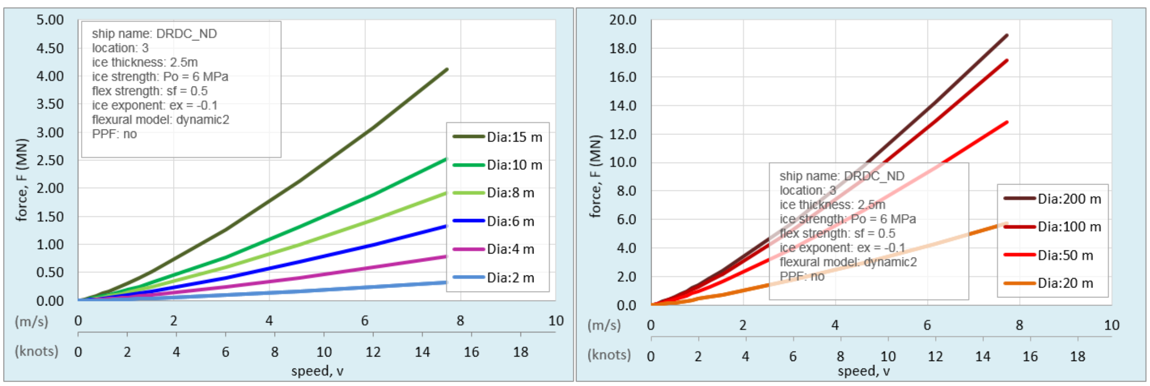

Figure 62: EP Collision Forces vs. Speed (2.5 m Ice Thk., various Floe Dia.)

Direct Limits, EP Collison Cases

The following plots provide an estimate of 'technical safe speed" in various ice conditions. These "EP Direct" plots take the elasto-plastic energy of ice and structure into account and bring the load up to the nominal plastic capacity. There should be no permanent deflection at all in these cases.

EP Direct-Technical Safe Speed vs Thicknesses and Floe Size, 4 Locations

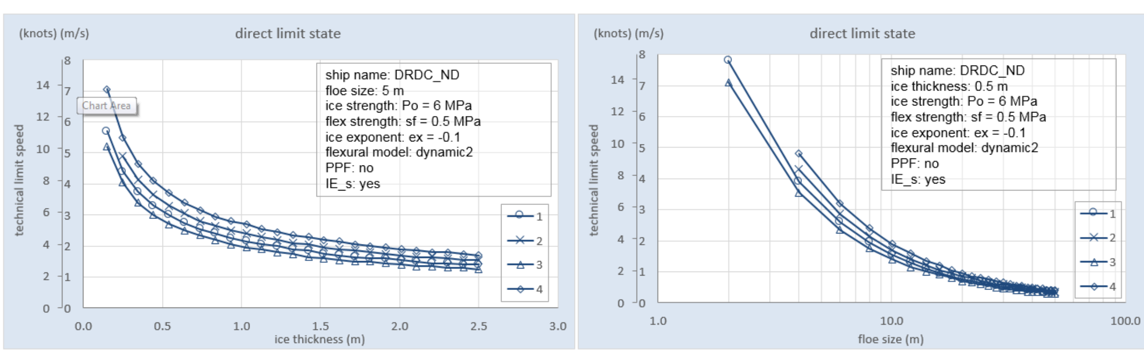

Figure 63: EP Direct Technical Safe Speed vs Ice Thk. (5 m Floe Dia.) and vs Floe Dia (0.5m Thk.)

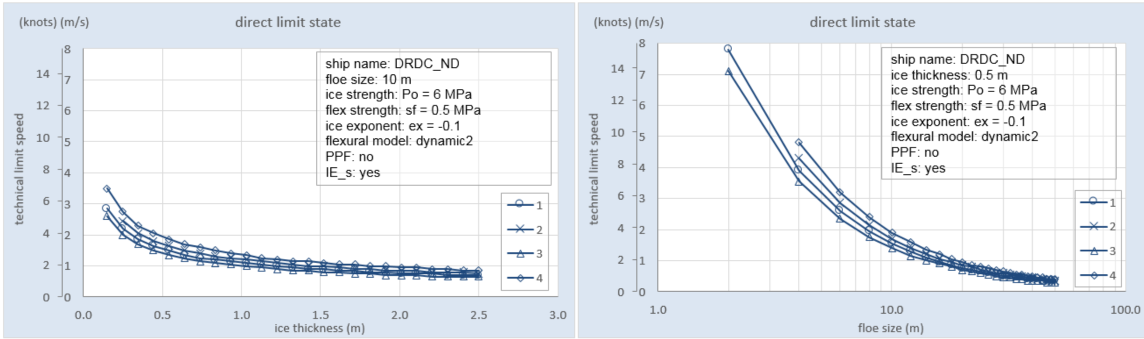

Figure 64: EP Direct Technical Safe Speed vs Ice Thk. (10 m Floe Dia.) and vs Dia (0.5m Thk.)

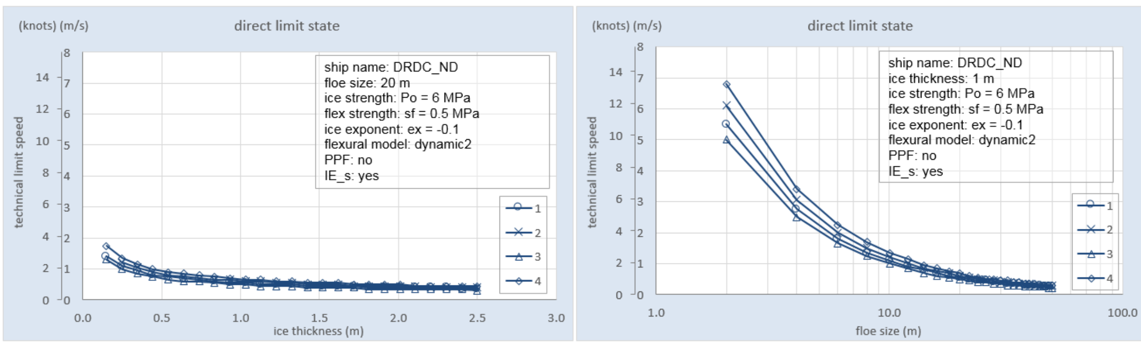

Figure 65: EP Direct Technical Safe Speed vs Ice Thk. (20 m Floe Dia.) and vs Dia (1.0 m Thk.)

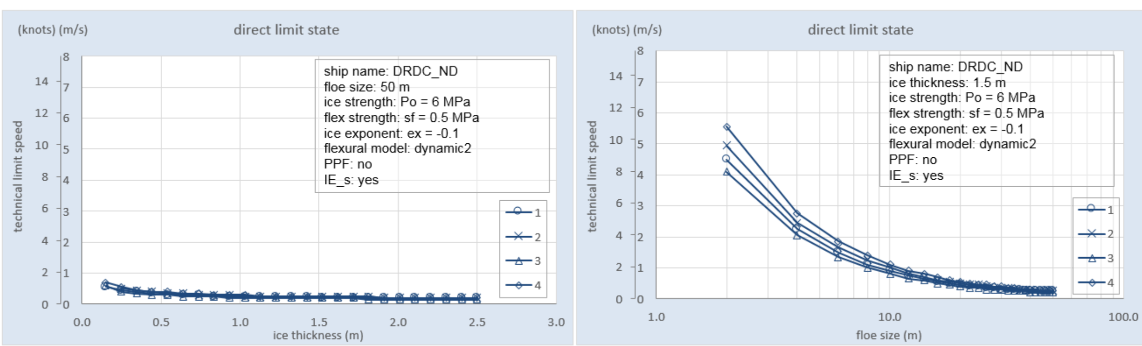

Figure 66: EP Direct Technical Safe Speed vs Ice Thk. (50 m Floe Dia.) and vs Dia (1.5m Thk.)

EP5cm-Technical Safe Speed vs Thicknesses and Floe Size, 4 Locations

The following plots provide an estimate of ‘technical safe speed in various ice conditions. These “EP5cm” plots take the elasto-plastic energy of ice and structure into account and bring the load up to the point of 5cm total relative movement. There should be very little permanent deflection in these cases, say less than 15mm (see eq. 2).

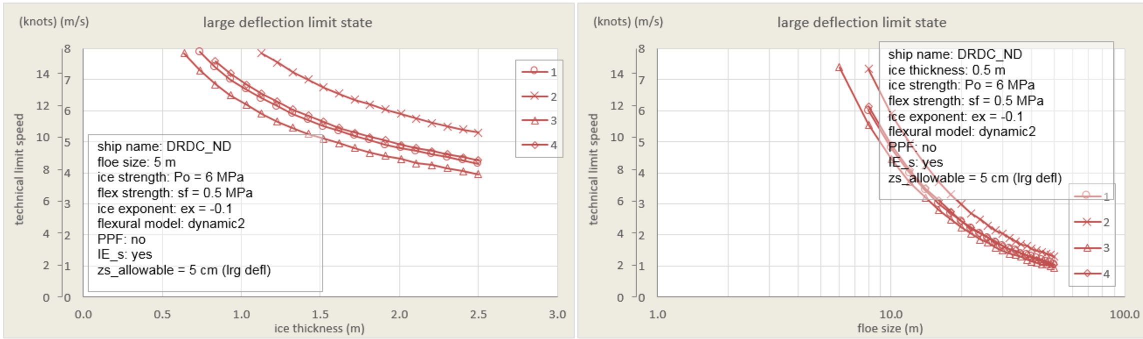

Figure 67: EP 5cm Technical Safe Speed vs Ice Thk. (5 m Floe Dia.) and vs Dia (0.5m Thk.)

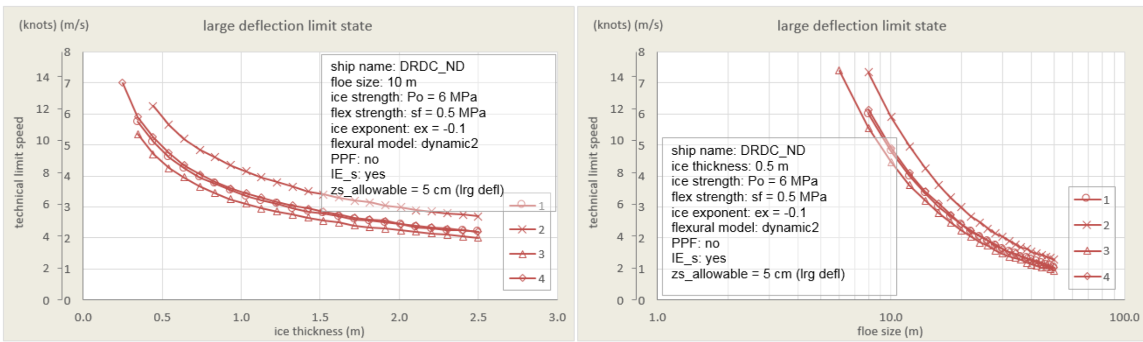

Figure 68: EP 5cm Technical Safe Speed vs Ice Thk. (10 m Floe Dia.) and vs Dia (0.5m Thk.)

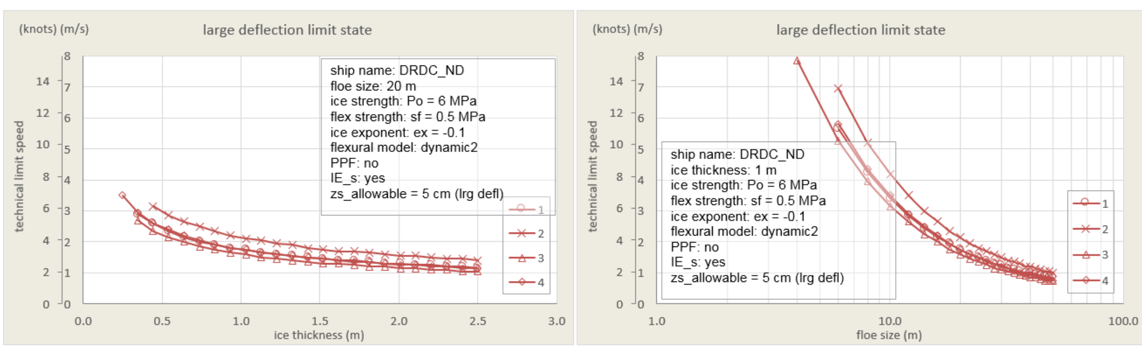

Figure 69: EP 5cm Technical Safe Speed vs Ice Thk. (20 m Floe Dia.) and vs Dia (1.0 m Thk.)

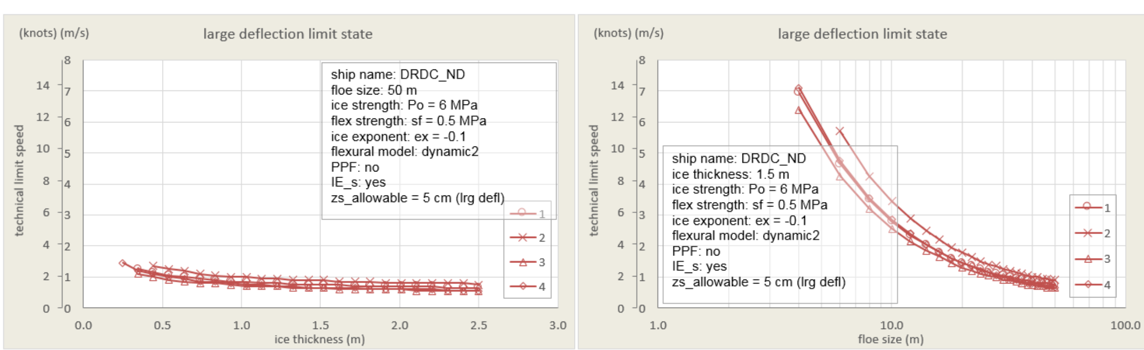

Figure 70: EP 5cm Technical Safe Speed vs Ice Thk. (50 m Floe Dia.) and vs Dia (1.5 m Thk.)

EP10cm-Technical Safe Speed vs Thicknesses and Floe Size, 4 Locations

The following plots provide an estimate of ‘technical safe speed in various ice conditions. These “EP10cm” plots take the elasto-plastic energy of ice and structure into account and bring the load up to the point of 10cm total relative movement. There will result in permanent deflections of about 47 mm (see eq. 2), and so be noticeable but not actually dangerous.

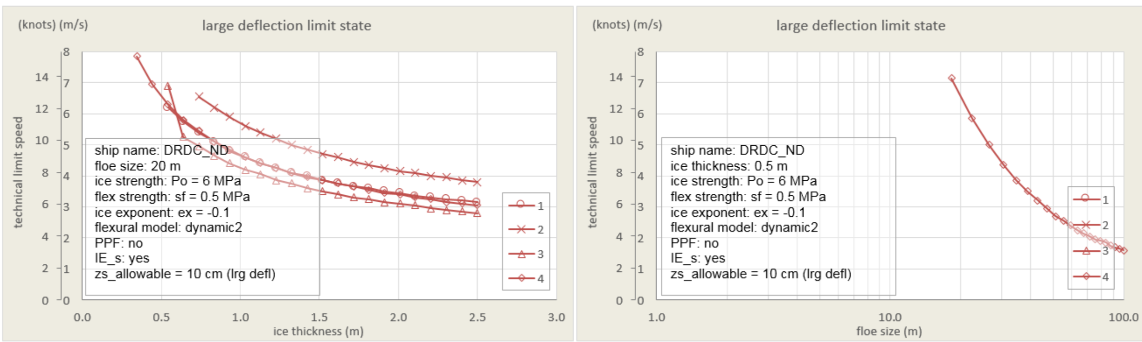

Figure 71: EP 10cm Technical Safe Speed vs Ice Thk. (20 m Floe Dia.) and vs Dia (0.5 m Thk.)

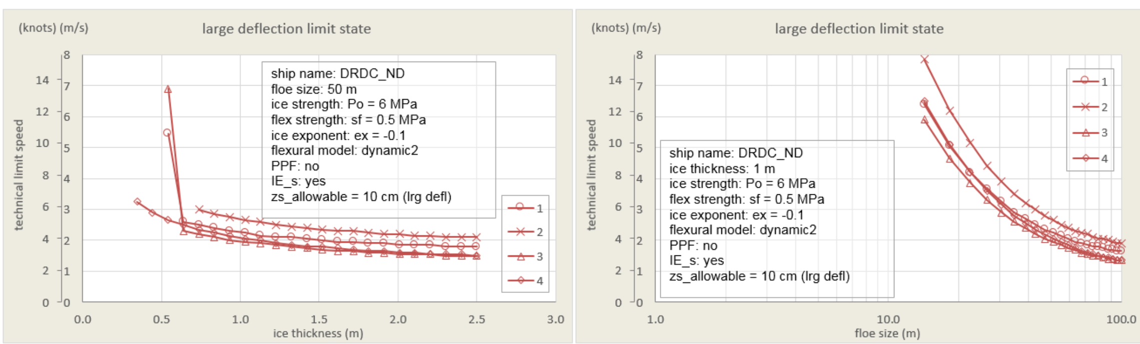

Figure 72: EP 10cm Technical Safe Speed vs Ice Thk. (50 m Floe Dia.) and vs Dia (1.0 m Thk.)

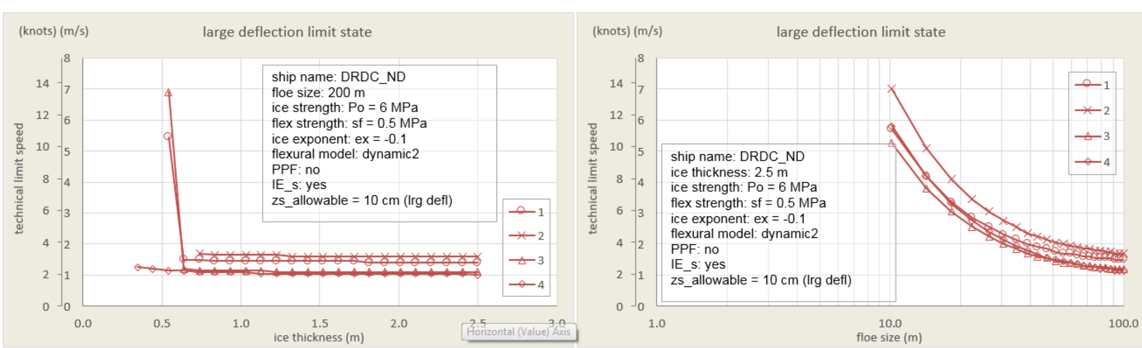

Figure 73: EP 10cm Technical Safe Speed vs Ice Thk. (200 m Floe Dia.) and vs Dia (2.5 m Thk.)

EP5cm vs EPDirect-Technical Safe Speed vs Thicknesses and Floe Size

The following plots compare 'technical safe speed' in various ice conditions for the "EP Direct" vs the "EP5cm" cases. This shows the effect of permitting a small permanent deflection of less than 15mm.

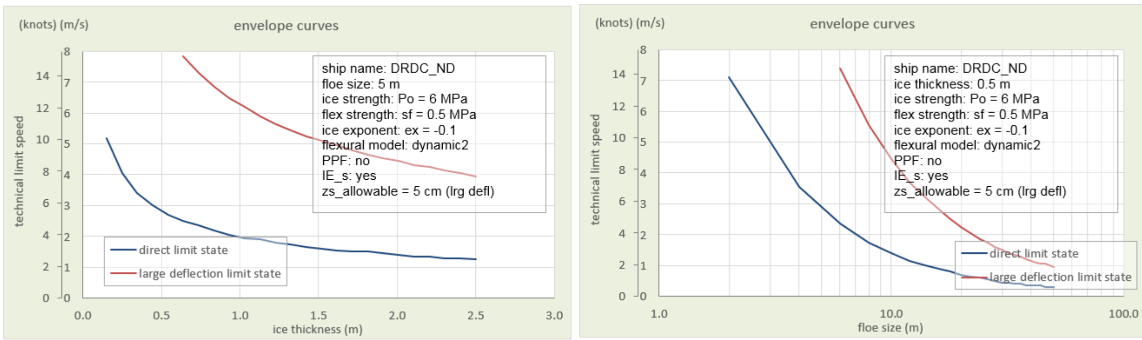

Figure 74: EP 5cm vs. EP Direct Safe Speeds vs Ice Thk. (5 m Floe Dia.) and vs Dia (0.5m Thk.)

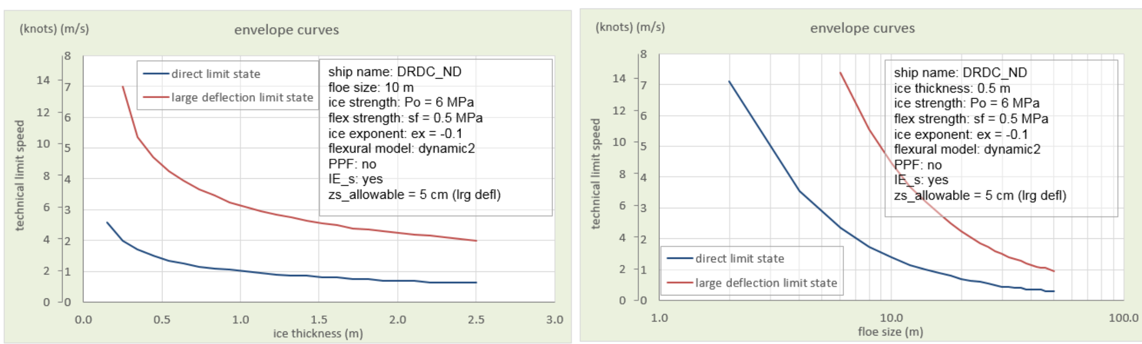

Figure 75: EP 5cm vs. EP Direct Safe Speeds vs Ice Thk. (10 m Floe Dia.) and vs Dia (0.5m Thk.)

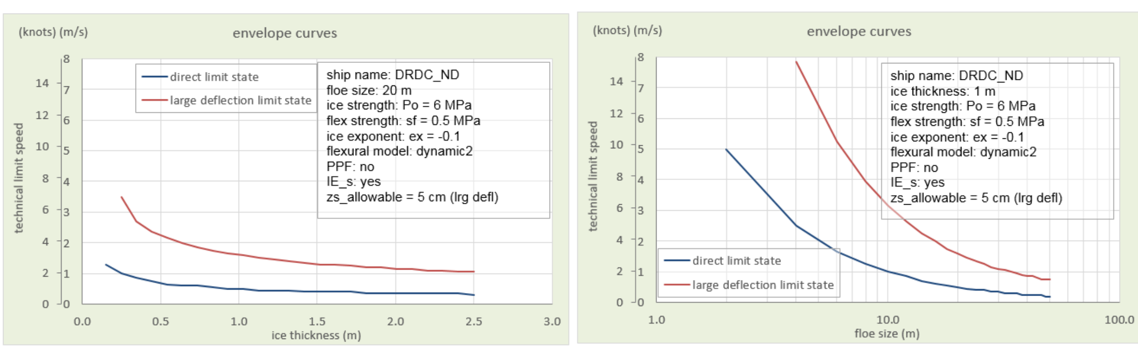

Figure 76: EP 5cm vs. EP Direct Safe Speeds vs Ice Thk. (20 m Floe Dia.) and vs Dia (1.0 m Thk.)

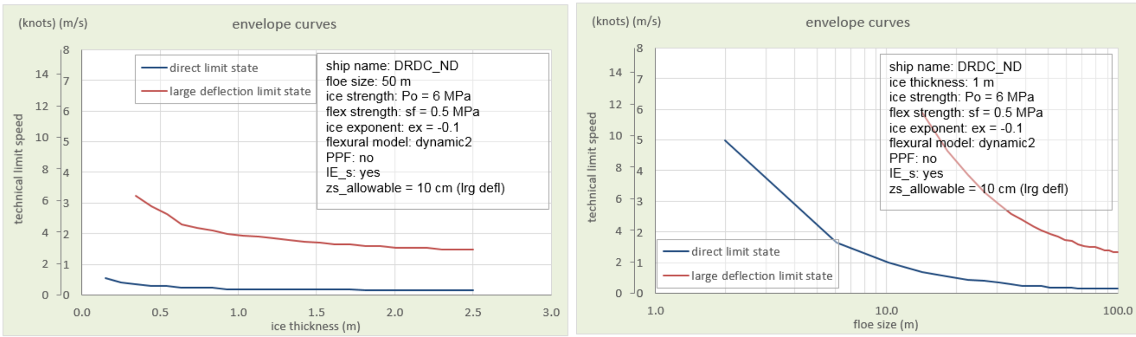

Figure 77: EP 5cm vs. EP Direct Safe Speeds vs Ice Thk. (50 m Floe Dia.) and vs Dia (1.0m Thk.)

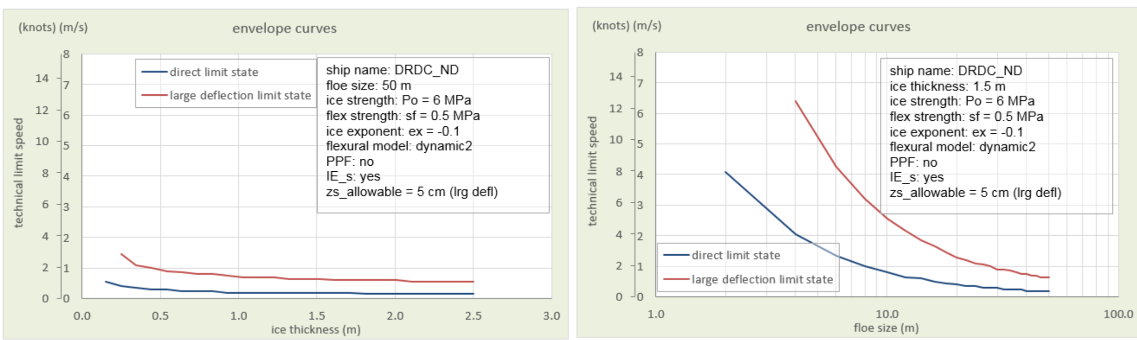

Figure 78: EP 5cm vs. EP Direct Safe Speeds vs Ice Thk. (50 m Floe Dia.) and vs Dia (1.5 m Thk.)

EP10cm vs EPDirect-Technical Safe Speed vs Thicknesses and Floe Size

The following plots compare 'technical safe speed' in various ice conditions for the "EP Direct" vs the "EP10cm" cases. This shows the effect of permitting a permanent deflection of about 45mm.

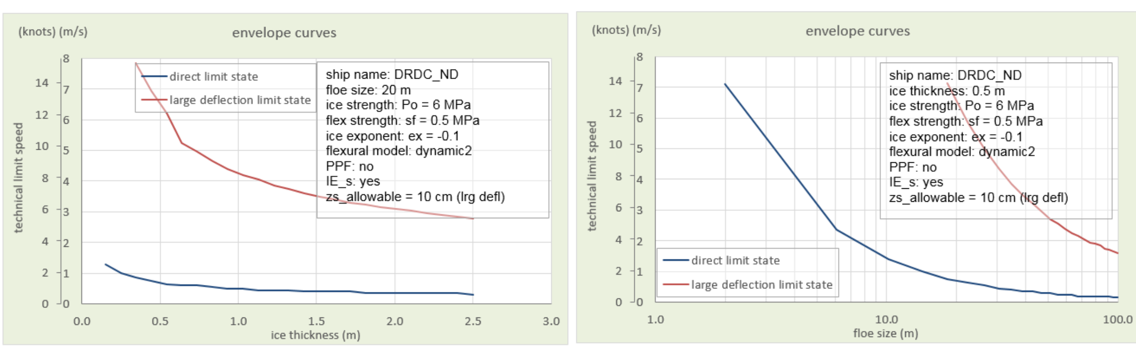

Figure 79: EP10cm vs. EPDirect Safe Speeds vs Ice Thk. (20 m Floe Dia.) and vs Dia (0.5 m Thk.)

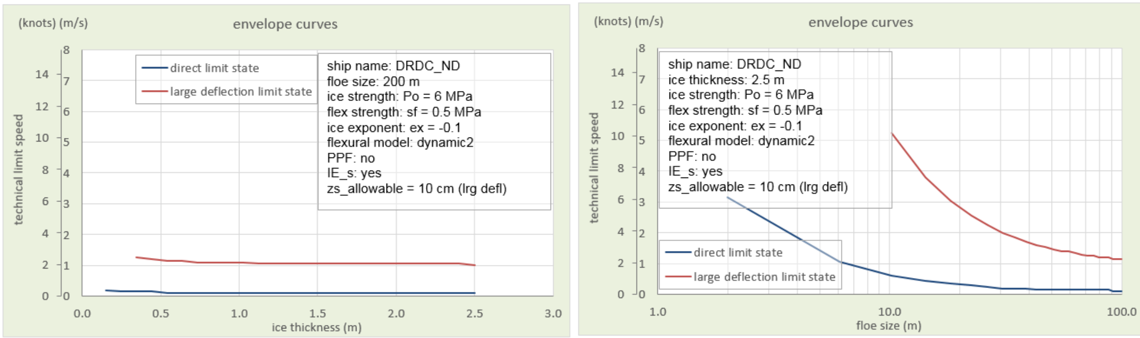

Figure 80: EP10cm vs. EPDirect Safe Speeds vs Ice Thk. (200m Floe Dia.) and vs Dia (2.5 m Thk.)

Discussion of Safe Speed Results

The above data show a complex set of relationships among several variables, including ice strength, thickness, floe diameter, structural response level and speed. The plots are useful to see individual relationships but provide almost too much data for easy decision making. As a way to summarize the results into a simpler form, the following plots have been produced. These plots give the technical safe speeds for any combination of floe size and thickness, which are the two most influential variables. All plots assume the hard ice (Po = 6 MPa). All plots assume an impact at Station 3 on the Notional Destroyer, with only forward speed, striking a single ice floe in calm water.

Figure 81 shows technical safe speeds for the Notional Destroyer, limited so that the structure does not exceed the plastic response assumptions in the Polar Rules. These limit states will result in no observable distortion of the hull (i.e. are pseudo-elastic). The figure indicates that, for this response condition, operational speeds would have to be kept very low except for the thinnest of ice or the smallest of floes. The Notional Destroyer could only operate in ice under 0.2m (termed Grey Ice). Thicker ice could only be contacted if it were in the form of very small floes (termed Ice Cakes)

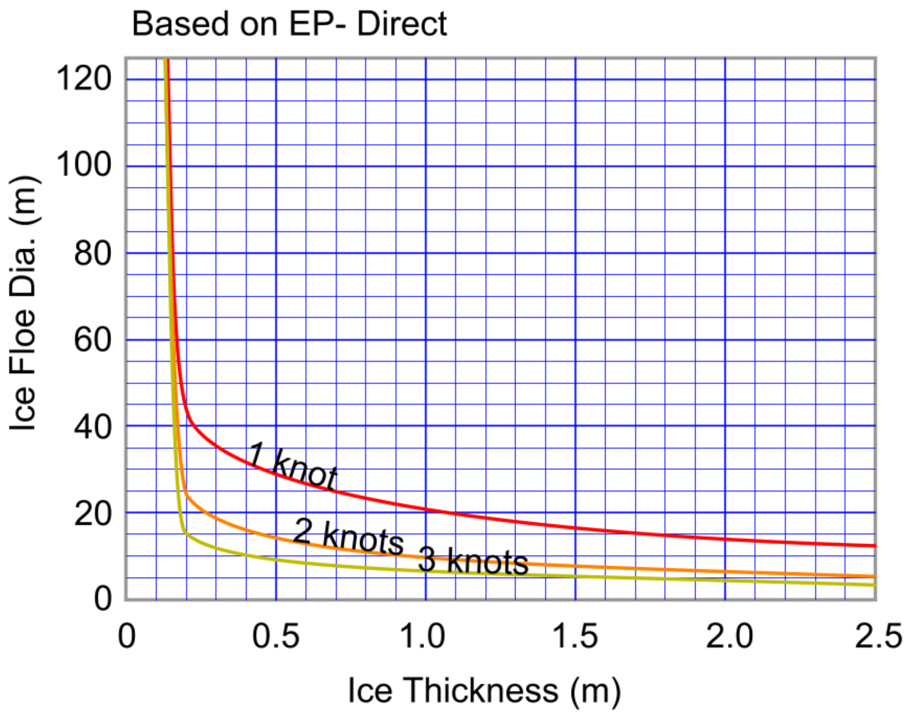

Figure 81: EPDirect Safe Speeds vs Ice Thk. and Dia.

Figure 82 shows technical safe speeds for the Notional Destroyer, limited by a plastic structural deformation of about 15mm (i.e very small but permanent deformation). These limit states will result in barely observable distortion of the hull. The figure indicates that, for this response condition, operational speeds would still have to be low in any ice above 0.5m (termed Thin First Year Ice – First Stage) and above 40m Dia floes (termed Small Ice Floes). The relatively minor plastic response adds considerably to the ability to move in marginal ice.

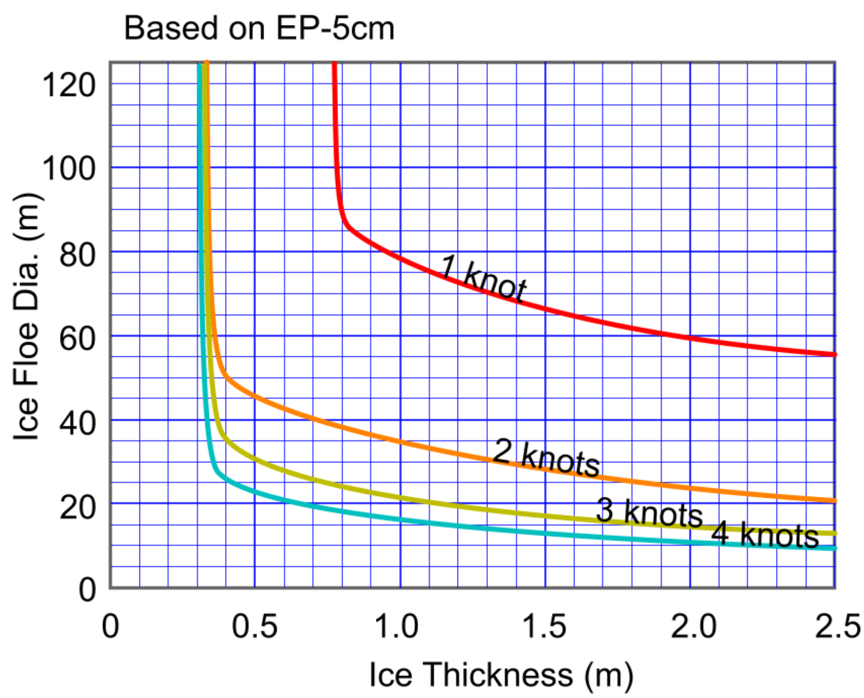

Figure 82: EP5cm Safe Speeds vs Ice Thk. and Dia.

Figure 83 shows technical safe speeds for the case of permitting about 45mm of permanent deformation (1+3/4 inch.). While these deformations would be visible, they would not increase with repeated impacts and would permit considerably more aggressive impacts. Cautious impacts could occur in all First Year ice, as long as floe sizes were under about 60m. Aggressive operations could occur in all ice up to 0.5m.

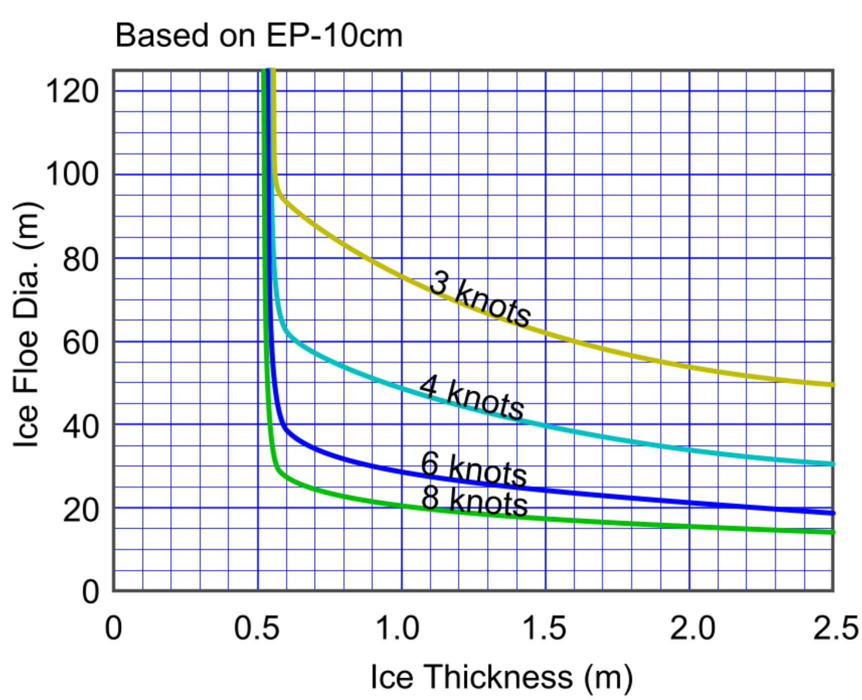

Figure 83: EP10cm Safe Speeds vs Ice Thk. and Dia.

The above three plots describe the consequences of various ice impact situations. It is clear that the Notional Destroyer has no practical ice capability in the normal meaning of the term. However, the structural consequences of operating in various types of First Year arctic sea ice are quite minor. In an emergency, a knowledgeable Master would be able to take the vessel through many forms of first year and even multiyear ice, as long as they understood the situation and were prepared to have minor permanent deformations of the hull. The vessel with such minor deformations is fully as safe as an un-deformed vessel. There would be no need, from a structural perspective, to make any repairs.

The above speeds are termed ‘technical safe speeds”. This term is used to clarify that the speeds are derived by a simple set of calculations for specific technical assumptions. An actual safe speed would need to take a variety of other factors into account, including various uncertainties, levels of training, field experience and organizational risk tolerance.

8. Conclusions

The report has examined the capacity for the Notional Destroyer (ND) to operate in ice covered waters. To determine the effects on the hull structure of various ice impacts a set of collision calculations have been performed. To prepare for these calculations, the hull form and structure of the ND was analyzed using limit state capacity equations and a finite element program (LS.Dyna).

The interactions were calculated using an enhanced program called DDePS (Direct Design of Polar Ships) which determines load by solving the ship-ice collision using an energy approach. The approach taken is, in the author’s opinion, the most advanced and realistic assessment of a vessel’s structural ice capacity available.

The analysis shows that operation in any but the lightest of ice conditions will result in minor permanent plastic deformation of the hull. The hull has a significant plastic reserve and if employed would allow the ND to impact moderate ice if operated cautiously and knowledgeably. The structural risks to the vessel from ice depend on many details, which is why knowledgeable operation is crucial.

9. Recommendations

The report made a number of assumptions, most of which are believed to be conservative. Likely the real capability of the ND is better than described above, but that can only be known if various issues are studied further. The following issues deserve additional study;

Thin Ice Mechanics

The assessment made use of methods that do not account for the flexural elasticity of the ice edge. In thin ice this might cause a significant error. Especially in the case of floe diameters exceeding 20x the thickness, the impacts will be over-estimated. Further study of the mechanics of contact with thin ice is warranted.

Turning

The assessment considered only pure forward motion. Maneuvering through pack ice results in impacts with various degrees of lateral speed. These will affect the loads both positively and negatively. Further study of the navigation in pack ice is warranted.

Floe-floe interaction

The assessment only considered impact with isolated floes. In pack ice, floes rest against other floes. This may or may not add to the effective mass of the ice and thus increase the loads significantly.

Ice degradation and strength effects

The assessment only considered a single case of ice edge shape and only two cases of ice strength, both quite high. Variations on edge shape and ice strength would give a more realistic range of loads.

Brackets

There were no brackets in the structural model. Minor structural changes, including brackets and other dimensional changes may have a noticeable effect of the ice capability.

True Bow structure

The model simply took the midbody structure and assumed it was in the bow. More realistic bow structure may behave quite differently, especially if it is transversely oriented, or capable of additional slamming loads.

Non-Bow cases

Only bow collision scenarios were considered. The ND may also have limits imposed by midbody or stern impacts with ice. These should be considered as well.

Fracture

The study only examined the elasto-plastic response of the hull. The strain levels observed, even with the plastic response were under 20%, so that no fracture would be expected. Nevertheless, the actual issue of fracture was not studied. In an emergency situation it would be good to know whether an ice operation would result in fracture of the outer skin or only plastic denting. The practical consequences are very different.

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APPENDIX 1:

LS-DYNA .k File Listing: SimND1.k

The following 5 pages show the main components of a typical .k file used to generate the LS-DYNA runs presented. The long listing of element nodes and nodal coordinates was shortened for brevity. A full listing would have been 597 pages long. All run parameters are listed.

```
$# LS-DYNA Keyword file created by LS-PrePost 4.2 (Beta) - 26Sep2014(23:00)
$# Created on Mar-14-2015 (21:59:07)
*KEYWORD MEMORY=500000000
*PARAMETER
R timet   0.20000
R timeu   0.312500
R dt      0.002500
R pen     0.20000
$ice strength paramters
R sigi    6.0000E+6
R ei      1.0000E+10
R eti     1.0000E+8
R roi     900.00000
R pri     0.300000
$structural paramters
R sigy    3.5500E+8
R ey      2.0000E+11R et      1.5000E+9

*TITLE
DRDC Notional Destroyer - sim01
*DATABASE_RCFORC
$#      dt    binary      lcur     ioopt
 2.5000E-3         0         0         1
*DATABASE_SPCFORC
$#      dt    binary      lcur     ioopt
 2.5000E-3         0         0         1
*SET_NODE_LIST_TITLE
NODESET(SPC) 3
$#     sid       da1       da2       da3       da4    solver
         3     0.000     0.000     0.000     0.000MECH
$#    nid1      nid2      nid3      nid4      nid5      nid6      nid7      nid8
     49543     49501     56266     55323         0         0         0         0
*SET_NODE_LIST_TITLE
NODESET(SPC) 4
$#     sid       da1       da2       da3       da4    solver
         4     0.000     0.000     0.000     0.000MECH
$#    nid1      nid2      nid3      nid4      nid5      nid6      nid7      nid8
     43244     49912     56512     49870     55569     50281     50239     56758
     55815     49174     56020     49132     55077     50568     56923     50486
     55980     50199     38968     56677     50117     55734     49830     56431
     49748     55488     49461     56185     49379     55242         0         0
*INCLUDE
control_1.k
ND_3x2m_mesh.k
mat_ice_PC1_d6.k
iceBlock_4.k
*END
```

Listing: Control_1.k

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$#    hgen      rwen    slnten     rylen
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*CONTROL_TERMINATION
$   endtim    endcyc     dtmin    endeng    endmas
$#  endtim    endcyc     dtmin    endeng    endmas
&timet             0     0.000     0.000     0.000
```

```
*CONTROL_TIMESTEP
$   dtinit    tssfac      isdo    tslimt     dt2ms      lctm     erode     ms1st
$#  dtinit    tssfac      isdo    tslimt     dt2ms      lctm     erode     ms1st
     0.000  0.700000         0     0.000     0.000         0         0         0
$   dt2msf   dt2mslc     imscl
$#  dt2msf   dt2mslc     imscl    unused    unused     rmscl
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*DATABASE_BINARY_D3PLOT
$       dt      lcdt      beam     npltc    psetid
$#      dt      lcdt      beam     npltc    psetid
&dt               0         0         0         0
$    ioopt
$#   ioopt
         0
*DATABASE_BINARY_INTFOR
$       dt      lcdt      beam     npltc    psetid
$#      dt      lcdt      beam     npltc    psetid
&dt               0         0         0         0
*BOUNDARY_PRESCRIBED_MOTION_RIGID
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$#     pid       dof       vad      lcid        sf       vid     death     birth
       101         1         2         7  1.000000         0     0.000     0.000
$#     pid       dof       vad      lcid        sf       vid     death     birth
       101         2         2         6  1.000000         0     0.000     0.000
$#     pid       dof       vad      lcid        sf       vid     death     birth
       101         3         2         6  1.000000         0     0.000     0.000
$#     pid       dof       vad      lcid        sf       vid     death     birth
       101         5         2         6  1.000000         0     0.000     0.000
$#     pid       dof       vad      lcid        sf       vid     death     birth
       101         6         2         6  1.000000         0     0.000     0.000
$#     pid       dof       vad      lcid        sf       vid     death     birth
       101         7         2         6  1.000000         0     0.000     0.000
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$=========================================================================
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$#      fs        fd        dc        vc       vdc    penchk        bt        dt
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$#     sfs       sfm       sst       mst      sfst      sfmt       fsf       vsf
  1.000000  1.000000     0.000     0.000  1.000000  1.000000  1.000000  1.000000
$#    soft    sofscl    lcidab    maxpar     sbopt     depth     bsort    frcfrq
         2  0.100000         0  1.025000  2.000000         2         0         1
*CONTACT_FORCE_TRANSDUCER_PENALTY_ID
$#     cid                                                                 title
         3
$#    ssid      msid     sstyp     mstyp    sboxid    mboxid       spr       mpr
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$#      fs        fd        dc        vc       vdc    penchk        bt        dt
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$#     sfs       sfm       sst       mst      sfst      sfmt       fsf       vsf
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*SECTION_SHELL_TITLE
7p
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$#      t1        t2        t3        t4      nloc     marea      idof    edgset
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*MAT_PLASTIC_KINEMATIC
$#     mid        ro         e        pr      sigy      etan      beta
         1 7850.0000&ey         0.300000&sigy     &et             0.000
$#     src       srp        fs        vp
     0.000     0.000     0.000     0.000
*SECTION_SHELL_TITLE
10p
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         4         2  0.866000         5  1.000000     0.000         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
```

```
 1.0000E-2 1.0000E-2 1.0000E-2 1.0000E-2     0.000     0.000     0.000         0
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$#      t1        t2        t3        t4      nloc     marea      idof    edgset
 4.0000E-3 4.0000E-3 4.0000E-3 4.0000E-3     0.000     0.000     0.000         0
*PART
$#                                                                         title
IcePart
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
       100       100       101         0         0         0         0         0
*SECTION_SOLID
$    secid    elform       aet
$#   secid    elform       aet
       100         1         0
*PART
$#                                                                         title
RigidPart
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
       101       100       102         0         0         0         0         0
*MAT_RIGID
$#     mid        ro         e        pr         n    couple         m     alias
       102 7850.0000&ey         0.300000     0.000     0.000     0.0000
$#     cmo      con1      con2
     0.000        0.        0.
$#lco or a1        a2        a3        v1        v2        v3
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$--------------------------------------------------------------------------
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3p
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$#      t1        t2        t3        t4      nloc     marea      idof    edgset
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$#      t1        t2        t3        t4      nloc     marea      idof    edgset
 1.2000E-2 1.2000E-2 1.2000E-2 1.2000E-2     0.000     0.000     0.000         0
*SECTION_SHELL_TITLE
8p
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         6         2  0.866000         5  1.000000     0.000         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
 8.0000E-3 8.0000E-3 8.0000E-3 8.0000E-3     0.000     0.000     0.000         0
*SECTION_SHELL_TITLE
11p
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         7         2  0.866000         5  1.000000     0.000         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
 1.1000E-2 1.1000E-2 1.1000E-2 1.1000E-2     0.000     0.000     0.000         0
*SECTION_SHELL_TITLE
15p
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         8         2  0.866000         5  1.000000     0.000         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
 1.5000E-2 1.5000E-2 1.5000E-2 1.5000E-2     0.000     0.000     0.000         0
*SECTION_SHELL_TITLE
18p
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         9         2  0.866000         5  1.000000     0.000         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
 1.8000E-2 1.8000E-2 1.8000E-2 1.8000E-2     0.000     0.000     0.000         0
```

```
*DEFINE_CURVE
$     lcid      sidr       sfa       sfo      offa      offo    dattyp
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
         6         0     0.000     0.000     0.000     0.000         0
$               a1                  o1
$#              a1                  o1
             0.000               0.000
&timet                           0.000
          1.000000               0.000
*DEFINE_CURVE
$     lcid      sidr       sfa       sfo      offa      offo    dattyp
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
         7         0     0.000     0.000     0.000     0.000         0
$               a1                  o1
$#              a1                  o1
             0.000               0.000
&timet              &pen
          1.000000&pen
*END
```

Listing: mat_ice_PC1_d6.k

```
$# LS-DYNA Keyword file created by LS-PrePost 4.2 (Beta) - 26Sep2014(23:00)
$# Created on Mar-14-2015 (21:59:07)
*KEYWORD
*TITLE
$#                                                                         title
LS-DYNA keyword deck by LS-PrePost
*MAT_PLASTIC_KINEMATIC_TITLE
Plastic_ice
$#     mid        ro         e        pr      sigy      etan      beta
       101&roi      &ei       &pri      &sigi     &eti           0.000
$#     src       srp        fs        vp
     0.000     0.000     0.000     0.000
*DEFINE_CURVE
$     lcid      sidr       sfa       sfo      offa      offo    dattyp
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp
         3         0     0.000     0.000     0.000     0.000         0
$               a1                  o1
$#              a1                  o1
             0.000        3.500000e+06
      2.000000e-02        3.500000e+06
      3.000000e-02        3.500000e+06
      4.000000e-02        3.500000e+06
      5.000000e-02        3.500000e+06
      6.500000e-02        3.500000e+06
      7.500000e-02        7.500000e+06
          0.100000        7.500000e+06
          0.500000        7.500000e+06
          0.800000        7.500000e+06
          0.890000        7.500000e+06
*END
```

Listing: ND3x2m_mesh.k

```
$# LS-DYNA Keyword file created by LS-PrePost 4.2 (Beta) - 26Sep2014(23:00)
$# Created on Mar-24-2015 (21:59:07)
*KEYWORD
*TITLE
$#                                                                         title
LS-DYNA keyword deck by LS-PrePost
*BOUNDARY_SPC_SET
$#    nsid       cid      dofx      dofy      dofz     dofrx     dofry     dofrz
         2         0         1         1         1         1         1         1
*SET_NODE_LIST
$#     sid       da1       da2       da3       da4    solver
         2     0.000     0.000     0.000     0.000MECH
$#    nid1      nid2      nid3      nid4      nid5      nid6      nid7      nid8
     17341     17342     17343     17304     17340     17339     17338     17337
     17336     17335     17334     17333     17332     17331     17330     17329
```

50 Lines Not Shown

```
*PART
$#                                                                         title
7w
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         1         3         1         0         0         0         0         0
*PART
$#                                                                         title
10f
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         2         4         1         0         0         0         0         0
*PART
$#                                                                         title
7pl
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         6         3         1         0         0         0         0         0
*PART
$#                                                                         title
4w
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         7        10         1         0         0         0         0         0
*PART
$#                                                                         title
7f
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         8         3         1         0         0         0         0         0
*SET_NODE_LIST_TITLE
NODESET(SPC) 1
$#     sid       da1       da2       da3       da4    solver
         1     0.000     0.000     0.000     0.000MECH
$#    nid1      nid2      nid3      nid4      nid5      nid6      nid7      nid8
       408       434       435       436       459       472       480       481
      1920      1936      1946      1947      1948      1984      1992      1993
      3996      3997      3998      3999      4000      4001      4002      4003
      4004      4005      4006      4007      4008      4009      4010      4011
```

154 Lines Not Shown

```
*ELEMENT_SHELL
$#   eid     pid      n1      n2      n3      n4      n5      n6      n7      n8
     555       1    1334     969     954    1329       0       0       0       0
     556       1     970     969    1334     962       0       0       0       0
     557       1     970     962     963     963       0       0       0       0
     558       1     969     971     955     954       0       0       0       0
```

9216 Lines Not Shown

```
*NODE
$#   nid               x               y               z      tc      rc
     267       -8.267277        2.000000        8.450000       0       0
     280       -8.174651        2.000000        8.450000       0       0
     292       -8.220920        2.000000        8.450000       0       0
     304       -7.608658        2.000000        5.750000       0       0
```

10389 Lines Not Shown

```
*END
```

Listing: iceBlock_4.k

```
$# LS-DYNA Keyword file created by LS-PrePost 4.2 (Beta) - 26Sep2014(23:00)
$# Created on Mar-24-2015 (21:59:07)
*KEYWORD
*ELEMENT_SOLID
$#   eid     pid      n1      n2      n3      n4      n5      n6      n7      n8
  100000     100  100644  100645  100646  100647  100000  100001  100002  100003
  100001     100  100648  100649  100650  100651  100004  100005  100006  100007
  100002     100  100645  100652  100653  100646  100001  100008  100009  100002
```

10092 Lines Not Shown

```
*NODE
$#   nid               x               y               z      tc      rc
  100000      -10.316535        2.000000        7.904222       0       0
  100001      -10.237804        2.000000        7.904222       0       0
  100002      -10.237703        2.080000        7.904222       0       0
```

11549 Lines Not Shown

```
*END
```