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Creation of Freshwater Ice POLARIS

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ABSTRACT

The IMO formally introduced POLARIS as a risk assessment system for operations in sea ice in IMO MSC.1/Circ. 1519. The POLARIS risk values were developed for operations in sea ice, not freshwater ice. Fresh water ice has greater crushing and flexural strength than sea ice due to the reduced presence of inclusions, particularly brine and brine pockets. As such, POLARIS' use for operations in freshwater ice is not well understood.

The authors developed a methodology using Nonlinear Finite Element Analysis to determine the response of representative ice class structural grillages up to a defined failure limit, projecting the response curves over the range of sea ice risk values for a given ice class. The sea ice pressure corresponding to a specific risk value is determined using the response curve and scaled using the ice crushing strength ratio between freshwater ice and sea ice to determine an equivalent freshwater ice pressure. The initial freshwater risk values can serve as an intermediary set of risk values until further development and validation can be done through more advanced simulations and dedicated measurement / field campaigns.

KEY WORDS: IMO POLARIS; Sea ice; Freshwater ice.

INTRODUCTION

The International Maritime Organization (IMO) created a risk assessment tool, the Polar Operational Limit Assessment Risk Indexing System (POLARIS) methodology under IMO Circular – MSC. 1-Circ. 1519 (2016). POLARIS provides a means to quantify the risk posed to the ship by ice conditions as described by the World Meteorological Organization (WMO) nomenclature and the ship's assigned ice class (or lack thereof). POLARIS can be used by a Master during ice operations or by shore-based individuals to determine the risk a route poses to the vessel for the given geographical location and time of year during voyage planning.

POLARIS assesses ice condition risk and quantifies it as a Risk Index Outcome (RIO) value determined by the following simple calculation:

$$RIO = (C_1 \times RV_1)+(C_2 \times RV_2)+(C_3 \times RV_3)+(C_4 \times RV_4) \tag{1}$$

Where:

C_1 - C_4 are the concentrations of ice types within an ice regime

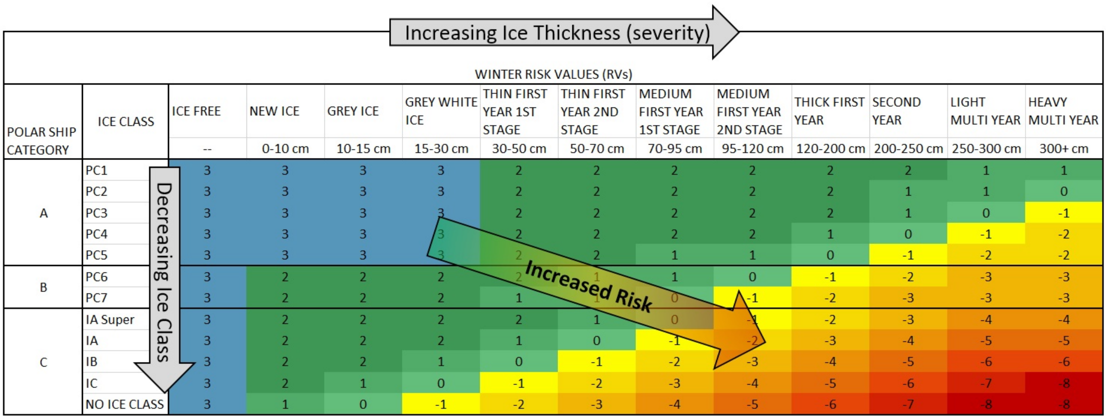
RV_1 - RV_4 – are the corresponding risk index values (RV) for a given Ice Class (see Table 1)

Note the maximum allowable number of partial concentrations in an egg code is 3, with small trace amounts (less than 1/10th concentration) outside of the egg code. Thus, the maximum number of partial concentrations and associated RVs is 4 (3 ice, 1 open water) for use in the RIO calculation.

The RVs are a function of ice type, ice class, and season of operation. The winter season table of RVs is shown in Table 1. Risk values are higher with increasing ice thickness and decreasing ice class. POLARIS provides RVs for the seven (7) IACS Polar Classes, four (4) Finnish-Swedish Ice Classes, and non-ice strengthened ships. The non-ice strengthened ships row or risk values is often used inappropriately. Although not explicitly mentioned in the IMO Circular, the risk values for non-ice strengthened ships are only intended for steel hull vessels.

A positive RIO indicates an acceptable level of risk where operations may proceed normally. A negative RIO indicates an increased risk level, potentially to unacceptable levels. For negative RIOs, the IMO suggests that operations should both be stopped and reassessed or proceed cautiously with reduced speeds. Note, for Category C ships, all negative RIO values are considered "Operation subject to special consideration", meaning this operation should not occur.

Table 1: POLARIS Risk Values



		WINTER RISK VALUES (RVs)											
POLAR SHIP CATEGORY	ICE CLASS	ICE FREE	NEW ICE	GREY ICE	GREY WHITE ICE	THIN FIRST YEAR 1ST STAGE	THIN FIRST YEAR 2ND STAGE	MEDIUM FIRST YEAR 1ST STAGE	MEDIUM FIRST YEAR 2ND STAGE	THICK FIRST YEAR	SECOND YEAR	LIGHT MULTI YEAR	HEAVY MULTI YEAR
		--	0-10 cm	10-15 cm	15-30 cm	30-50 cm	50-70 cm	70-95 cm	95-120 cm	120-200 cm	200-250 cm	250-300 cm	300+ cm
A	PC1	3	3	3	3	2	2	2	2	2	2	1	1
	PC2	3	3	3	3	2	2	2	2	2	1	1	0
	PC3	3	3	3	3	2	2	2	2	2	1	0	-1
	PC4	3	3	3	3	2	2	2	2	1	0	-1	-2
	PC5	3	3	3	3	2	2	1	1	0	-1	-2	-2
B	PC6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
	PC7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
C	IA Super	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
	IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
	IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
	IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8
	NO ICE CLASS	3	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-8

The winter RVs in Table 1 were developed for sea ice and not freshwater ice. Freshwater ice is generally stronger than sea ice (for the same thickness) due to freshwater ice having less inclusions, particularly brine and brine pockets. Due to this difference in strength the use of POLARIS for freshwater ice is not well understood.

FRESHWATER POLARIS CONVERSION METHODOLOGY

The authors developed a methodology to convert a sea ice POLARIS RV to an equivalent freshwater RV using NLFEA and the ratio of freshwater ice strength to sea ice strength. An overview of the methodology is outlined below.

1. Conduct NLFEA of minimum passing structure from no load up to structural collapse (20% total strain or von Mises stress of 490 MPa, aligning with the ultimate strain/stress).
    a. Extract the total strain, von Mises stress, applied load, for each time stamp of the simulation.
    b. Use the strain and von Mises stress to determine the time step of the yield point (0.2% strain, 355 MPa stress) and collapse point (20% strain, 490 MPa stress, whichever occurs first) for the grillage.

2. Using the start of the simulation (0 load), yield, and collapse time steps as reference points, create plots of applied pressure vs sea ice RVs. The RVs were plotted on the x-axis using the reference points as follows:
    a. An RV of 3 (ice free) was aligned with the origin (0 load).
    b. An RV of 0 was aligned with the point where the structure first begins to experience plastic deformations (yield).
    c. An RV of -8 (lowest possible RV for POLARIS) aligned with the collapse point.
    d. All other RVs were linear scaled between these reference points.
3. For each sea ice RV for that ice class, draw a vertical line from the x-axis up to the response curve and draw a horizontal line to the y-axis to determine the corresponding sea ice pressure.
4. Multiply the sea ice pressure by the strength ratio for the given ice type associated with the sea ice RV to determine the freshwater pressure.
5. From the freshwater pressure, draw a horizontal line to the response curve, then draw a vertical line down to the x-axis to determine the corresponding freshwater RV.

This process was completed for ice classes IC through PC4, (and for a non-ice strengthened structure) for all ice types. Ice Class PC3, PC2, and PC1 were excluded as there are no negative RVs using POLARIS, except for PC3 and heavy multiyear ice which does not occur for freshwater bodies that have winter freezing. Note the strength ratio for light and heavy multiyear were modified from Aly et al (2019) to match the decreasing pattern for the thinner ice.

Table 2: Freshwater Ice to Sea Ice Strength Ratio (Aly et al, 2019)

Ice free	New Ice	Grey Ice	Grey White Ice	Thin First Year Ice 1st Stage	Thin First Year Ice 2nd Stage	Medium First Year ice < 1m	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Light Multiyear Ice	Heavy Multiyear Ice
1.7	1.7	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1	1

NONLINEAR FINITE ELEMENT ANALYSIS

For each ice class a three dimensional (3D) and finite element model was created. The scantlings for each ice class were determined using the ABS Marine Vessel Rules (2023) and an in-house tool, ABS Ice QuickCheck. This tool allows for rapid assessment of rule compliance for all Finnish-Swedish Ice Classes and Polar Classes. Several input parameters were kept constant for all ice classes (and non-ice strengthened) as outlined in Table 3 and Table 4. All 3D models were created using Rhinoceros before being used as the geometry input for ANSYS. ANSYS was used to solve all NLFEA for each model.

The differences in stringer spacings between the ice classes is due to the difference in rule sets and minimum passing scantlings. For a frame with a 3.3 m span to pass the minimum scantling requirements for the higher ice classes would require an impractically large frame, so large that a designer would never consider such a large span. For the minimum passing grillages to be grounded somewhat in reality the spans were reduced for the polar class grillages.

Table 3: Constant Particulars

Parameter	Value
Displacement (tonnes)	40,000
Propulsion Power (kW)	7,200
Frame Spacing (mm)	400
Web Frame Spacing (mm)	2,400
Stringer Spacing – PC7 & PC6 (mm)	1,750
Stringer Spacing – PC5 & PC4 (mm)	1,250
Stringer Spacing – Finnish-Swedish and Non-ice Strengthened (mm)	3,300

Table 4: Hull Angles (For Polar Class Load Calculations)

Location	1	2	3	4
X/L_{ui}	0.07	0.14	0.21	0.28
Waterline angle (alpha) (degrees)	23.5	23.4	20.0	15.4
Frame angle (beta) (degrees)	20.6	22.6	24.5	20.6

All models had the same extent (9.9 m tall by 7.2 m wide) and material properties (corresponding to ABS AH36 material properties) as outlined in Table 5. A bilinear model was used to represent the elastic and plastic portion of the material stress strain curve. The ABS Guidance Notes on Nonlinear Finite Element Analysis of Marine and Offshore Structures (2021) was used as reference for conducting all the analysis.

Table 6 outlines the scantlings for each ice class. All main frames were chosen as a bulb profile in terms of meeting the minimum scantlings but converted into an equivalent angle within the 3D models for ease of creation. The stringers for Finnish-Swedish ice classes were simple webs (no flanges), whereas the Polar Class models had T stringers. All ice class web frames were modelled as T shapes. The non-ice strengthened vessel had simple web-only stringers and web frames. Note design details such as brackets, cutouts, welds, etc. were not modeled as this is a preliminary study. In future revisions of this work actual ship structures should be used.

The difference in stringer type is due to the Polar Class rules penalizing non flanged frames, web frames, and stringers more harshly than the Finnish-Swedish Ice Class Rules.

Table 5: Material Properties

Property	Value
Density (kg/m^3)	7850
Yield Strength (MPa)	355
Ultimate Strength (MPa)	490
Young’s Modulus (GPa)	207
Tangent Modulus (GPa)	1

All models were loaded via a 500 mm x 500 mm square patch located centrally on the model (mid span on the central frame) using a uniform pressure from 0 MPa up to 50 MPa. The applied load at the end of the simulation was significantly higher than the grillage's capacity. Once a model reached the specified failure limit (20% plastic strain or ultimate stress) the simulation was arrested. Data beyond this point was excluded from the analysis as it was beyond the intended scope of the criteria. All models had fully fixed boundary conditions at the outer edges of all plating, frames, stringers, and web frames. Strains were monitored throughout the analysis to ensure no plastic strains were found at the boundary nodes & elements to ensure the validity of the boundary conditions.

A mesh convergence study was done to optimize the computational time without sacrificing simulation accuracy. The models were meshed using shell elements, mainly square elements, and in transition areas unequal 4 sided and triangular elements were used. The mesh converged at a size of 50 mm, however the central 3 frames and associated plating had a mesh edge length of 25 mm. All remaining structural elements were meshed with 75 mm edge length elements. This was done to ensure the nonlinear behaviour of the plating and framing under the load was captured during the entire simulation without prohibitively increasing the computational time. Figure 1 highlights the mesh for the Finnish-Swedish Ice Class IC.

Table 6: Grillage Scantlings (mm)

Ice Class	Shell Thickness	Main Frames	Stringers	Web Frames
PC4	27.5	BP 430x20	W 650 x 17 F 130 x 8	W 900 x 23 F 180 x 11
PC5	24	BP 370 x 16	W 600 x 16 F 120 x 8	W 850 x 21 F 170 x 11
PC6	21.5	BP 340 x 15	W 550 x 14 F 110 x 7	W 800 x 20 F 160 x 10
PC7	19.5	BP 320 x 13	W 500 x 13 F 100 x 7	W 750 x 19 F 150 x 10
IAA	21.5	BP 280 x 13	W 575 x 13	W 825 x 15 F 150 x 15
IA	20.5	BP 280 x 10.5	W 530 x 13	W 750 x 14 F 150 x 13
IB	19.5	BP 260 x 10	W 480 x 13	W 680 x 13 F 120 x 13
IC	19	BP 240 x 12	W 450 x 13	W 650 x 13 F 100 x 13
None	15	BP 240 x 11	W 720 x 11	W 720 x 11

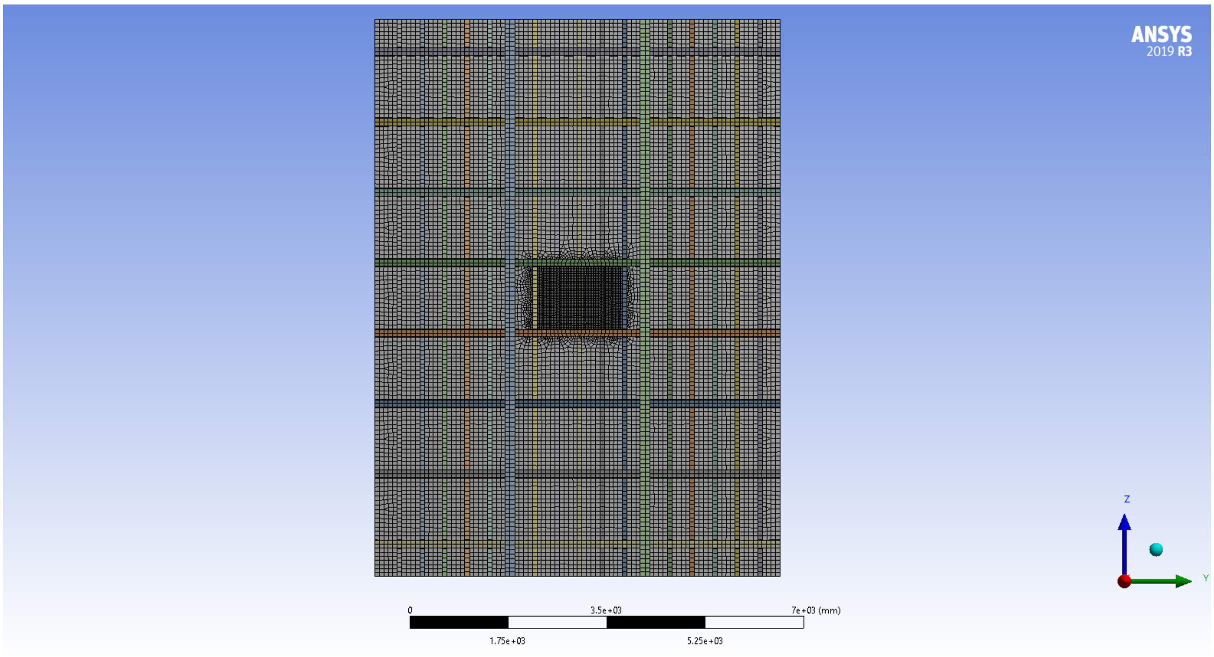


Figure 1: Finnish-Swedish Ice Class IC Mesh

For each model and subsequent analysis, the following data was extracted:

- Total equivalent strain, plastic strain, and Von Mises stress to determine when the grillage first reached plasticity and when the grillage has reached "collapse."
- The reaction force at the boundaries up to collapse. The reaction force was then divided by the area of the patch to determine the applied pressure.

Using this data, pressure vs sea ice RVs tables and figures were created. The sea ice RV curves were created using the following reference points:

- An RV of 3 (ice free) was aligned with the origin (0 load).
- An RV of 0 was aligned with the point where the structure first begins to experience plastic deformations.
- An RV of -8 (lowest possible RV for POLARIS) aligned with the collapse point on the response curve.
- All other RVs were linear scaled between these reference points.

The ice class IC pressure vs sea ice RV curve is outlined in Figure 2 below. Note the difference in slope between the elastic portion (RV 3 to 0) and plastic portion (0 to the lowest RV for that ice class). The plastic portion (0 to -8) is not linear as the grillages behave nonlinearly past the yield point.

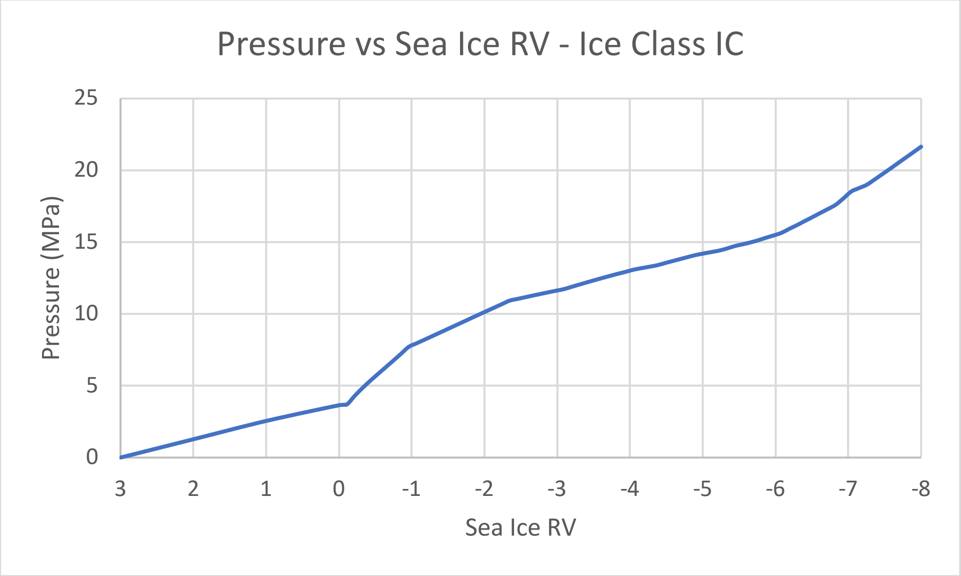


Figure 2: Pressure vs Sea Ice RV – Ice Class IC

RESULTS

Models of each ice class were created and NLFEA carried out to produce the pressure vs sea ice RV curves. Using the process outlined above, the sea ice pressures were converted to freshwater pressures and the corresponding freshwater RVs were determined. The raw unmodified Freshwater RVs are presented in Table 7. The authors suggest several modifications to the RVs as highlighted in Table 8:

- No Ice Class: There is a very large jump between Grey ice and Grey White Ice. This jump is due to the strength multiplier, conservative rounding, and the structure being very poorly optimized for a non-ice classed ship. Non ice classed vessels have shown some capabilities in freshwater ice (such as on the Great Lakes), however using the RVs outlined below would not allow very much operational freedom. It is suggested to make the following changes to better align the RVs:
    - Grey White Ice: Switch from -4 to -3
    - Thin First Year Ice First Stage: Switch from -5 to -4
    - Thin First Year Ice Second Stage: Switch from -6 to -5
    - Medium First Year Ice < 1m: Switch from -6 to -7
- Ice Class IB: Decrease grey ice RV to 1. By decreasing the RV, it will better fit the scaling of the other ice classes above and below an IB.
- Ice Class IA: Increase RVs by one for New Ice and Grey Ice. When conducting the analysis, the freshwater RV was close to 1.5 but was rounded down for initial conservatism. As the IB and PC6 grey ice RVs are 2 it would be appropriate to increase the RVs for continuity.
- Ice Class IAA: Increase RV by one for New Ice, Grey Ice, and Grey White Ice. See justification for Ice Class IA.
- Ice Class PC7: Increase RVs for New ice, grey ice, grey white ice, and thin first year ice 1st stage by 1. See justification for Ice Class IA.
- Ice Class PC6: Increase RVs for thin first year ice 2nd stage by one. Will allow for

better alignment with the other ice classes, such as with an Ice Class IAA (which is approximately equivalent).

- Ice Class PC5: Increase RV for Medium First Year Ice < 1m and Thick First Year Ice by one. This change is suggested to scale the values better linearly.

Table 7: Unmodified Freshwater Ice RVs

Ice Class	Ice Free	New Ice	Grey Ice	Grey White Ice	Thin First Year Ice 1st Stage	Thin First Year Ice 2nd Stage	Medium First Year ice < 1m	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Light Multiyear Ice	Heavy Multiyear Ice
PC4	3	3	3	3	2	2	2	2	1	-1	-1	-2
PC5	3	3	3	3	2	2	0	0	-3	-2	-2	-2
PC6	3	2	2	2	2	0	0	-2	-3	-3	-3	-3
PC7	3	1	1	1	0	0	-1	-2	-3	-3	-3	-3
IAA	3	1	1	1	1	0	0	-1	-3	-3	-4	-4
IA	3	1	1	1	0	-1	-2	-3	-4	-5	-5	-5
IB	3	2	2	0	-1	-2	-4	-4	-5	-6	-6	-6
IC	3	1	0	-1	-3	-5	-5	-6	-6	-7	-7	-8
None	3	0	0	-4	-5	-6	-6	-6	-8	-8	-8	-8

Table 8: Modified Freshwater Ice RVs

Ice Class	Ice Free	New Ice	Grey Ice	Grey White Ice	Thin First Year Ice 1st Stage	Thin First Year Ice 2nd Stage	Medium First Year ice < 1m	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Light Multiyear Ice	Heavy Multiyear Ice
PC4	3	3	3	3	2	2	2	2	1	-1	-1	-2
PC5	3	3	3	3	2	2	1	0	-2	-2	-2	-2
PC6	3	2	2	2	2	1	0	-2	-3	-3	-3	-3
PC7	3	2	2	2	1	0	-1	-2	-3	-3	-3	-3
IAA	3	2	2	2	1	0	0	-1	-3	-3	-4	-4
IA	3	2	2	1	0	-1	-2	-3	-4	-5	-5	-5
IB	3	2	1	0	-1	-2	-4	-4	-5	-6	-6	-6
IC	3	1	0	-1	-3	-5	-5	-6	-6	-7	-7	-8
None	3	0	0	-3	-4	-5	-6	-7	-8	-8	-8	-8

CONCLUSIONS

POLARIS is an internationally recognized methodology for assessing the risk of an ice regime for a given ice class. However, POLARIS was created and tuned for sea ice operations. Freshwater ice has stronger material properties than sea ice (for the same thickness). As such, POLARIS' use in freshwater ice is not well understood.

Using the methodology described above the POLARIS sea ice RVs were converted to Freshwater ice RVs. The authors suggested several modifications of the freshwater RVs for ease of use and to correct over conservative rounding. These freshwater ice RVs can serve as a starting point for the continual development and tuning through extensive numerical studies and further validated through field trials in freshwater ice fields such as on the Great Lakes or Bohai Sea.

In future revisions the minimum Rule compliant structures (which have less than optimized arrangements) should be replaced with real ship structures. The frame spacing of a non-ice classed vessel would not be the same as a PC4, and likely the non-ice classed vessel would be longitudinally framed and built of regular carbon steel. If real vessel structures with a history of operating in freshwater ice were modelled, the confidence in the subsequent freshwater RVs would be significantly higher. The freshwater RVs could then be used along with historical ice charts and vessel AIS data to look at known voyages and cross reference with the vessel's logs.

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