Evaluation of Structural Loading Algorithm for Ship-Ice Collisions during Simulator Training

by

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Abstract

Simulator training is an attractive option for ice navigation training, as it lacks the financial and safety risk of real-world training. An important aspect of effective ship operation in ice is the ability of the operator to understand the capacity of their structure with regard to ice loads, but simulators lack advanced systems to help build on this experience. To this end, an algorithm was developed that can be used to provide simulator trainees with real-time feedback about structural loads from ship-ice collisions during simulator training. The methodology presented demonstrates how to determine a safe limit of collision energy for a given ship structure using non-linear finite element analysis. The calculation is then given for an example structure of Polar Class PC7. The algorithm is then implemented in a training simulator to calculate individual loads, and a user interface developed to communicate the magnitude of individual loads as compared to the pre-determined safe thresholds. An experimental campaign was designed to test the benefit of the system as a training tool. The campaign involved putting human participants through a series of ice navigation training scenarios, either with or without the benefit of the real-time feedback system. Eighteen participants, each novices without any seafaring experience, were recruited. Participants were assessed on a number of performance and safety metrics, such as time to complete the objective, average speed, and number of unsafe collisions. The results suggest that participants with real-time feedback were more comfortable with and were better able to judge ice-collisions during the training. The results also found that participants with access to real-time feedback were able to perform significantly faster in emergency scenarios, without greatly exceeding the capacity of their ship, as compared to participants who did not benefit from feedback.

Acknowledgements

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α	Waterline hull angle
β'	Normal frame angle
ϕ	Ice wedge angle
B	Beam
C_B	Block coefficient
C_m	Midship coefficient
C_{wp}	Block coefficient
H	Height
L	Length
T	Draft

List of abbreviations

CG	Control Group
FB	Feedback Group
FEA	Finite Element Analysis
IACS	International Association of Classification Societies
IMO	International Maritime Organization
PC	Polar Class
POLARIS	Polar Operational Limit Assessment Risk Indexing System
UI	User Interface

1. Introduction

Using marine simulators to train individuals to operate vessels in ice-covered waters offers significant advantages over real-world practice, as it removes the risk and expense inherent in practical training. However, current marine simulators lack certain sophisticated measures as compared to real-world training. Specifically, simulators often lack a system that monitors the structural response of the vessel from ship-ice interactions. Such a system could be used to train operators to better understand the limits of a vessel in an environment without consequences for exceeding this limit, unlike the financial and safety risks associated with damaging a vessel in real-world training. This research aims to develop such a system that can be easily implemented in existing simulators and demonstrate that such a system can positively influence simulator training.

The system developed for this research was designed to aid simulator trainees by giving them access to precise feedback on the magnitude of loads caused by individual ship-ice collisions. The system so far is focused on collisions with individual floes of broken ice. This is because when operating in drift ice, there are many factors that will influence the structural loads of individual collisions, as compared to level ice. Factors such as floe size, shape, thickness, or how the floe strikes the hull will all influence the loading, and each requires the operator to exercise judgment regarding the safety of the operation. By providing feedback on individual loads, the goal is to build experience that the operator can draw on so that they may understand the relative risk of their actions in a safe environment.

1.1 Scope and Objectives

The purpose of this research was to develop and test the use of an ice-load feedback system for simulator training. To achieve this goal, the research had three primary components: 1. develop a methodology for determining ice loads for a simulator environment, 2. implement the system in a simulator, and 3. perform an experiment using human participants to test the effect of the system on simulator training.

The methodology developed for ice loads is based on collision energy. Using collision energy allows for the vessel's speed, the mass of individual floes, and the geometry of collisions to be accounted for. Each of these has a large effect on the magnitude of ice loads and are factors that the operator of a vessel can directly influence. At its core, the system uses the Popov energy method to calculate the energy of individual collisions [1]. Structural loads were then determined from the collision energy using an adaptation of the glancing blow-to-shoulder scenario, as used in the IACS Polar Class rules [2, 3].

Implementing the system into a simulator involved developing a program that could calculate the loads as they occur in real-time during simulator training. It also involved the development of a user interface to communicate the magnitude of individual loads as they occur. It also involved setting safe thresholds for individual loads, which was done using finite element analysis of an example ship structure.

To test the use of the system in training, an experimental campaign was designed and performed. The campaign involved testing 18 participants by putting them through a number of scenarios involving operating a ship in ice. Participants were split into two groups: those who were given access to feedback information from the system, and a control group who was given conventional guidance. Participants were assessed on a variety of performance and safety metrics to assess how exposure to the feedback system changed their behaviour in the simulator environment.

2. Literature Review

Ice-class ships operating in the Arctic must contend with a variety of ice conditions. Historically, level icebreaking was the main driving factor in icebreaker performance. Now, however, change in Arctic ice coverage has led to broken ice fields (a.k.a. ice floes) becoming the predominant ice condition along shipping routes [4]. This has also allowed increased traffic from lighter ice-class ships, which can navigate through open fields of ice floes, but would not be able to contend with level ice of any significant thickness [5].

Broken ice fields have unique challenges for navigators. Level ice fields are relatively uniform, with the exception of some features such as ridges or rafted pieces. By contrast, broken ice fields are highly variable within the field, as each piece of ice can vary in size, shape, thickness, and proximity to other pieces. When in such a condition, the operator must rely on their experience to know how to best manoeuvre the vessel and what speed to travel [6]. Excessive speed is a major cause of ice damage [6]. The use of simulators to train operations in ice has become increasingly popular, with the reasons for their success being their low-risk opportunity to train skills that would otherwise be expensive or time-consuming to train [7]. These issues are prevalent for the training of operators to know the safe limits of their vessels, making them a promising solution.

2.1 Operational Limit Systems

A number of systems have been devised to assist in determining the limits of vessels operating in ice. The *Arctic Ice Regime Shipping System* (AIRSS) is a regulator standard introduced in the 1990s by Transport Canada. This system provided guidance to operators by creating a system where ice conditions could be classified as ‘ice regimes’ [8]. Depending on the quantity and description of ice present in a regime, a score can be calculated for the regime, known as the ‘ice numeral’. This score can then be compared to the ice class of a vessel to determine if it is suitable to travel through the regime. While this system served the role of providing additional tools for operators to assess ice conditions present in front of them, it doesn’t offer additional guidance once the vessel has entered a condition, and still relies on the experience to know how to safely operate the vessel.

Next, the *Polar Operational Limit Assessment Risk Indexing System* (POLARIS) was adopted by the International Maritime Organization (IMO) as part of the Polar Code [9]. POLARIS behaves similarly to the AIRSS system, with each type of ice being given a risk value (RV) for a given ice class. By summing the RV of each ice or open water condition present (in tenths), the resulting score is referred to as a Risk Index Outcome (RIO). Like AIRSS, this then allows the operator to make the decision on whether it is appropriate to proceed into the ice condition. RIO scores represent increasing risk as they become increasingly negative, with scores of 0 or greater representing normal operation, and conditions with negative RIO scores to be avoided. POLARIS has some allowances for Polar-Class ships that happen into conditions of RIO score of 0 to -10, where they may continue under ’elevated operational risk’ conditions. In these conditions Polar-Class ships may continue on, ideally to escape the elevated risk conditions. POLARIS provides recommended speed limits for each Polar Class when operating under elevated operational risk. These speeds, however, are intended as a starting point and allow for adjustment based on trials or ship instrumentation.

There have been multiple attempts to create a methodology to assess safe speed of travel through ice. A recent approach was created by Dolny in *A technical methodology* *for establishing structural limitations of ships in pack ice* [10]. The methodology is based on the Popov energy model, with the addition of the pressure-area model and interaction scenarios used in the IACS Polar Class rules [11]. The methodology works by defining a collision scenario, involving variables such as the thickness and mass of ice struck, the failure mode (flexural or inertial), and the geometry of the vessel being struck. Simple added mass terms are used to approximate hydrodynamic effects. Structural loads can be determined from the collision model using the pressure-area model, and applied to the ship structure. Thus, the collision energy, and therefore speed that exceeds the structural limit can be determined. This speed can thus be taken as the maximum that can be safely travelled at if the defined collision is expected to occur. The methodology has since been used for both ice- and non-ice-classed vessels, with a pressure area model of 2 MPa being preferred [12, 13].

2.2 Ice Simulation

The methodology developed for this research was designed to be used to calculate loads occurring during marine simulator training. The simulator used to test the methodology used the Nvidia PhysX engine, with rigid-body physics for the ship and ice mechanics [14]. Work by Lubbed & Løset has shown that this physics engine can be used for real-time simulations of ship-ice interactions that have satisfactory agreement with full-scale testing [15]. Simulators using PhysX as the basis of the physics engine have since been used in multiple studies to evaluate human factors or performance while operating in ice [16, 17, 18].

Ice loads on ships can be divided into global or local loads, where global loads are related to resistance and used for ship performance, and local loads relate to structural damage or safety [19]. A review by Li and Huang [19] on computer simulations methods for ships advancing in ice found that most computer simulation methods at the publication date (2022) have focused on resistance to the ship and identified a need for work on estimating local loads for structural safety. The review identifies assumed contact area as of large importance, as the assumed width will change how many frames are supporting a given load. It also found that there was not a conclusive relationship between ship speed and local ice loads from existing simulations.

One of the mentioned simulation methods is GEM, which stands for General-Event-Mechanics [20]. This methodology uses a computer GPU processor to perform real-time or faster-than-real-time simulations of a ship transiting through pack ice. Collisions are handled using energy methods based on Popov et al. [1]. The use of event mechanics makes the collision calculations very light compared to other methods, allowing faster than real-time speeds. GEM has been used to predict loads that agree with regards to distribution of full-scale data [21]. GEM uses rigid body physics for ice floes, but with flexural limits implemented, as well as future plans for floe splitting [21].

Other simulation methods make use of the discrete element method (DEM), which involves simulating ice as a number of discrete bodies that are held together by some form of bond. DEM excels at ice failure modes, and so has been used to model phenomena such as ice rubble accumulation [22], ships passing through ice ridges [23] or level ice sheets [23]. It has also been used to model fields of broken ice, and in some cases to study local loads to a ship from ice floes [24]. Discrete element methods have the advantage of more easily applying to larger bodies as compared to rigid body physics, as they model behaviours such as crushing or cracking from flexing, whereas rigid body mechanics must have additional limit states to account for these behaviours [19].

DEM was utilized for the ship-ice simulator known as *Simulator for Arctic Marine Structures* (SAMS). SAMS is a software package capable of simulating ice conditions such as level ice, or ice ridges, and has been used to calculate global and local loads in broken ice fields that show strong agreement with full-scale data [25]. The SAMS simulator utilizes the non-smooth discrete element method, which offers significant computational advantage over traditional DEM, although it still only near-real time, making it unsuitable for simulator training [26].

2.3 Human Factors

A review by Kujala et al. [27] investigated important elements of risk-based ship design for ice-class ships. One of the elements was human factors. The review indicated there was a lack of data relating to the role of human factors in risk analysis for Arctic shipping. This is despite human factors' potential to play an important role in risk management [27]. Previous work has also shown human factors to be a major contributor to marine accidents across all domains [28].

3. Methodology

In this section, the methodology for determining structural loads is described. This includes both determining safe thresholds for loads, as well as determining the magnitude of loads of individual collisions. The process of implementing this into a marine simulator is described, as well as the interface design to communicate this information to a participant undergoing simulator training. Finally, the design of the experimental campaign to test the efficacy of the system as a training tool is described.

3.1 Basis

The methodology for the algorithm is based on the Popov energy method, as it was adapted for the IACS Polar Class rules. The Popov energy method works by equating collision energy to the amount of ice crushing that would occur during the collision. It does this by making a number of simplifying assumptions, which include:

1. The ship structure is a rigid body
2. The ice is a rigid body, except for the portion being crushed
3. Hydrodynamic effects are limited to added mass, which is constant for each degree of freedom
4. Friction forces between ice and ship are negligible
5. The collision occurs over a short duration
6. All non-impact forces are negligible
7. The highest force occurs at the moment of maximum crushing

By doing so, the problem may be reduced from a 6-degree-of-freedom to a single degree, where each energy level corresponds to a level of crushing. By assuming ice properties and a collision geometry, peak ice forces for a given collision can be determined by knowing the mass properties of both the ship and the ice.

3.2 Load Calculation

The IACS Polar Class rules adapted this methodology into specific scenarios for use in designing Polar Class ships. To this point, the algorithm focuses on using one scenario, the glancing blow-to-shoulder scenario. This scenario involves a wedge of ice colliding normal to the hull of the ship, colliding with the bow of the ship.

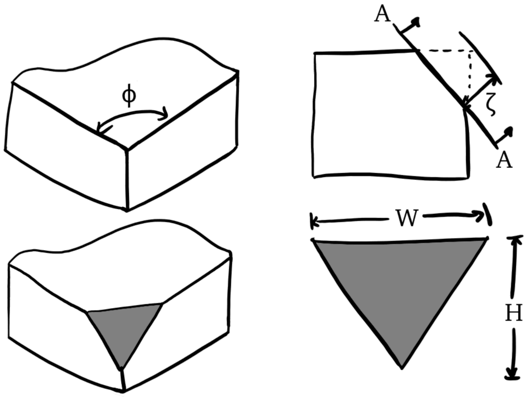

Figure 3.1: Ice wedge crushing

To convert energy into ice crushing, a pressure-area model can be used. This is an empirical model which represents the material response of the ice, with higher values representing ice that is more resistant to crushing. For the IACS Polar Class rules, this pressure area model consists of two components: first P_0, which represents the nominal pressure to crush one square metre of ice. The second is ex, which is the empirical ice crushing constant, which models how the required crushing pressure changes with area. These are used to calculate the average pressure of a contact patch (P_{av}) for a given area (A) using:

$$P_{av} = P_0 \cdot A^{ex} \tag{3.1}$$

To determine the amount of crushing in a collision, a contact geometry needs to be determined. For a wedge normal to the ship's bow, the parameters to be decided are the wedge angle (ϕ), and the normal frame angle of the ship (β'). The wedge angle is how wide the angle is of the wedge of ice being collided with. The normal frame angle represents the angular position of the hull relative to the water, and is measured as the angle between the hull at the measured point, and the plane that runs normal to the waterline, down the centreline of the ship. They can be used to calculated two form factors, f_x and f_a. These two form factors, alongside the empirical ice-crushing coefficient, turn the crushing process into a one-dimensional process, and allow the amount of crushing to be expressed in a single straight-line measurement from the original corner of the wedge where contact occurs to the centre of the resulting crushed surface. The equations to calculate the form factors are:

$$f_x = 3 + 2ex \tag{3.2}$$

$$f_a = [\frac{\tan\frac{\phi}{2}}{\sin(\beta')\cos^2(\beta')}]^{1+ex} \tag{3.3}$$

Incorporating a chosen ice-crushing strength, we can calculate the amount of ice-crushing (ζ) using equation 3.4. The normal force of the collision at maximum crushing can be calculated using 3.3. Combining these two equations results in equation 3.6, which allows for the resulting force directly from collision energy.

$$\zeta = (\frac{KE \cdot f_x}{P_o \cdot f_a})^{\frac{1}{f_x}} \tag{3.4}$$

$$F_n = P_o \cdot f_a \cdot \zeta^{f_x - 1} \tag{3.5}$$

$$F_n = P_o \cdot f_a \cdot (\frac{KE \cdot f_x}{P_o \cdot f_a})^{\frac{f_x - 1}{f_x}} \tag{3.6}$$

With the force from a collision, all that is needed to apply it for structural analysis is the contact area over which to apply the force. The contact dimensions from the wedge (pictured in figure 3.1) can be calculated using equations 3.7, 3.8, and 3.9 to calculated the width, height, and area respectively.

$$W_{nom} = \frac{2\zeta \tan(\frac{\phi}{2})}{\cos(\beta')} \tag{3.7}$$

$$H_{nom} = \frac{\zeta}{\sin(\beta')\cos(\beta')} \tag{3.8}$$

$$A_n = \zeta^2 \cdot \frac{\tan(\frac{\phi}{2})}{\sin(\beta')\cos^2(\beta')} \tag{3.9}$$

This results in a triangular load patch, which the IACS Polar Class rules transform into rectangular load patch to account for load concentration and ice spalling at the edges. The transformation from triangular load patch to rectangular load patch is done by first calculating the aspect ratio of the patch using equation 3.10. Both dimensions are then reduced by 30% to account for spalling, which is done using equations 3.11 and 3.12.

$$AR = \frac{W_{nom}}{H_{nom}} = 2\tan(\frac{\phi}{2})\sin(\beta') = \frac{W}{H} \tag{3.10}$$

$$W = 0.7 \cdot W_{nom} \tag{3.11}$$

$$H = \frac{AR}{W} \tag{3.12}$$

Thus, using these equations the area of the load patch, and the force applied over it can be determined for a given energy. Using this, the structural response for a collision of a given energy can be determined.

3.3 Structural Analysis

A method of determining the structural response to a given ice load is needed for the analysis. Two main methods are obvious, namely the IACS Polar Class rules, and non-linear finite element analysis (FEA). Using the Polar Class rules would allow the response to be determined analytically, which would conveniently allow the response to be determined using a series of equations which can be performed in a spreadsheet. However, by doing so the analysis would be anchored to the assumptions that the Polar Class rules are built on. These revolve around how the Polar Class rules are designed to be used to design ships of Polar Class. This means they are meant for use with a single failure criteria (the design load), and that they are meant for structures built to comply with the Polar Class rules. Instead, non-linear finite element analysis was used to analyze an example structure. This has the benefit of allowing multiple failure criteria (namely, above and beyond the design load), while also demonstrating how an analysis might be performed on a ship not built in the style that Polar Class ships are usually built.

3.4 Failure Criteria

Non-linear FEA was used for this study. The design load has been used in previous safe-speed work as a conservative limit, so it was selected as a safety threshold. An additional threshold was set at 1 cm of total deformation. This was measured as the total resulting displacement of any node, although it was found that most of the displacement occurred as indentation of the shell plating. A previous safe-speed work also used deformation limits, as they allow for some damage while still having considerable plastic reserve in the structure [11].

3.5 Example Structure

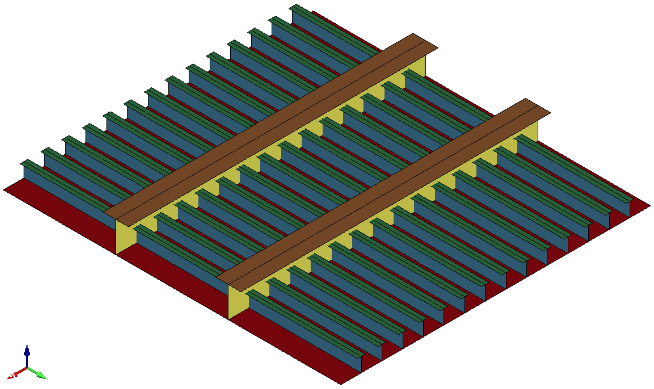

Figure 3.2: Structure Geometry

An example structure was needed to demonstrate the methodology. As an example, the ship structure described in the paper *Response of IACS URI Ship Structure to Real-time Full-scale Operational Loads* [29] was used. This paper provides examples of structures of ships built to each of the 7 IACS Polar Classes, designed specifically for use with non-linear finite element analysis. The lowest ice class, PC7, was chosen for the example calculation, using the built-T variation. The grillage design parameters are listed in

Table 3.1, while the grillage particulars are listed in Table 3.2.

Table 3.1: IACS URI grillage design parameters

Parameter	**Value**	**Unit**
Displacement	13.4	kt
Hull Region	Bi	–
Frame Orientation Angle	90	deg
Frame Orientation Type	Transverse	–
Water Density	1025	kg/m^3
Frame Attachment Parameters	2	–
Yield Strength of Steel	315	MPa
Elastic Modulus of Steel	207	GPa
Main Frame Span	2210	mm
Main Frame Spacing	406	mm

Table 3.2: Grillage Particulars for PC7

Particular	**Dimension (mm)**
Plate Thickness	15.5
Frame Scantlings	280 x 10 150 x 10
Stringer Scantlings	600 x 16 50 x 10

3.6 Finite Element Modelling

A finite element model of the example grillage was needed for analysis. To do so, the geometry was modelled in Rhino3D. The structure was modelled as a flat panel (Figure 3.2), consisting of five parts: the shell plating, frame webs, frame flanges, stiffener webs, and stiffener flanges. An area of 6620 mm x 6910 mm was modelled, spanning 2 longitudinal stringers and 14 frames. The model was meshed using Hypermesh. The finite element simulation was performed using LS-Dyna. The geometry was meshed entirely using 4-noded shell elements of Belytschko-Tsay formulation, with five through-thickness integration points. Table 3.3 shows the material model, a bilinear elastic-plastic model which was also specified by the source paper [29]. No dynamic or time-dependent effects were accounted for in the model.

Table 3.3: Material Model

Parameter	**Value**	**Unit**
Density	7850	kg/m^3
Young's Modulus	207	GPa
Poisson's Ratio	0.3	unitless
Yield Stress	315	MPa
Tangent Modulus	1000	MPa

The boundary conditions for the model are that the outer nodes on all 4 sides are fixed in all 6 degrees of freedom. Analysis of the results found no issues with plastic strains occurring at the boundaries, indicating the boundaries were functioning appropriately. The model was solved implicitly using automatic time-stepping. The simulation was run over the course of 1 second, with the load be applied and then removed as defined by the curve in figure 3.4.

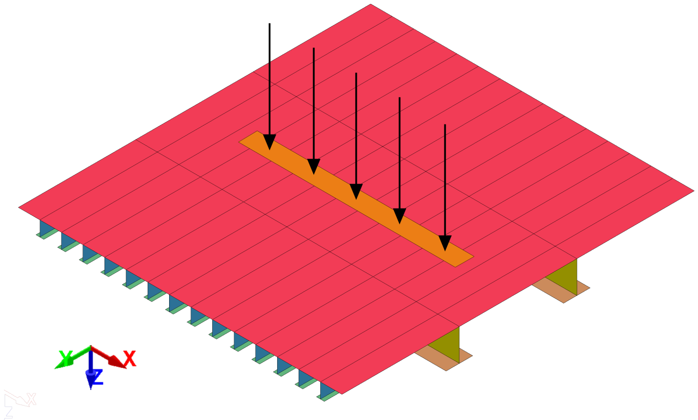

Figure 3.3: Load patch applied to plating

Loads were applied to the outside of the plating using a rectangular pressure patch. For each trial, the size of patch was selected, and the corresponding pressure for the trial was applied as per the load curve described by figure 3.4. Figure 3.3 depicts how the load patch was applied to the grillage. In all cases, only the peak pressure and area were applied, as opposed to transiently increasing pressure and load patch as a process.

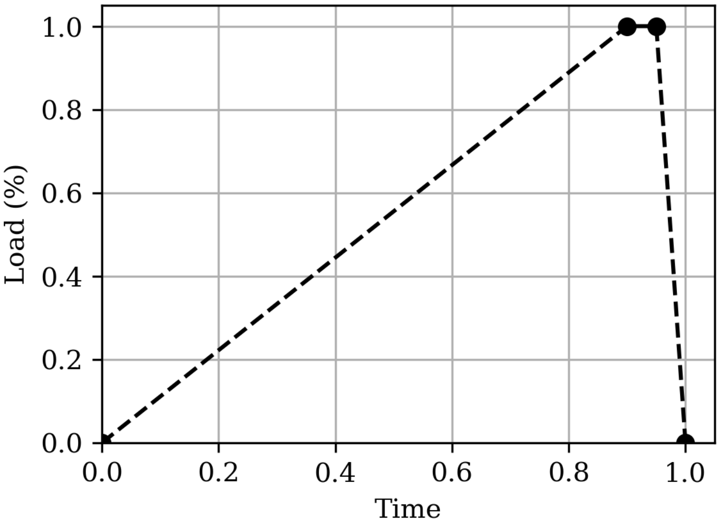

Figure 3.4: Magnitude of load applied over simulation time

3.7 Mesh Convergence Analysis

A mesh convergence study was performed on the model. Meshes with elements ranging in size from 50 mm to 12.5 mm in width were studied. The analysis was done by measuring the greatest resulting deformation of a node (occurring in each instance at the centre of the load patch). The maximum load patch used for the results was run, which was a load patch of 5.1 m x 0.3 m, at a pressure of 4.5 MPa. This is larger in pressure and patch size than any of the results used, and so demonstrates that the mesh used was adequate.

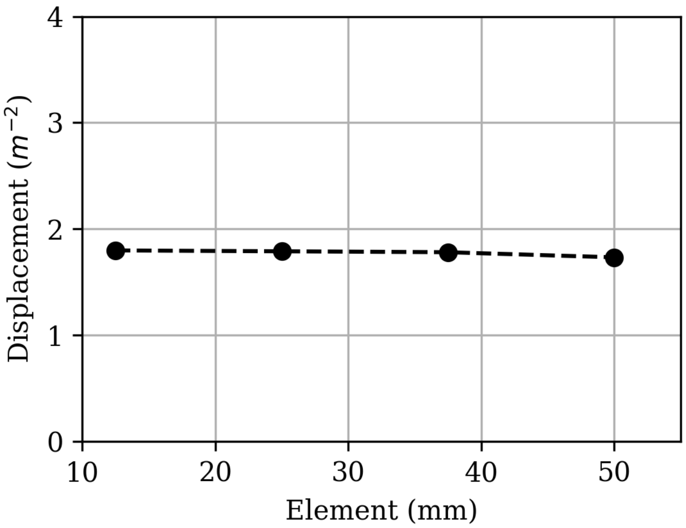

Figure 3.5: Results of mesh convergence analysis

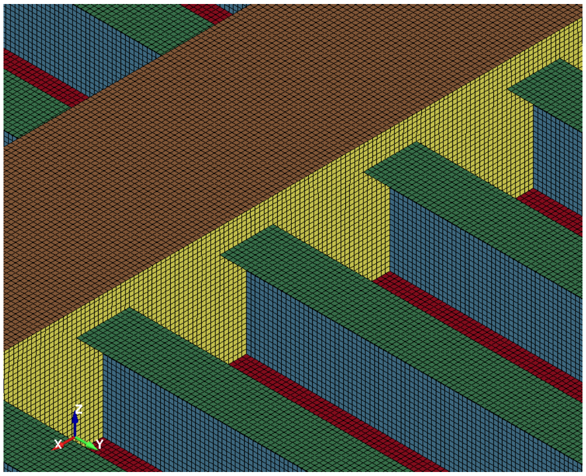

Figure 3.6: 12.5 mm Mesh

3.8 Benchmarking

The model was benchmarked using the design load that was provided in the source paper. The design load for PC7 was provided as 2.586 m x 0.458 m in dimension and 2.7 MPa in pressure. This load was applied to the model in the method described above. The design load for IACS Polar Class rules is meant to be the onset of plasticity, and this is what occurred, with the percent plastic strain at max deformation being less than 1%. The max deformation from this design load was found to be 1mm, which was used later as a stand-in for the design load being met for other similar loads using different pressure-area models.

3.9 Failure Criteria

To determine what constitutes a safe or unsafe load, a failure criteria must be selected which represents the transition from an acceptable to an unacceptable load. To smooth the transition and to provide a greater understanding of the level of risk of an individual load (e.g. cosmetic damage versus catastrophic damage), two failure criteria were used. The first was the design load of the structure, and the second was 1 cm of resulting deformation.

The design load represents the onset of plasticity. Below this point, any loading should not result in any resulting damage to the structure, and so can be considered completely safe from a structural standpoint. Because ships are designed to have considerable plastic reserve, slightly exceeding this limit doesn't necessarily mean the ship is at risk of catastrophic damage. For this reason, the second threshold of 1 cm resulting deflection was used. This was meant to represent when damage of the ship transitions from cosmetic damage, to damage that may have to be repaired and thus would be desirable to avoid in most scenarios.

It would be possible to add additional higher thresholds still. However, for any given threshold, the safe energy limits were very dependent on the ice crushing strength. For this reason, a strong understanding of the ice condition to be operated in would be useful before implementing less-conservative thresholds.

3.10 Energy Limits

To find the energy limit for a given ice condition, a series of increasing loads based on increasing energy can be applied to the structure, until it is determined that the failure criteria is met. The safe energy limit can then be found by linearly interpolating the last two trials. Table 3.4 shows a load schedule for $P_0 = 1.25$, and a frame angle β' of 51 degrees. In this table, the loadings are increased by energy increments of 25 kJ, starting with 300 kJ. Figure 3.7 shows the results of this analysis, resulting in an energy limit of 434 kJ for the trial.

Table 3.4: Example Load Schedule for $P_0 = 1.25$ MPa

Energy kJ	**Ice Penetration** m	**Patch Width** m	**Patch Height** m	**Pressure** MPa
300	0.289	3.26	0.28	3.62
325	0.298	3.32	0.29	3.67
350	0.306	3.38	0.30	3.71
375	0.313	3.44	0.30	3.74
400	0.321	3.50	0.31	3.78
425	0.328	3.55	0.31	3.81
450	0.334	3.60	0.32	3.84

Table 3.5: Load Schedule for $\zeta = 0.33$m

Pressure MPa	**Deformation** m	P_0 MPa	**Energy** kJ
2.5	0.00004	0.94	328
3	0.00038	1.14	396
3.5	0.00158	1.33	461
3.26	*0.001*	1.23	426

This method is useful when a specific ice condition is of interest. However, it has the disadvantage of being time-consuming to perform. This is because each loading requires creating a new load patch, which cannot be easily automated. For a large number of

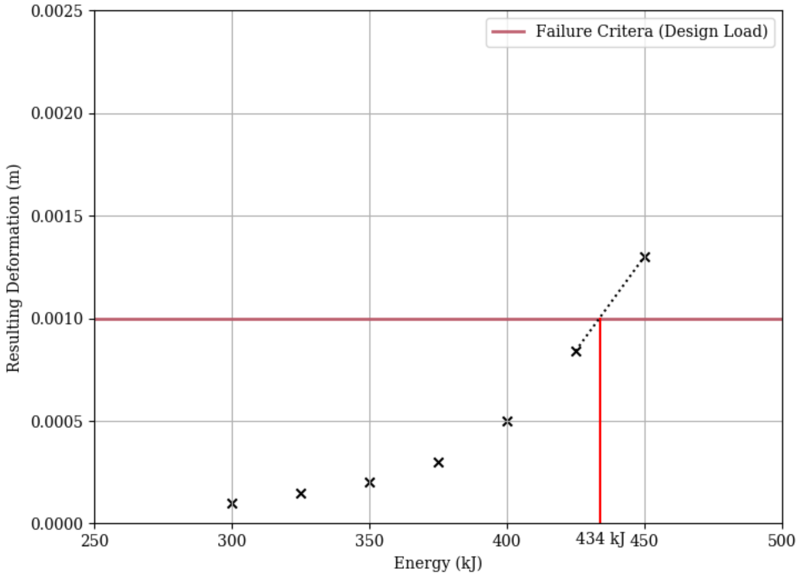

Figure 3.7: Results of Trial for $P_o = 1.25$, Safe limit occurs at 434 kJ

trials, a less time-consuming method is to continually increase pressure for a single-sized load patch. By instead varying pressure (which can be done easily by changing a single value), when the failure criteria is met, the ice-crushing strength and energy that correspond to the load patch and pressure can be calculated using equations 3.4 and 3.5. This allows for many data points for many ice conditions to be calculated rapidly.

Table 3.5 shows the schedule for one of these trials, using a load patch corresponding to 0.2 m of penetration. Performing many of these trials allows the results to be plotted with a curve fitted, which is shown in figure 3.8. This allows the flexiblity for many ice conditions to be chosen from for testing. It also demonstrates the dependence of what a safe collision is on the ice condition.

3.11 Individual Load Calculation

To calculate the energy of a collision, the IACS Polar Class rules use equation 3.13, where V is the velocity of the ship normal to the collision point, and M_c is the effective mass of

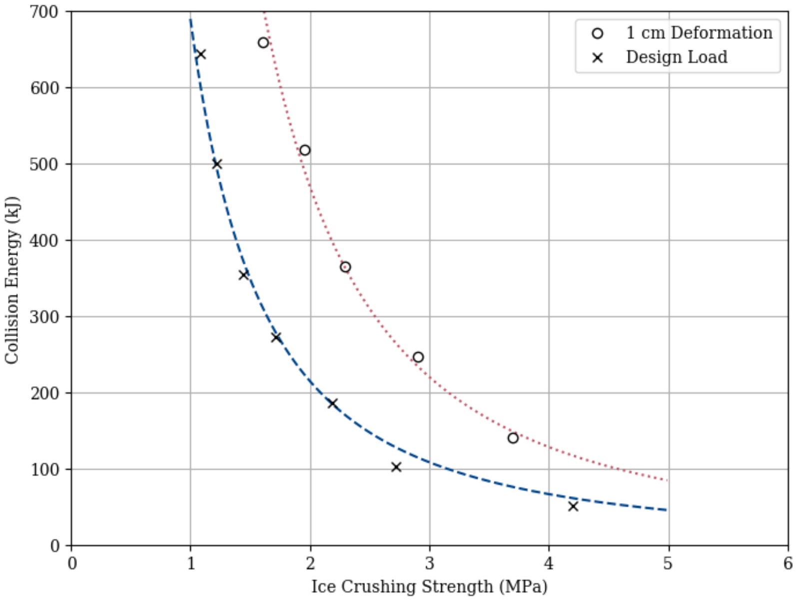

Figure 3.8: Safe energy limits for both thresholds vs Ice-Crushing Strength

the collision [2]. M_c can be calculated using equation 3.14 by using the effective mass of both the ship (M_e) and the ice floe (M_I) [3]. This is useful from a design perspective as it allows a piece of ice that is to be collided with to be specified.

$$KE = \frac{1}{2} M_c V^2 \tag{3.13}$$

$$M_c = (M_e^{-1} + M_I^{-1})^{-1} \tag{3.14}$$

For simulator operations, however, it is easier to use just the state of the ship and allow the physics engine to handle the ice. This can be done by modifying equation 3.13 to use the initial and final states of the ship before and after the collision. This can be done using the momentum of the ship I. Equation 3.15 equates the ship's impulse to the mass and the change in velocity.

$$I = \Delta P = M_e \Delta V = M_e(V_i - V_f) \tag{3.15}$$

This velocity change is a function of the relative masses of the ice and ship (Equation 3.16). Manipulating this, it can be shown that the impulse to the ship can be put into terms of the mass of the collision (Equation 3.19).

$$V_f = V_i \cdot \frac{M_e}{M_e + M_I} \tag{3.16}$$

$$I = M_e \cdot \Delta V = M_e \cdot (V_i - V_i \cdot \frac{M_e}{M_e + M_I}) \tag{3.17}$$

$$I = V_i[M_e(1 - \frac{M_e}{M_e + M_I})] \tag{3.18}$$

$$[M_e(1 - \frac{M_e}{M_e + M_I})] = M_c \therefore I = V_i \cdot M_c \tag{3.19}$$

This can then be combined with Equation 3.13. Doing so yields equation 3.21, which gives the energy of the collision in terms of the effective mass of the ship and the change in velocity of the ship normal to the collision.

$$KE = \frac{1}{2}[\frac{I}{V_i}]V_i^2 = \frac{1}{2}IV_i = \frac{1}{2}[M_e(V_i - V_f)]V_i \tag{3.20}$$

$$KE = \frac{1}{2}M_e(V_i^2 - V_iV_f) \tag{3.21}$$

3.12 Effective Mass Calculation

The effective mass (M_e) of the ship varies depending on the location of a collision. This is because the effective mass of the ship represents the apparent mass of the ship, when collided with normal to the hull at a given point. This reduces the six degree-of-freedom object into a single degree-of-freedom. It also allows for simple hydrodynamic effects to be accounted for by using added mass. The effective mass of the ship is calculated using equation 3.22, where M_s is the total mass of the ship, and C_o is the mass reduction coefficient.

$$M_e = \frac{M_s}{C_o} \tag{3.22}$$

$$C_o = \frac{l^2}{1+AM_x} + \frac{m^2}{1+AM_y} + \frac{n^2}{1+AM_z} + \frac{{\gamma_1}^2}{rx^2(1+AM_{rol})} + \frac{{\mu_1}^2}{ry^2(1+AM_{pit})} + \frac{{\eta_1}^2}{rz^2(1+AM_{yaw})} \tag{3.23}$$

The mass reduction coefficient is calculated using equation 3.23. This equation involves many geometric parameters of the ship at the point of location, all of which are described in table 3.6. The parameters x,y, and z, are locational coordinates of the collision about the centre of gravity. α, and β represent the angle of the collision surface relative to the forward axis of the ship. The calculation requires some general constants of the ship for the hydrodynamic estimates, namely, the beam, draft, height, length, block coefficient, waterplane coefficient, and midship coefficient.

Parameters l, m, and n are directional cosines that represent the angle between each of the axes and the vector normal to the collision. They are calculated using the angles α and β using equations 3.24, 3.25, and 3.26.

Table 3.6: Parameters used for C_o Calculation

	Symbol	Description	Unit
Location			
	x	x-axis coordinate	m
	y	y-axis coordinate	m
	z	z-axis coordinate	m
	α	Waterline hull angle	rad
	β'	Normal Frame angle	rad
Ship			
	B	Beam	m
	T	Draft	m
	H	Height	m
	L	Length	m
	C_B	Block Coefficient	-
	C_{wp}	Waterplane Coefficient	-
	C_m	Midship Coefficient	-
Calculated			
	l	x-axis directional cosine	rad
	m	y-axis directional cosine	rad
	n	z-axis directional cosine	rad
	γ_1	Roll moment arm	m
	μ_1	Pitch moment arm	m
	η_1	Yaw moment arm	m
	rx	Roll gyrad	m
	ry	Pitch gyrad	m
	rz	Yaw gyrad	m
	AM_x	Added mass - x	-
	AM_y	Added mass - y	-
	AM_z	Added mass - z	-
	AM_{rol}	Added mass - roll	-
	AM_{pit}	Added mass - pitch	-
	AM_{yaw}	Added mass - yaw	-

$$l = \sin\alpha \cdot \cos\beta' \tag{3.24}$$

$$m = \cos\alpha \cdot \cos\beta' \tag{3.25}$$

$$n = \sin\beta' \tag{3.26}$$

Parameters γ_1, μ_1, and η_1 are the moment arms, which are needed to calculate the moment of force for the three roll axes. They can be calculated using Equations 3.27, 3.28, and 3.29.

$$\gamma_1 = n \cdot y - m \cdot z \tag{3.27}$$

$$\mu_1 = l \cdot z - n \cdot x \tag{3.28}$$

$$\eta_1 = m \cdot x - l \cdot y \tag{3.29}$$

Parameters rx, ry, and rz are the mass radii of gyration for each of the roll axes. They represent the rotational inertia for each axis, and can be calculated using equations 3.30, 3.31, and 3.32

$$rx^2 = C_{wp}\frac{B^2}{11.4C_m} + \frac{H^2}{12} \tag{3.30}$$

$$ry^2 = 0.07C_{wp}L^2 \tag{3.31}$$

$$rz^2 = \frac{L^2}{16} \tag{3.32}$$

Finally, the added mass (AM) components are used to add apparent mass due to hydrodynamic effects to each of the degrees of freedom. They are calculated using the following equations:

$$AM_x = 0 \tag{3.33}$$

$$AM_y = 2\frac{T}{B} \tag{3.34}$$

$$AM_z = \frac{2 \cdot B \cdot C_{wp}^2}{3 \cdot T(C_b(1 + C_{wp})} \tag{3.35}$$

$$AM_{rol} = 0.25 \tag{3.36}$$

$$AM_{pit} = \frac{B}{T(3 - 2 \cdot C_{wp})(3 - C_{wp})} \tag{3.37}$$

$$AM_{yaw} = 0.3 + 0.05\frac{L}{B} \tag{3.38}$$

To reduce computational load, the mass reduction coefficient can be calculated for any location where collisions may occur, and tabulated prior to running simulations. The number of points that need to be calculated can be drastically reduced by assuming all collisions occur at the waterline, and thus that $z \approx 0$. As the ship is symmetric down the long axis, the coefficient only needs to be calculated for one side of the ship, further reducing the number of points that must be calculated. Table 3.7 shows the parameters used for the example ship. Table 3.8 shows the resulting mass reduction coefficients at 10 metre intervals.

Table 3.7: Values used for example calculation

Parameter	**Symbol**	**Value**	**Unit**
Beam	B	16.2	m
Draft	T	6.2	m
Height	H	6.7	m
Length	L	82	m
Block Coefficent	C_B	0.57	-
Waterplane Coefficient	C_{wp}	0.81	-
midship Coefficient	C_m	0.74	-

Table 3.8: C_o Results for Example Ship

x (m)	**y (m)**	α **(deg)**	β **(deg)**	C_o
30	4.2	17.3	26.5	1.85
20	6.4	9.8	26.9	1.06
10	7.5	1	20.5	0.45
0	7.4	1	20.5	0.37
-10	7.3	1	20.5	0.44
-20	7.2	1	20.5	0.67
-30	6.6	-12	24.5	0.99

3.13 Hull Section Adjustments

The model so far assumes the entire hull is built to the same strength as the example panel. However, the IACS Polar Class rules only require the bow area to be built to this strength. Other areas of the hull are built to a proportion of the design load depending on the ship's Polar Class.

Table 3.9 shows the hull area factors for each area of the hull for PC7. The simplest method of applying this (and the method used for this analysis) was to multiply the C_o result from the previous section by the proportional strength constant for that hull area. Table 3.10 shows an example of the results of doing so.

Table 3.9: PC7 Hull Area Factors

Area	Proportional Strength
Bow	1.00
Midbody	0.45
Stern	0.35

Table 3.10: Combined Hull Area Factor and Mass Reduction Coefficient

x (m)	C_o	Proportional Strength	Combined Coefficient
30	1.85	1.00	1.85
20	1.06	0.45	0.48
10	0.45	0.45	0.20
0	0.37	0.45	0.17
-10	0.44	0.45	0.20
-20	0.67	0.45	0.30
-30	0.99	0.35	0.35

3.14 Normal Velocity Determination

For calculating the collision energy, the velocity component is the velocity normal to the point at which the collision occurs. Normal velocity (V_n) can be calculated using the positional coordinates of the collision, the directional cosines at that position, and the velocity of the ship in six degrees-of-freedom ($V_x, V_y, V_z, V_{roll}, V_{pitch}, V_{yaw}$), using Equation 3.39.

$$V_n = l \cdot (V_x + V_{pit} \cdot z - V_{yaw} \cdot y) + m \cdot (V_y + V_{yaw} \cdot x - V_{rol} \cdot z) + n \cdot (V_z + V_{rol} \cdot y - V_{pit} \cdot x) \quad (3.39)$$

Assuming the collision occurs at the waterline ($z \approx 0$), this can be reduced to:

$$V_n = l \cdot (V_x - V_{yaw} \cdot y) + m \cdot (V_y + V_{yaw} \cdot x) + n \cdot (V_z + V_{rol} \cdot y - V_{pit} \cdot x) \quad (3.40)$$

3.15 Simulator Implementation & Program

A program was developed to detect and record collisions on a computer running separately from the simulator. It works by having the simulator send constant updates on the ship's position, velocity, and heading. The simulator will also send a report when contact is detected, sending where the collision occurred on the ship's hull. When the program detects a collision, it matches where the collision occurred on the ship to the change in velocity. It then uses this information to calculate the energy of each collision using the algorithm. The resulting energy is then plotted on a chart to be displayed to the user.

3.16 User Interface

In order to use the ability to calculate individual load energies to help participants, a user interface (UI) was needed to convey the relevant information during training. To do so effectively, the interface needs to convey the energy of individual loads and how that energy relates to the safety thresholds that have been set. The display also needs to convey when these loads occur timewise, so the participant can relate a collision occurring in the simulator to the corresponding collision on the display. This is especially important in higher-concentration ice conditions, where many collisions may occur in rapid succession. Operating the simulator requires the user's immediate attention to operate the controls, so they may not be able to immediately assess the information. It was also desired to have information on individual collisions available for a suitable length of time, so they may make decisions about their operating behaviour based on the recent history of the collision loadings.

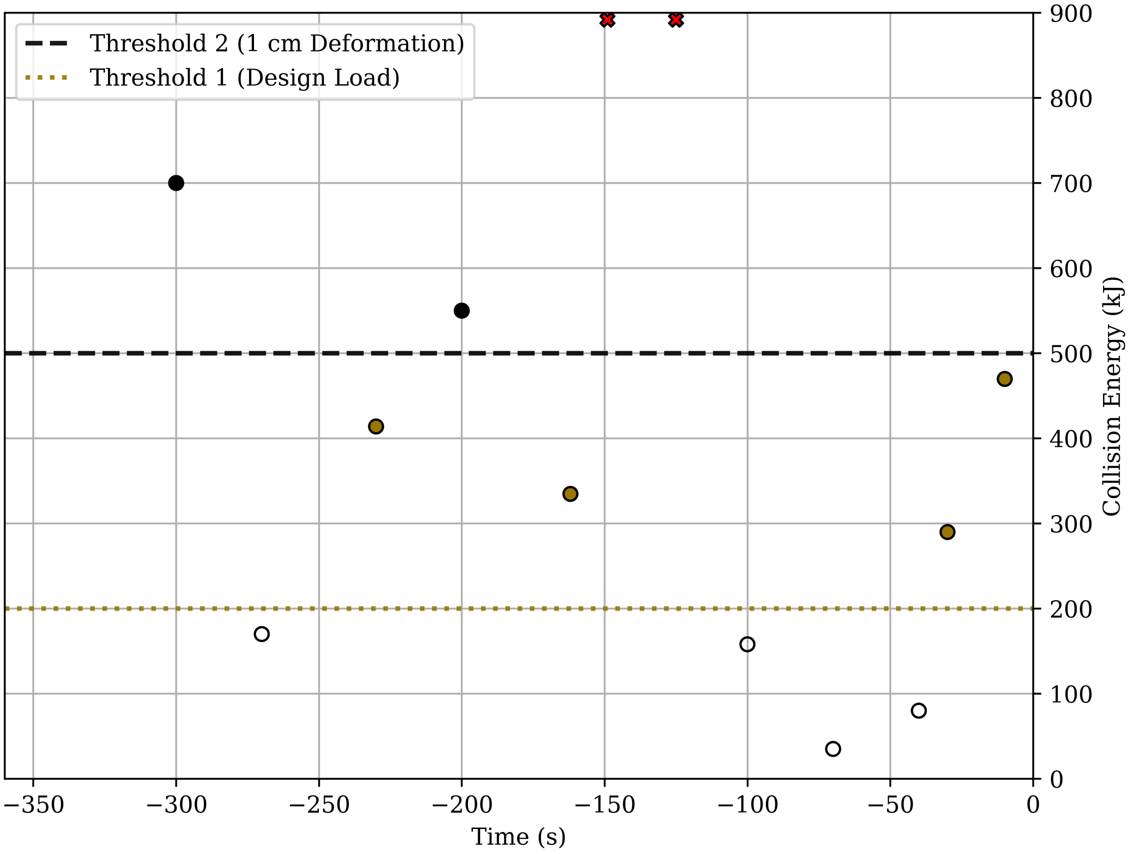

Figure 3.9: User interface with example data

To accommodate these requirements, the interface was designed as a chart, displayed to the user on an additional screen. Figure 3.9 shows the chart as it was displayed to users. Here loads are displayed as points on the graph, with the y-axis representing the collision energy of each collision, and the x-axis representing the number of seconds since the collision occurred. When collisions occur, they appear on the right side of the graph, and drift left over time for a maximum of 360 seconds. The graph is updated multiple times per second, meaning the points drift continuously for the duration they are displayed.

The points are displayed differently depending on their collision energy relative to the two thresholds. The two thresholds appear as dotted lines, with the lower threshold (design load) occurring at 200 kJ and being amber colour-coded, and the upper threshold (1 cm deformation) occurring at 500 kJ and being black colour-coded. Points occurring below the lower threshold appear as simple circles with no infill. Points over the first threshold have an amber infill. Points that exceed the second threshold are given a black infill. Points that exceed the upper limit of the y-axis at 900 kJ are represented by an 'X' with a black outline and red infill.

The decision to implement the 'overload' system with the red and black 'X' was because the largest loads that could be experienced are so large that displaying it on the same graph makes the safe energy area difficult to see. In preliminary testing, a user operating at high speed could easily exceed 10 000 kJ in a collision. Rather than accommodate this on the chart, the decision was made to have the instructor read the collision energy aloud if requested. Even without the specific value, the overload marker makes it clear that the capacity of the vessel has been greatly exceeded.

3.17 Experiment Design

To test the utility of the load feedback system (that is, the individual load algorithm, safety thresholds, and user interface as a complete system) an experiment was designed. This experiment had the hypothesis that participants who had access to the load feedback system would perform better in simulator training than participants who did not benefit from the system. The experiment was designed around a number of transit scenarios, where the goal of the trainee was to travel from one position to another, as quickly and safely as they could. With the benefit of the load feedback system, it was hypothesized that the participants with access to the feedback information would better understand the capabilities of their ship. With this information, they could hypothetically use their ship closer to full capacity, without exceeding the capacity, and thus perform better without compromising safety.

The format of the experiment was to split participants into two groups, both of which would go through a number of training scenarios. One group, referred to as the control group (or CG) would perform the scenarios with only basic guidance. The second group, referred to as the feedback group (or FB), would not receive any direct guidance, but instead would have access to the load feedback system during the scenarios. By splitting the participants into these two groups, the difference in the effect of exposure to the feedback over time could be assessed.

In order to isolate the effect of the feedback system, the participants selected for testing were novices to ice operations of ships. This was so they did not have any strong prior notions of what safe operation of vessels in ice consisted of, and instead would be bound by their ability to interpret the data presented to them. Participants were recruited from post-secondary students, who were at least 18 years old, had normal (or could be corrected to normal) vision, and had not had prior experience with a marine simulator. The target participant was intended to be representative of those who are most likely to go through simulator training. While cadets in a marine program have been used in other previous experiments, other works have had recruitment problems due to the small pool of participants, and also found minimal difference between first-year cadets and a general post-secondary population [18].

All participants were first put through a habituation scenario, where they were given a chance to become familiar with the controls of the simulator, and the information available to them on screen (with the exception of the feedback system). The habituation scenario lasted roughly 10 minutes and was finished once participants were comfortable with each of the control systems. The sequence of scenarios each participant was put

Figure 3.10: Simulator setup

through followed table 3.11. The testing consists of 4 scenarios, each approximately the same in terms of duration and task.

Table 3.11: Scenario schedule for experiment

Scenario	**Control Group**	**Feedback Group**
1	Test (No Guidance)	
2	Train (Guidance)	Train (Feedback)
3	Train (Guidance)	Train (Feedback)
4	Test	

For the first scenario, neither group is given any sort of guidance towards completing their objective. Instead, the goal of safely but promptly reaching the objective is explained to them. They are told that it would be possible to operate the ship in a manner that would cause damage to the structure of a real ship, and that they should attempt to operate the ship safely according to their best judgment. This scenario serves to give each participant a chance to acclimate to operating the vessel in ice, as well as a chance to set a baseline for performance, against which the effect of exposure to feedback can be measured.

The second and third scenarios are the exposure scenarios. Here, the two groups are

Figure 3.11: Simulator controls

given different treatments. The control group was given advice regarding speed, being told that below 4 knots collisions are completely safe and that direct collisions above that speed would start to risk damage to the ship. This value of 4 knots was found using a safe-speed assessment, and was confirmed to be accurate using the feedback system prior to participant testing. Participants were told that they were permitted to go above 4 knots if they felt they could do so safely. In contrast, the feedback group was not given any additional guidance or advice prior to the second or third scenarios. Instead, the feedback system was displayed and explained to them. They were told that collisions below the 200 kJ first threshold were completely safe, that collisions above the 200 kJ threshold would start to risk ‘minor or cosmetic damage’, and that collisions above the 500 kJ threshold would begin to risk more significant damage to the structure.

Figure 3.12: On-screen information

The design of the second and third scenarios was similar, both being transit operations where they must reach a specified location. The context given to the participants was different between the two scenarios. In scenario two, they were told that they had come upon an ice field while on patrol, and needed to cross it to continue on their way, and so their objective was to cross the ice field safely and promptly. Scenario three was an emergency scenario. Prior to the simulation beginning, the participants are told they have received a distress signal from a nearby fishing vessel, and they were the closest vessel and needed to respond. They were given no additional guidance or advice on operating the vessel, but were told that given the emergency circumstances, a fast response was important, and so taking on an increased risk of damage to the ship was acceptable.

Scenario four was a repeat of the first scenario. Participants were not given any additional guidance, and the feedback group no longer had access to the feedback monitor. The intention for this scenario was to see if the feedback group would retain their training once the feedback was no longer immediately available, as well as to provide a direct comparison between scenarios one and four, to see what the effect of the two different exposures was.

3.18 Experiment Procedure

This experiment plan was reviewed and approved by Memorial University of Newfoundland and Labrador's Interdisciplinary Committee on Ethics in Human Research (ICEHR). The corresponding file number was #20231087-EN. All forms and documents used for the experiment were approved by the committee and are included in Appendix 1. Many of the materials used were derived with permission from those used in previous experiments involving marine simulators, namely Soper's *An investigation of the influence of a decision support system on simulated ice management performance* [18].

The procedure began with recruitment. Recruitment materials were distributed via email to incoming students of the engineering department, and recruitment posters were placed around the university campus. Visits were also made to classes to distribute recruitment materials and explain the experiment to potential participants. Potential participants who were interested were asked to contact the researcher via the provided channels, and participants who contacted the researcher were scheduled into a time slot that was compatible with the schedules of both parties. Participants were randomly assigned to one of the groups at the time of their participation but were not informed of their group until after the scheduled session had ended.

Upon arriving at the agreed testing area, participants were given an informed consent form, which acknowledged their role in the testing, the testing procedure, and the researcher's responsibilities to the participant during and after participation. Participants were then asked to complete an experience questionnaire, which was intended to capture both demographic information, and any relevant seagoing experience. This included information such as the participant's age, educational background, and any experience at sea or operating ships in ice. To ensure the safety of participants, simulator sickness screening was performed repeatedly throughout the session. Screening involved having the participant complete a questionnaire self-assessing for several commonly known sickness symptoms, examples of which include fatigue, headache, or dizziness. This assessment was performed once before any exposure to the simulator to set a baseline for the participant's condition and then again prior to beginning each of the scenarios.

Upon completion of the informed consent form, experience questionnaire, and baseline simulator sickness assessment, participants would be allowed to begin habituation. Habituation involved a short scenario involving moving the vessel a short distance (500 m) forward, concluding when the participant reached a marker in a small ice field. This gave the instructor time to explain each of the control systems of the vessel (namely the propulsion, rudder, and camera systems), explain the on-screen information (speed-over-ground, heading, rotation, course-over-ground, propeller RPM gauge, and rudder position gauge), as well as nuances of the simulator (the simulator will produce noises in contact with ice, but the loudness of the sound is constant, and doesn't change with how hard ice is struck).

Each scenario after habituation followed the same procedure. The pre-scenario simulator sickness assessment was performed prior to beginning any scenario. Next, the participant would be briefed with the relevant information for each scenario (context to scenario, objective, feedback system or guidance if provided). The scenario would be performed. Following the completion of the scenario, a debriefing interview would be performed. Questions asked during the interview were drawn from the debriefing questionnaire. Not all questions were asked of each participant or for each scenario, as some of the questions were not always applicable (e.g. feedback system questions wouldn't apply to the control group). Following the final scenario, participants were asked to refrain from discussing their experience with others to avoid influencing other potential candidates.

3.19 Scenario Design

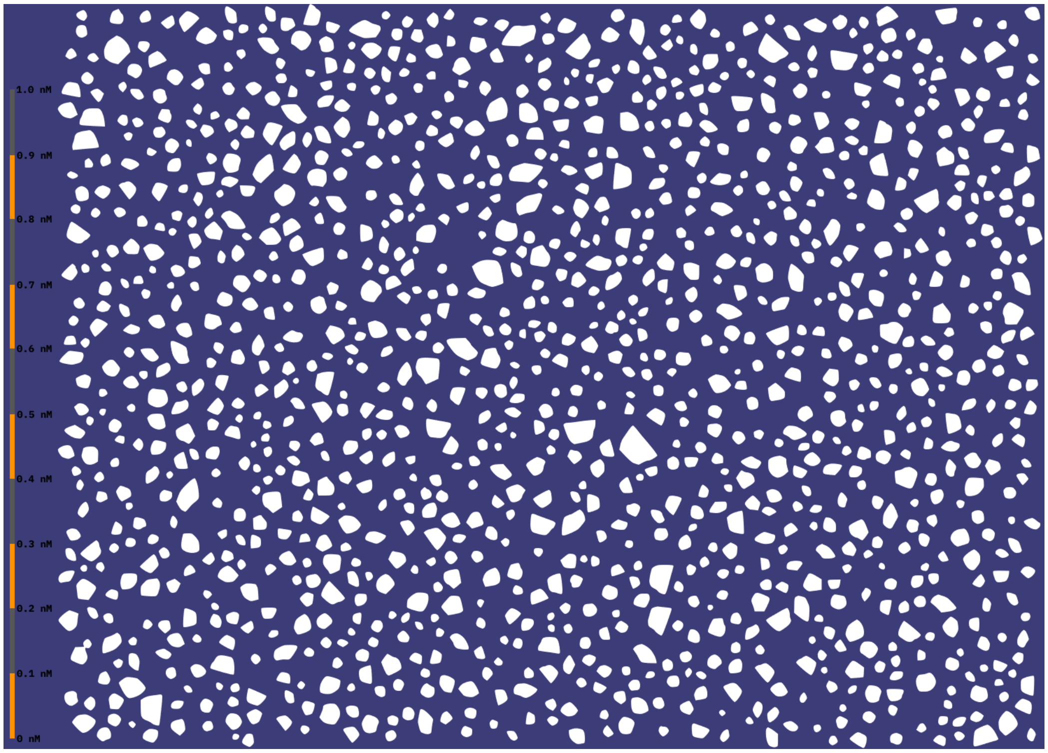

Figure 3.13: Ice field used for scenarios

Each scenario was designed using the same ice condition so that performance in each could be compared directly. Figure 3.13 shows a top-down view of the ice field used. The ice field was approximately 1.1 nautical miles by 1.3 nautical miles in dimension. The field has two-tenths of ice coverage, consisting of first-year ice floes. The floes average 30 metres in diameter, distributed log-normally, with the smallest and largest floes being 15 to 90 metres, respectively. The ice thickness is approximately uniform, with 75 cm being the average thickness for all pieces. This condition results in a positive risk outcome for PC7 within the POLARIS system, meaning it would be considered within the bounds of normal operation for a PC7-classed vessel.

Each scenario was designed to require about 1.5 nautical miles of travel in a straight line. Allowing for a buffer zone at the beginning and end of scenarios, each scenario had a 2500 m section along which the participants could be assessed. Each scenario begins with the participant's vessel in a static position and ends when they approach within a set distance of the objective. The buffer zone at the beginning served to let the participant get settled at their station and get their vessel up to speed, while the buffer zone at the objective was necessary as the participants didn't necessarily take the same path to the objective.

3.20 Analysis

Participants were evaluated using a number of metrics intended to measure either performance or safety, with the ideal participant being able to perform well in both without sacrificing one for the other. The performance metrics for the participants were as follows:

- **Time:** Time (in seconds) it took for the participant to complete the objective
- **Average Speed:** Average forward speed (in knots) that the participant operated the vessel
- **Standard Deviation of Speed:** How much the participants' speed varied during the trial
- **Distance:** How far the participant travelled to reach the objective
- **Fuel Consumption:** The amount of fuel burned by the engines to reach the objective

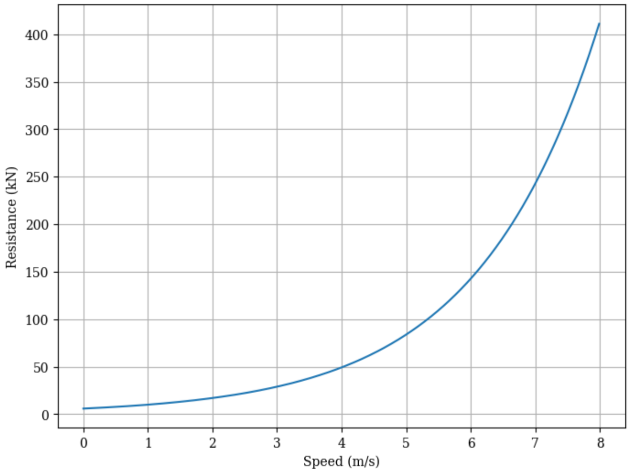

Figure 3.14: Resistance vs speed for ship

While the first four metrics could be calculated directly, the calculation for fuel consumption required multiple steps. First, a speed-resistance curve was established for the hull geometry using the Holtrop model [30]. The result is shown in figure 3.14, which was approximated to equation 3.41. Using Newton's second law of motion, equation 3.42 equates the forces of resistance of the hull and thrust from the ship's propellers to the resulting acceleration of the ship. As the ship's mass is known, and the acceleration can be calculated from the velocity data, the propellers' thrust force can be calculated using equation 3.43. Knowing the thrust for a time step, the effective power generated during that timestep could be calculated using equation 3.43.

$$R = 5.8586 \cdot e^{0.532*V} \tag{3.41}$$

$$\sum F = m \cdot a = R + T_{prop} \tag{3.42}$$

$$T = R + M_{ship} \cdot (V_i - V_{i-1}) \tag{3.43}$$

The engines were assumed to generate this power at 50% efficiency based on the resistance results. The fuel consumption could then be assumed to be 180 $\frac{g}{kwH}$, which is typical of large, medium-speed marine diesel engines [31]. Using this, the fuel consumption for a given timestep was calculated using equation 3.45, where η is the efficiency, and FC is the fuel consumption in grams per kilowatt-hour.

$$P_{\text{EFF}} = T \cdot V \tag{3.44}$$

$$\textsc{Fuel} = \frac{P_{\text{EFF}} \cdot \text{FC}}{\eta} \tag{3.45}$$

The safety metrics, each relating to ship-ice collisions, were as follows:

- **Number of Floes:** Number of unique ice floes collided with
- **Number of Collisions over Energy Level:** Number of collisions that occurred above a set energy level. 200, 500, 900, and 1800 kJ were used as they correspond with the two thresholds, the overload limit, and 2 times the overload limit.
- **Average Energy:** Average energy level of all collisions
- **Maximum Energy:** Maximum energy level for a single collision
- **Total Energy:** Sum of the energy from all collisions

4. Results

4.1 Scenario 1

Table 4.1: Participant Performance Statistics for Scenario 1

Participant	Time	Velocity - Avg.	Velocity - St.dev.	Distance Travelled	Fuel Consumed
	s	kn	kn	m	kg
CG1	884	5.6	1.2	2574	925
CG2	751	6.6	1.5	2572	1395
CG3	422	12.1	2.2	2636	5966
CG4	833	5.9	0.8	2548	1123
CG5	1254	4.0	1.4	2574	587
CG6	520	9.5	1.7	2551	3230
CG7	730	6.7	1.1	2539	1394
CG8	1005	5.4	1.7	2816	1005
CG9	951	5.3	2.4	2636	1492
FB1	660	7.9	3.4	2691	2938
FB2	881	5.6	1.2	2551	911
FB3	1003	4.9	1.0	2535	673
FB4	696	7.1	1.7	2564	1711
FB5	602	8.2	1.8	2545	2489
FB6	963	5.1	1.4	2526	1024
FB7	691	7.3	1.6	2606	1475
FB8	405	12.3	1.2	2574	5353
FB9	717	7.0	2.6	2603	2070
Average	776	7.0	1.7	2591	1987
Average-CG	817	6.8	1.6	2605	1902
Average-FB	735	7.3	1.8	2577	2072
p-value	0.22	0.34	0.27	0.21	0.41

The performance metrics for each participant during scenario 1 are shown in Table 4.1. To reach the objective 2500 m away, the participants took an average of 776 seconds (12 minutes 56 seconds), with the fastest participant taking 405 seconds (6 minutes 45 seconds), and the slowest participant taking 1254 seconds (20 minutes 54 seconds). Likewise, the average speed for the group was 7 knots, with the fastest participant averaging 12.3 knots and the slowest averaging 4.0 knots. The standard deviation of velocity for the participants averaged 1.7 knots, which was the lowest average value for any of the scenarios. Participants averaged 2591 meters of travel to reach the objective and averaged roughly 2000 kg of fuel to do so.

Table 4.2: Participant Collision Statistics for Scenario 1

Participant	**# of Floes**	**# of Collisions Over:**				**Avg. Energy**	**Max. Energy**	**Total Energy**
		200 kJ	*500 kJ*	*900 kJ*	*1800 kJ*			
	–	–	–	–	–	kJ	kJ	kJ
CG1	8	6	1	0	0	257	535	2310
CG2	25	14	6	4	1	580	2782	10447
CG3	29	31	23	18	11	1123	4370	47180
CG4	24	1	1	0	0	179	679	1969
CG5	15	0	0	0	0	47	47	47
CG6	27	23	11	8	2	562	2876	19686
CG7	17	1	0	0	0	153	223	611
CG8	24	11	7	3	1	1073	8731	15029
CG9	28	8	4	3	2	520	2746	8841
FB1	19	22	11	7	6	916	5821	32053
FB2	26	6	3	0	0	266	804	4260
FB3	20	1	0	0	0	260	425	520
FB4	23	10	5	3	2	677	2244	9476
FB5	21	14	7	4	1	632	2711	12013
FB6	26	5	1	1	0	293	926	2343
FB7	11	0	0	0	0	73	73	73
FB8	24	18	12	8	4	995	4031	21896
FB9	26	10	5	4	0	770	1730	8471
Average	22	10	5	4	2	521	2320	10957
Average-CG	22	11	6	4	2	499	2554	11791
Average-FB	22	10	5	3	1	542	2085	10123
p-value	0.48	0.41	0.37	0.33	0.38	0.34	0.40	0.39

Table 4.2 shows the safety metric statistics for each participant for scenario 1. Participants collided with an average of 22 floes of ice to reach the objective. The participants exceeded the 200 kJ threshold an average of 10 times, the 500 kJ threshold 5 times,

and 9 of the 18 participants exceeded the 2 times overload limit of 1800 kJ. The average collision energy for any given collision by a participant was 521 kJ. On average, the largest collision a participant experienced was roughly 2300 kJ, and the sum of collision energy for a participant averaged to roughly 11 000 kJ.

4.2 Scenario 2

Table 4.3: Participant Performance Statistics for Scenario 2

Participant	**Time**	**Velocity - Avg.**	**Velocity - St.dev.**	**Distance Travelled**	**Fuel Consumed**
	s	kn	kn	m	kg
CG1	837	6.0	0.9	2602	1067
CG2	1078	4.7	1.3	2613	911
CG3	543	9.7	2.9	2693	4313
CG4	1222	4.1	1.4	2612	591
CG5	1476	3.4	1.0	2572	400
CG6	831	6.0	2.5	2563	2584
CG7	878	5.6	1.5	2533	1147
CG8	1423	3.4	0.8	2542	395
CG9	1030	4.8	2.9	2550	2970
FB1	779	7.5	2.7	3029	2398
FB2	928	5.3	1.3	2527	866
FB3	832	5.9	2.0	2532	1584
FB4	993	5.1	2.0	2611	1094
FB5	603	8.2	3.0	2546	3554
FB6	1262	3.9	1.3	2514	692
FB7	873	7.9	2.0	2807	2375
FB8	715	7.0	1.6	2534	1571
FB9	872	5.7	2.0	2550	1275
Average	954	5.8	1.8	2607	1655
Average-CG	1035	5.3	1.7	2587	1597
Average-FB	873	6.3	2.0	2628	1712
p-value	0.096	0.122	0.194	0.257	0.42

Table 4.3 shows the performance statistics for scenario 2. Both groups were slower, with the average time for all participants now 954 seconds, up from 776 seconds in

scenario 1. The difference between the average completion time was larger for scenario 2. In scenario 2, the feedback group took on average 873 seconds, which was 162 seconds faster on average than the control group, who averaged 1035 seconds to complete the scenario. The feedback group averaged a higher speed at 6.3 knots vs the control group's 5.3 knots. Table 4.4 shows a summary of the collision statistics. All collision statistics are lower for both groups.

Table 4.4: Participant Collision Statistics for Scenario 2

Participant	**# of Floes**	**# of Collisions Over:**				**Avg. Energy**	**Max. Energy**	**Total Energy**
		200 kJ	*500 kJ*	*900 kJ*	*1800 kJ*			
	–	–	–	–	–	kJ	kJ	kJ
CG1	11	2	0	0	0	132	281	923
CG2	25	2	0	0	0	264	380	791
CG3	29	14	8	6	1	632	4523	14545
CG4	18	1	0	0	0	207	296	413
CG5	13	0	0	0	0	103	117	205
CG6	16	0	0	0	0	77	77	77
CG7	18	0	0	0	0	84	98	169
CG8	9	0	0	0	0	0	0	0
CG9	13	1	1	1	0	625	1091	1251
FB1	32	13	9	4	1	629	2071	11322
FB2	22	2	0	0	0	191	469	1722
FB3	3	0	0	0	0	94	94	94
FB4	16	1	0	0	0	156	275	624
FB5	19	6	2	1	0	378	1682	3776
FB6	25	1	0	0	0	250	442	501
FB7	15	6	2	1	0	429	1592	3857
FB8	20	4	0	0	0	186	403	1677
FB9	17	2	2	0	0	280	740	2241
Average	18	3	1	1	0	262	813	2455
Average-CG	17	2	1	1	0	236	762	2042
Average-FB	19	4	2	1	0	288	863	2868
p-value	0.29	0.21	0.31	0.45	0.50	0.30	0.43	0.34

4.3 Scenario 3

Table 4.5: Participant Performance Statistics for Scenario 3

Participant	**Time**	**Velocity - Avg.**	**Velocity - St.dev.**	**Distance Travelled**	**Fuel Consumed**
	s	kn	kn	m	kg
CG1	761	6.7	0.7	2617	1320
CG2	917	5.4	1.3	2552	946
CG3	392	12.6	1.2	2542	5917
CG4	1039	4.8	2.0	2569	1107
CG5	900	5.5	1.7	2547	1151
CG6	636	7.8	2.8	2552	2585
CG7	885	5.5	1.0	2516	929
CG8	673	7.8	2.4	2717	2140
CG9	587	8.5	3.2	2560	4632
FB1	632	8.4	2.7	2747	3038
FB2	780	6.4	1.6	2543	1454
FB3	660	7.4	2.7	2536	1963
FB4	575	8.7	2.5	2570	3265
FB5	611	8.0	1.4	2520	2044
FB6	744	6.6	1.0	2513	1353
FB7	649	7.7	1.4	2586	1830
FB8	694	7.1	2.2	2538	1924
FB9	848	5.8	1.9	2530	1373
Average	721	7.2	1.9	2570	2165
Average-CG	754	7.2	1.8	2575	2303
Average-FB	688	7.3	1.9	2565	2027
p-value	0.193	0.418	0.376	0.380	0.34

The results of scenario 3 found that participants operated more aggressively due to the emergency nature of the scenario. Participants reached the objective in an average of 721 seconds, which is less than the average for either scenario 1 or 2. The control group took an average of 754 seconds, while the feedback group was 66 seconds faster, taking 688 seconds on average. All participants went much faster, with an average speed of up to 7.2 knots. Velocity standard deviation was up slightly to 1.8 average. Both groups took more direct paths than the previous scenario, average 2570 meters travelled. And as would be expected with the increased aggressiveness, fuel consumption was up considerably to 2165 kg average.

Table 4.6: Participant Collision Statistics for Scenario 3

Participant	**# of Floes**	**# of Collisions Over:** *200 kJ*	*500 kJ*	*900 kJ*	*1800 kJ*	**Avg. Energy**	**Max. Energy**	**Total Energy**
CG1	18	2	1	0	0	330	714	1319
CG2	22	1	0	0	0	157	223	627
CG3	33	17	8	6	3	820	2807	15579
CG4	20	0	0	0	0	66	96	132
CG5	19	1	1	0	0	204	579	1020
CG6	20	1	0	0	0	155	247	774
CG7	30	2	0	0	0	169	447	1518
CG8	28	29	17	9	2	669	2199	24760
CG9	30	6	4	3	0	410	1113	5328
FB1	36	13	6	3	0	485	1328	8238
FB2	27	2	1	0	0	172	651	1720
FB3	23	3	1	0	0	220	543	1982
FB4	29	8	3	1	0	380	1456	4937
FB5	27	12	4	2	0	405	1732	7293
FB6	26	5	2	0	0	250	621	2747
FB7	19	3	2	0	0	332	669	1662
FB8	27	7	4	3	0	377	1192	5273
FB9	25	2	1	0	0	179	761	1964
Average	26	6	3	2	0	321	965	4826
Average-CG	24	7	3	2	1	331	936	5673
Average-FB	27	6	3	1	0	311	995	3980
p-value	0.20	0.45	0.35	0.21	0.09	0.42	0.43	0.29

The collision statistics, shown in table 4.6, show an increase in ship-ice collisions compared to scenario 2. However, the number of unsafe loads does not appear to increase correspondingly, as both groups appear to have found better understanding of the limits of the vessel. Only two participants (both in the control group) exceeded the 1800 kJ threshold. Seven participants (3 control group, 4 feedback) exceed the 900 kJ threshold. All participants in the feedback group exceeded the 500 kJ threshold, while four control group participants never exceeded this threshold, and two more only exceeded it a single time.

4.4 Scenario 4

Table 4.7: Participant Performance Statistics for Scenario 4

Participant	**Time**	**Velocity - Avg.**	**Velocity - St.dev.**	**Distance Travelled**	**Fuel Consumed**
	s	kn	kn	m	kg
CG1	867	6.4	1.0	2756	1243
CG2	843	6.1	2.3	2676	1592
CG3	391	12.7	1.2	2564	5620
CG4	1007	5.0	2.2	2634	1353
CG5	914	5.5	2.0	2607	1093
CG6	725	6.9	2.8	2602	2056
CG7	1086	4.5	0.8	2547	582
CG8	805	6.5	3.5	2724	3434
CG9	502	10.4	3.1	2657	5464
FB1	538	9.5	1.6	2644	3157
FB2	863	5.7	1.0	2539	928
FB3	700	7.1	1.5	2561	1645
FB4	716	7.0	2.7	2581	2036
FB5	727	6.8	1.4	2548	1494
FB6	752	6.5	2.8	2537	1993
FB7	618	8.1	2.1	2580	2394
FB8	900	5.6	1.9	2618	1348
FB9	1118	4.8	2.7	2745	1389
Average	782	7.0	2.0	2618	2157
Average-CG	793	7.1	2.1	2641	2493
Average-FB	770	6.8	2.0	2595	1821
p-value	0.405	0.366	0.338	0.087	0.17

Scenario 4 saw worse performance and safety for both groups. The performance metrics (table 4.7) show both groups being slower than both scenario 3 and scenario 1, averaging 782 seconds with little variation between the groups. The groups averaged a speed of 7 knots. This is slightly lower than the previous scenario, but still considerably faster than the previous non-emergency scenario. Participants took longer paths than previous scenario, averaging 2618 meters. The participants consumed on average 2157 kg of fuel, which is much closer to the consumption of scenario 3 than scenario 1.

Table 4.8: Participant Collision Statistics for Scenario 4

Participant	**# of Floes**	**# of Collisions Over:** *200 kJ*	*500 kJ*	*900 kJ*	*1800 kJ*	**Avg. Energy**	**Max. Energy**	**Total Energy**
CG1	11	3	0	0	0	188	360	1689
CG2	20	7	3	1	0	372	1125	4832
CG3	21	21	14	10	5	741	4146	28150
CG4	15	1	1	0	0	745	745	745
CG5	19	2	0	0	0	210	211	420
CG6	22	3	2	0	0	314	854	2198
CG7	17	1	1	1	0	569	1041	1139
CG8	30	19	11	7	6	1028	5454	24682
CG9	27	21	10	7	4	877	3578	21051
FB1	29	24	13	10	10	914	4161	31086
FB2	27	6	1	0	0	271	508	2710
FB3	21	3	0	0	0	235	484	1644
FB4	25	11	1	1	0	328	915	4591
FB5	26	9	3	1	1	461	2506	6916
FB6	26	4	2	1	0	568	1192	2272
FB7	18	2	1	0	0	423	889	1270
FB8	27	11	5	4	0	464	1604	8347
FB9	23	5	1	0	0	212	743	2547
Average	22	9	4	2	1	496	1695	8127
Average-CG	20	9	5	3	2	560	1946	9434
Average-FB	25	8	3	2	1	431	1445	6821
p-value	0.03	0.47	0.24	0.28	0.38	0.16	0.26	0.30

The degraded performance is also apparent in the safety and collision statistics. Five participants exceeded the 1800 kJ, with four of those participants having exceeded in many times and by considerable margins. Ten of 18 (56%) also exceed the 900 kJ margin. Interestingly, while the feedback group interacted with 25 floes on average (which is comparable to previous scenarios), the control group interacted with only 20 floes on average.

5. Discussion

5.1 Scenario 1

Scenario 1 saw the most varied performance values between participants, as was expected due to the lack of guidance. While there was some variation between the groups, a one-tailed, unpaired student t-test found no statistical significance (highest p-value of 0.21), which indicates that the two groups started at approximately the same competency. Behaviour concerning ship-ice interactions also varied greatly during the first scenario. With no guidance on safe operation, the safety of each participant's performance relied on how closely their intuition of what was reasonable behaviour compared to the reality of safe operation. Nine of the 18 participants (50%) exceeded the overload threshold by a factor of two (>1800 kJ). Most of the participants (11 of 18) exceeded the 500 kJ threshold three or more times. The participants who didn't were those who avoided significant contact with ice or who operated at a low speed. This supports the idea that without a form of guidance, participants have little basis to judge how aggressively they should operate.

As with the performance statistics, no statistical significance was found between the behaviour of the two groups. The behaviour of individuals varied greatly, with many participants behaving in an 'all or nothing' fashion with regards to collisions, being either very avoidant or very comfortable with collisions. Five of the participants (CG1, CG5, CG7, FB3, and FB7) demonstrate this avoidant behaviour, as they as a group had very few collisions, and tended to avoid ice if at all possible. In contrast, participants CG3, CG6, CG8, FB1, FB5, and FB8 where all very aggressive, taking on many collisions and often exceeding the capacity of the vessel by large amounts. The remaining participants' behaviour was somewhere in between these two groups.

5.2 Scenario 2

Scenario 2 saw a significant shift in behaviour for both groups. Both groups were slower on average, with the control group requiring an additional 219 seconds as compared to scenario 1, and the feedback groups requiring an additional 138 seconds on average. Given some guidance to the capacities of their vessels, the participants seemed to act more carefully.

All but two participants increased in time; CG1 and FB3 were the only participants who decreased in time as compared to scenario 1. These two participants were both from the largely avoidant groups in scenario 1, and continued to avoid contact with ice in the second scenario. A simple explanation of this is that these participants were mostly uninfluenced by the guidance, and their time improvement was caused by an improvement in their ability to manoeuvre the vessel. Interestingly, CG1 and FB3 had very similar times for scenario 2, finishing in 837 and 832 seconds, respectively. They averaged 5.9 and 6.0 knots, both 50% faster than the safe speed of 4 knots. These performances are examples of how fast novice participants were able to go by adopting the strategy of avoiding ice if at all possible. These performances were above average for the group, demonstrating the validity of the strategy.

Most of the participants who went faster than 830 seconds had higher load statistics than CG1 and FB3 (ice-avoidant), with the exception of FB8. This participant had max loads similar to CG1 and FB3 (no loads exceeding 500kJ), but overall was involved in more collisions than the ice-avoidant group. This is shown by how they interacted with 20 floes, more than CG1 and FB3 combined. This participant was able to complete the scenario in 715 seconds, maintaining an average speed of 7.0 knots. This performance improvement of ̃120 seconds and a full knot in average speed over the ice-avoidant group shows the potential gain in performance that the feedback system is trying to capture. A participant who understands the limit of their vessel has the potential to go significantly faster than an operator who avoids ice contact while being just as safe.

Two participants behaved very aggressively in the scenario: CG3 and FB1. These participants each had total collision energies exceeding 10 000 kJ, and were the only participants to exceed the 1800 kJ threshold. Both of these participants were very aggressive in scenario 1, and although they both reduced their speeds and collisions from the previous scenario, they still remained the most aggressive by a large margin.

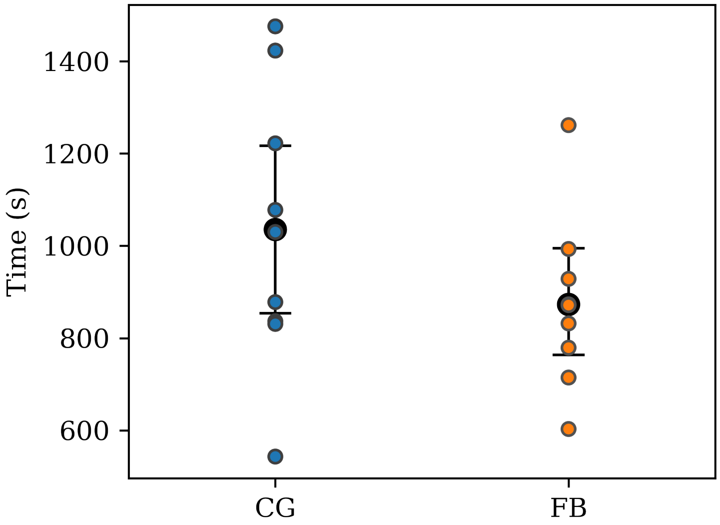

Figure 5.1: Time for Scenario 2 with 95% confidence intervals

Figure 5.1 shows the times for each participant by group, along with 95% confidence intervals for the group. Here it can be seen that while there is still overlap of the confidence intervals, there appears to be a difference between the two groups. The feedback group had a tighter confidence interval, reflecting their more consistent performance. This seems to suggest that the feedback system is guiding the participants towards a more consistent behaviour. At the same time, Figure 5.2 shows the average and the

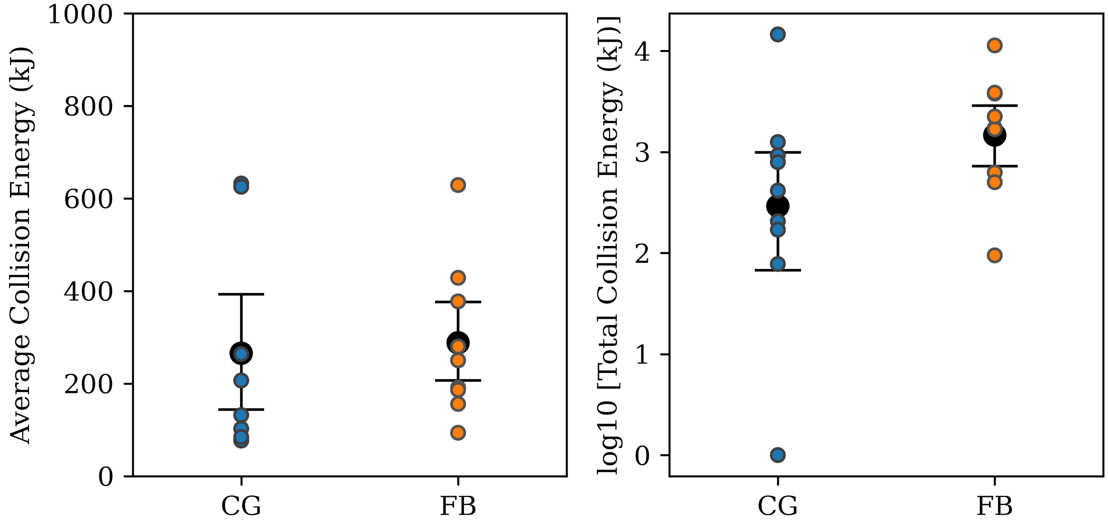

Figure 5.2: Average and Total Collision Energy for Scenario 2 with 95% confidence intervals

total collision energies for each of the participants, split into their groups. This shows that the average collision energy is similar in distribution between the two groups, suggesting both are similar in safety. At the same time, the total collision energy for the feedback group seems to be significantly higher. This indicates that the feedback group is able to have more ship-ice collisions without compromising the safety of the vessel, as compared to the control group.

5.3 Scenario 3

Scenario 3 was an emergency scenario, where it was made clear to the participants that time was of increased performance and that it was acceptable to risk minor damage to the vessel as long as the damage wasn't so severe as to compromise the mission. This is strongly reflected in the performance, as there was a significant decrease in completion time from 954 to 721 seconds for all participants, corresponding to an increase in average speed from 5.8 to 7.2 knots.

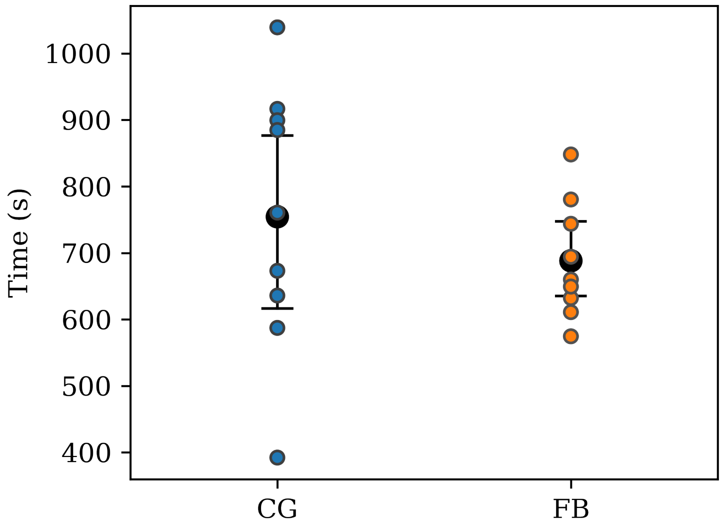

Figure 5.3: Time for Scenario 3 with 95% confidence intervals

While on average it appears the two groups performed similarly, the distribution of the performances is strikingly different. Figure 5.3 shows the average time for each of the participants, split by groups. The feedback group has a tight distribution, with the difference between the fastest and slowest performance being only 273 seconds. By contrast, the fastest and slowest control group members had a difference of 647 seconds, with very few of the performances being close to the mathematical mean. What is being seen here is likely that feedback group members were able to adjust their performance to the new conditions, whereas the control group tended to either not speed up as much or to speed up far too much and expose the vessel to undue risk.

This is reflected in the collision statistics. While the number of ship-ice interactions and the average speed of ships were up, all participants in the feedback group were able to complete the scenarios without any single load exceeding 1800 kJ, and without total collision energy exceeding 10 000 kJ. This is indicative of substantial improvement over previous scenarios, and that participants are becoming more adept at gauging the safety of individual collisions.

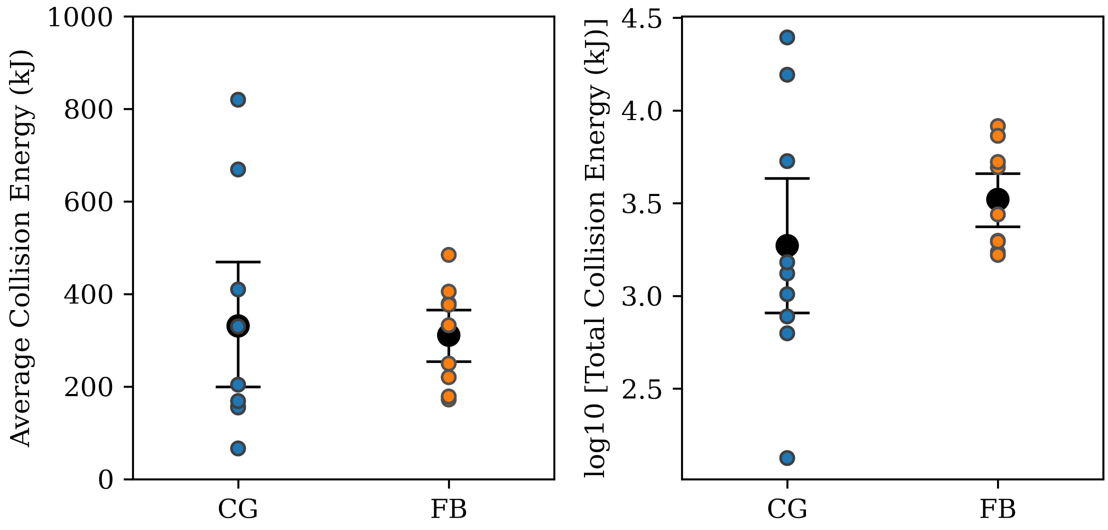

Figure 5.4: Average and Total Collision Energy for Scenario 3 with 95% confidence intervals

In contrast, two participants in the control group (CG3, CG8) went substantially faster than the rest, and as a result had a large number of very high collisions. These participants seem to demonstrate how, without feedback or advanced guidance, control group members struggle to perform in emergency scenarios without substantially increasing risk to the vessel. Figure 5.4 shows the average and total collision energy for each participant. The two participants, can clearly be seen as behaving much more aggressively than the rest of the participants.

To assess participants who were able to complete the scenario without exceeding these higher thresholds, Table 5.1 shows a combination of performance and safety for the participants who stayed below the threshold. The table is in order of least time to complete the scenario, separated by group. Here, a statistical difference between the two groups becomes obvious. The average time for this control group is 818 seconds, 130 seconds slower on average than the feedback group. The p-value for a one-tailed,

Table 5.1: Scenario 3 Combined Statistics for Participants who didn't exceed 1800 kJ

Participant	**Time**	**Velocity-Average**	**# of Collisions Over:** *200 kJ*	*500 kJ*	*900 kJ*	**Ave. Energy**	**Max. Energy**
	s	kt	–	–	–	kJ	kJ
CG9	587	8.5	6	4	3	410	1113
CG6	636	7.8	1	0	0	155	247
CG1	761	6.7	2	1	0	330	714
CG7	885	5.5	2	0	0	169	447
CG5	900	5.5	1	1	0	204	579
CG2	917	5.4	1	0	0	157	223
CG4	1039	4.8	0	0	0	66	96
FB4	575	8.7	8	3	1	380	1456
FB5	611	8.0	12	4	2	405	1732
FB1	632	8.4	13	6	3	485	1328
FB7	649	7.7	3	2	0	332	669
FB3	660	7.4	3	1	0	220	543
FB8	694	7.1	7	4	3	377	1192
FB6	744	6.6	5	2	0	250	621
FB2	780	6.4	2	1	0	172	651
FB9	848	5.8	2	1	0	179	761
Average	745	6.9	4	2	1	268	773
Average-CG	818	6.3	2	1	0	213	488
Average-FB	688	7.3	6	3	1	311	995
p-value	0.045	0.062	0.010	0.020	0.184	0.057	0.011

unequal variance t-test is 0.045 for this metric, indicating that the difference is statistically significant. The feedback group also had a statistically higher number of collisions over the 200 and 500 kJ thresholds. This seems to indicate that the feedback group was able to achieve this higher performance by increasing how much of the capacity of the structure they were using, but were able to judge an amount of additional risk they felt was appropriate.

5.4 Scenario 4

Scenario 4 was designed as a repeat of scenario 1, with the intention of seeing how the behaviour of the participants had been changed by the exposure to the guidance or feedback provided. As such, real-time feedback was not provided to the feedback group, and no additional guidance was given to the control group.

Scenario 4 saw worse performance for both groups. Participants took an average of 782 seconds, which is slower than scenario 3 and 6 seconds slower than it took to complete scenario 1. The remaining statistics followed similar trends, with the difference between the two groups being smaller than in any other scenario. This is also reflected in the collision statistics, although for the first time, the control group was slightly more aggressive than the feedback group. One notable exception is that the feedback group interacted with a statistically higher number of floes than the control group, suggesting that even once the feedback was removed, the feedback group continued to be more comfortable interacting with ice.

The cause of the degraded performance for scenario 4 is an important point for consideration. As the feedback group no longer had access to the load monitoring system, it would have been understandable if the performance of the group had declined. While this may explain why the feedback group perhaps declined more, losing any advantage over the control group, the performance of both groups dropped considerably, even though the control group did not lose access to any resources for the scenario. Instead, it is likely an experimental issue that caused this decline. A possible explanation is that the participants were fatigued by this time in testing, as participants had been operating the vessel on average for over 40 minutes at this point. It's also possible that because scenario 4 was a repetition of scenario 1, participants were not as engaged as in previous novel scenarios and struggled to pay as close attention. Another possible factor is that scenario 4, a non-emergency scenario, was performed directly after scenario 3, an emergency scenario where participants were instructed to go fast. It is possible that participants had become used to operating in the manner of the previous scenario and struggled to adjust their behaviour back to 'normal' operating conditions.

5.5 Participant Interviews

After the scenarios, participants were asked questions from the debriefing questionnaire (Appendix 1). Participants were not asked each question at each opportunity, as all the questions were not always relevant to each participant (e.g. the questions regarding the feedback system weren't relevant to the control group).

Important Factors

One of the questions asked was what participants thought were the important factors for success in the scenarios. The participants' responses all fell into 4 categories of speed control, ship control, route planning, and collision understanding. Six participants stated that controlling speed was important. Five responded that understanding collisions, in terms of when the ship would come in contact and predicting how hard a collision would be, was important. Four participants said control of the ship's steering was important. Three participants stated they thought planning a route through the ice was important.

Challenges

Participants were asked what aspects they found most challenging about the scenario. Nine participants stated they found it difficult to judge when the ship was going to contact ice. Several elaborated on this point, explaining that because the ship's waterline wasn't visible from the bridge, they found it difficult to judge when or if a collision would occur. Other participants also stated they found it difficult to judge the width of the ship, and also found it difficult to judge if a gap in the ice they spotted was large enough for the ship to fit through.

Six participants responded that they found controlling and manoeuvring the ship difficult. Participants elaborated to explain the way the vessel handled was difficult for them, specifically, the delay between operating the control panel and the ship response. Another participant said they had difficulty judging how sharply the vessel was going to turn based on the rudder position.

Five participants stated that they found route planning difficult, stating that they found it difficult to pick a path through the ice. Two of these participants stated that they had difficulty spotting larger pieces of ice until they were too close to avoid.

Two participants stated they found managing collisions to be challenging. Two of these participants specified that they found it difficult to judge how hard a collision with ice would be, especially with regard to speed.

Two participants stated they found controlling the speed of the vessel to be challenging. Similar to the steering answer, both said that the delay between the controls of the vessel and the response of the vessel made it difficult to operate the vessel.

Two participants stated that they found the deflection of the ship from collisions to be challenging. The participants said that the amount the ship was knocked off course by collisions made it difficult for them to reach the objective.

Change in Approach

Between scenarios, participants were asked if they would change their approach if they were to repeat the scenario. Half of the participants answered that they would make adjustments to their speed, with three specifying that they would slow down more before collisions. Seven participants stated that they would have gone a different route through the ice if they were to repeat the scenario. Four participants stated that they would increase the amount of steering and manoeuvring they had performed around ice. One single participant, who was in the control group, stated that they would make more effort to hit ice with the shoulder of the ship instead of the stem, as they felt those collisions weren't as hard.

User interface

Participants in the feedback group were asked questions specifically in regard to the feedback interface. All nine participants in the feedback group responded that they found the feedback helpful. When asked if they thought the feedback gauge had affected their behaviour, six participants responded that they had modified their speed in direct response to the feedback gauge.

When asked how they would alter the feedback to make it more helpful for them, four participants responded. Two stated that they would like the time between a collision occurring in the simulator and it appearing on the feedback to be reduced. One stated that they wish the feedback responded to smaller collisions, and acknowledged every time the ship came in contact with ice. A final participant stated they would have liked a predicted component of the feedback, so that they could act on collisions before they occurred.

6. Conclusions

A methodology for assessing structural loads from collisions with individual ice floes during simulator training is presented. The methodology allows the energy of a collision to be calculated from the change in velocity as the result of the collision by using a modification of the Popov energy method. The methodology also presents a method of determining safe limits of energy for a single collision, by using an adaptation of the glancing blow to should scenario from the IACS Polar Class rules. This approach was used on an example ship structure to determine potential safe energy limits for a variety of ice conditions. A program was developed to calculate loads in real-time for a specific simulator, and a user interface was developed to communicate the magnitude of individual loads relative to the safe energy limits previously calculated. A series of simulated ice scenarios was created to test participants undergoing simulator training on a number of performance and safety metrics.

Testing was performed on 18 human participants. Participants were recruited from post-secondary students who had no prior experience with either operating ships in ice, or with the marine simulator being used. After an initial scenario to set a baseline for performance, participants were divided into two groups of 9. The first group was a control group, and was given guidance in terms of a speed limit above which collisions with ice would be increasingly unsafe. The second group was not given guidance, but instead had access to the feedback system for a portion of the training. Participants then completed three additional scenarios involving reaching an objective by crossing a field of ice floes.

The results from normal operating conditions found some difference between the two groups, but largely not to a statistically significant degree. However, under emergency conditions, the difference in performance between the two groups shows statistically significant improvements in the feedback group. The feedback group was better able to utilize the full capacity of the vessel, without exceeding the limits of the hull. Participants in the feedback group were also able to collide with ice more frequently without exceeding the safe limits of their vessels. Considering the short time of exposure, and the inexperienced nature of the participants, this evidence suggests that the real-time load feedback system can positively influence participants' ability to navigate ice loads, and under certain circumstances, operators with exposure to this guidance have improved performance during simulator training.

6.1 Recommendations and Future Work

There are a number of improvements or expansions to the methodology that could be made. Firstly, the simulator physics engine in use utilizes rigid-body physics, but the methodology currently doesn't account for the flexural failure of ice, potentially resulting in overestimated loads where ice would have flexed and yielded in real-life. This has been partially addressed by limiting the size of floes for this experiment, but implementing a system to account for flexural failure would improve the system for very large and/or thin ice floes.

Furthermore, to this point, the feedback system has only been tested on broken ice fields of relatively low concentration. Investigating the performance of the system in different ice concentrations could be a further area of work.

Currently, the structural model for setting safe energy limits is relatively rudimentary. Additional work involving assumptions such as the grillage shape, the centring of loads on or around frames, or the contact geometry of collisions may increase the fidelity of these calculations.

To this point, the structural analysis was only applied to a single structure of a single Polar Class. Performing the analysis and training with other ship structures may provide valuable information, such as the human factors relevant to different Polar Class operations.

Finally, there is the potential to use the methodology as part of a predictive system, providing information to operators prior to collision rather than after as feedback. Such a system may be more useful for participants or may be useful for route finding or planning outside of simulator training.

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Appendix 1: Ethics Documents

Informed Consent Form

Title: Evaluation of the effects of digital decision support technology on marine ice management performance in a simulator environment

Researcher: Logan Miller, Graduate Student, Faculty of Engineering and Applied Science, Memorial University, (782) 370-1003, lmiller21@mun.ca

Supervisor: Dr. Brian Veitch, Supervisor, Faculty of engineering and Applied science, Memorial University, (709) 864-8970, bveitch@mun.ca

You are invited to take part in a research project entitled *"Experimental assessment of a real-time ice load feedback algorithm as a training tool for a marine simulator."*

This form is part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. It also describes your right to withdraw from the study. In order to decide whether you wish to participate in this research study, you should understand enough about its risks and benefits to be able to make an informed decision. This is the informed consent process. Take time to read this carefully and to understand the information given to you. Please contact the researcher coordinator *Logan Miller*, if you have any questions about the study or would like more information before you consent.
It is entirely up to you to decide whether to take part in this research. If you choose not to take part in this research or if you decide to withdraw from the research once it has started, there will be no negative consequences for you, now or in the future.

Introduction:
I am Logan Miller, a Masters Student in the Faculty of Engineering and Applied Science's Department of Ocean and Naval Architectural Engineering at Memorial University of Newfoundland in St. John's. As part of my Masters thesis I am conducting research under the supervision of Dr. Brian Veitch. The research is being conducted as a part of the Safety at Sea project, funded by Husky Energy, Natural Sciences and Engineering Research Council (NSERC), and Virtual Marine

Purpose of Study:
The Safety at Sea group has performed a number of previous experiments using marine simulators in order to test their use for marine training. You are being asked to be a participant on a study designed to evaluate the efficacy of new piece of technology for the simulator, one which allows ice loads to be assessed during simulator training. This research may be used to inform future use of this technology as a training tool during simulator operation.

What You Will Do in this Study:

If you choose to participate in this study, you will be asked to complete a simulated emergency ice management procedure in an ice management simulator.

You will work with a member of the research team to schedule times that are convenient for you to participate in this study. It is expected that your session for this study will take a maximum of three (3) hours.

Each session will take place at the Safety at Sea project's Simulation Lab (EN1035) in the Engineering and Applied Sciences (SJ Carew) building on Memorial University's St. John's campus.

You will arrive at the ice management simulator at the scheduled time where you will meet a member(s) of the research team.

The sessions will be split into four parts: (1) Briefing, (2) Familiarization, (3) Testing, and (4) Feedback and Closing.

Refreshments (water and snacks) will be on hand for you during the trials. We will have time for you to take multiple breaks throughout the sessions to allow you to have some refreshments, move around outside of the simulator, or use the washroom.

1. *Briefing:*

We will explain the research and an opportunity to ask questions or express concerns. If satisfied, you will indicate your free and informed consent by completing this Informed Consent Form.

Before you start any trials, we will ask you to complete an experience questionnaire. We will also ask you to fill out a simulator sickness questionnaire (SSQ) in order for us to establish a baseline score for you. We will administer the SSQ to you throughout the trials to see if you are developing simulator sickness, which will be indicated by a higher score.

2. *Familiarization Trial:*

Once in position on the console, you will be asked to perform a familiarization trial. These trials are designed to allow you to get familiar with the ice management simulator, and how the ship handles in the simulation. This trial are expected to take approximately 5-10 minutes. After the familiarization trials are completed, we will move on to the testing and training scenarios.

3. *Testing and Training Scenarios:*

Testing will involve a series of five ice management scenarios, each taking 15-30 minutes to complete. Prior to starting the ice management scenario, you fill out a SSQ and go through a planning exercise with us.

When the scenario has been completed, you will be escorted off the ice management simulator and fill out another SSQ to determine if you are experiencing any symptoms of simulator sickness. You will then be shown a sped up video replay of your current scenario, where we will ask you interview style questions about your ice management techniques. We will ask you a series of questions to get your opinion on your performance and what factors you considered during ice management. If provided, you will be asked whether you used load-feedback, and whether you found it to be helpful. Your answers will be recorded on paper.

4. *Feedback and Closing:*

You will be asked to give feedback on the habituation scenarios, the training scenarios, and post-trial questions. After this, the session will be completed.

Length of Time:
Your session is expected to take a maximum of three (3) hours.

Your Participation:
Your involvement in this study is voluntary and confidential. As such, you participation is not a requirement of your employment. We will not identify you as a participant in this study, nor report your participation to your superiors or co-workers. The data collected in this study will not be traced back to you.

Withdrawal from the Study:
You can withdraw from this study at any point during your participation without giving any reason, and all data collected up until that point will be destroyed. There are no consequences to you for withdrawal from the study. If you choose to withdraw from the study after your participation, your data can be removed from the study up to two weeks after your participation. To withdraw from the study at any time, inform the researcher, Logan Miller

Possible Benefits:
For your participation in the study, you will receive a 20$ gift card.
Data collected from this study will benefit in the development of marine simulators for ice-management training.

Possible Risks:
A risk associated with participating in this study is the potential development of simulator-induced sickness. Simulator-induced sickness is very similar to motion sickness and can occur when people use equipment such as virtual reality headsets or simulators. Symptoms can include fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, stomach awareness, blurred vision, dizziness, vertigo, and burping. The symptoms can sometimes occur during, immediately after or several hours after exposure to the simulator.

We will be monitoring you for simulator sickness throughout the ice management scenarios by asking you complete the simulator sickness questionnaire (SSQ). If you self-report any of the above symptoms as “moderate” or “severe”, we will pause the trials and you will be provided with a rest period until your symptoms have subsided. You can decide whether you would like to resume the trials after the rest period. If the symptoms subside, and you choose to do so, we can continue with the trials. If you choose to not continue with the trials, we will stop the trials and you will exit the simulator.

If after the session ends the symptoms of simulator sickness persist for more than 20 minutes, we will arrange for you to get home safely.

Your performance in the simulator will be recorded throughout the study. For some individuals, this may cause performance anxiety or stress. This anxiety or stress may be caused by poor performance in the scenarios, by the difficulty or novelty of the task, or by repeated trials. To reduce the likelihood of anxiety and stress, where possible, we will guide you through the scenarios of the study. You will receive a break between scenarios to rest and you will be instructed not to worry or dwell on the previous scenarios.

You will be reminded that if you are not comfortable with any aspect of the trials, then you have the right to withdraw from the study at any point. To reduce the likelihood of embarrassment, you will perform the task individually and you will be reminded that your performance in the simulator will be anonymous. That is, your data is not linked to your identity and that your performance or withdrawal will not be reported to anyone.

If at any time you experience symptoms or discomfort, which prevent you from continuing in this study you retain the right to withdraw from the study.

As discussed in the *Anonymity* section of this form, the researchers cannot guarantee your complete anonymity in this research. While your name will not be reported, you may be identifiable to other people based on other information you provide. This means there is a risk of being identified based on your participation in this study. To reduce the likelihood of you being identified the researchers will avoid reporting any identifiable information such as specific vessels you have worked on.

There is a risk of embarrassment in this study if you feel you cannot answer the researchers' questions adequately. To reduce the likelihood of embarrassment you will be reminded that you are not being tested by these simulator trials.

Confidentiality:
The ethical duty of confidentiality includes safeguarding participants' identities, personal information, and data from unauthorized access, use, or disclosure. Protecting your privacy and maintaining confidentiality is important to the research team. The information gathered in this study will be used solely for research purposes. Only researchers involved in this study will have access to the data.

Anonymity:
Anonymity refers to protecting participants' identifying characteristics, such as name or description of physical appearance.

Protecting your privacy is an important goal for the research team and this means ensuring all personal data recorded during your participation remains anonymous. You will not be directly identified in publications. The study will use a number to identify you, not your name. For example, researchers will use an alphanumerical participant code (e.g. AB001) to identify you in all reports of your data including when direct quotations are used. Only the principal investigator will be able to link this number to your name. Measures have been taken to remove any other possible identifiers other than your name, like number of years of experience onboard a specific type of vessel, for instance. You will not be video or audio recorded in this study.

Recording of Data:
As part of this study, we will be collecting the following data from you:

- Name and contact information.
- Shipboard experience.
- Simulator sickness questionnaire scores.
- Ice management scenario performance (from the simulator)
- Video footage from the simulator
- Post-trial debrief questionnaire.

Use, Access, Ownership, and Storage of Data:
The research team will collect and use only the information they need for this research study. Your name and contact information will be kept in a locked office on a password protected computer by the research team at MUN. It will not be shared with others without your permission. You will receive a randomized alphanumeric participant code (e.g. AB001). All information collected from you will be recorded with the participant code. Your name will not appear in any report or article published as a result of this study.

Information collected, anonymized, and used by the research team will be stored by the Principal Investigator, Brian Vietch.

A hardcopy of your questionnaire responses will be kept in a filing cabinet in a locked office accessible by the research team. This data will have no identifiable information and will be kept separate from your signed consent form. Electronic data recorded in this study will be kept in a password protected file on a hard drive accessible only by the research team. This data will not have any identifiable information. Data will be kept for a minimum of five years, as required by Memorial University's policy on Integrity in Scholarly Research. After five years, all electronic records of your participation will be permanently deleted and all paper files will be appropriately destroyed. Data collected in this study will be documented in an Ocean Engineering Research Center (OERC) report. This will make the data accessible to other researchers but not the general public. This report will not include any of your identifiable information.

Reporting of Results:

The research team intends to publish the findings of this study in peer-reviewed journals and academic conferences. Formal reports will be made available to the research project partners (the National Research Council, Husky Energy, and Virtual Marine). Upon completion, my Masters thesis will be available at Memorial University's Queen Elizabeth II library, and can be accessed online at: http://collections.mun.ca/cdm/search/collection/theses. The data will be reported in a summarized statistical and descriptive form. Individual information or data will not be reported without your exclusive written consent.

Sharing of Results with Participants:

When data analysis is completed a report will be prepared and participants who wish to be informed of the results will have the opportunity to receive a copy of this report. The results will also be reported in my Masters thesis, which be available at Memorial University's Queen Elizabeth II library, and can be accessed online at: http://collections.mun.ca/cdm/search/collection/theses

Questions:

You are welcome to ask questions before, during, or after your participation in this research. If you would like more information about this study, please contact: Jonathan Soper (jksoper@mun.ca) or Brian Veitch (bveitch@mun.ca).

ICEHR Approval Statement:

The proposal for this research has been reviewed by the Interdisciplinary Committee on Ethics in Human Research and found to be in compliance with Memorial University's ethics policy. If you have ethical concerns about the research, such as the way you have been treated or your rights as a participant, you may contact the Chairperson of the ICEHR at icehr@mun.ca or by telephone at 709-864-2861.

Consent:

Your signature on this form means that:

- You have read the information about the research.
- You have been able to ask questions about this study.
- You are satisfied with the answers to all your questions.
- You understand what the study is about and what you will be doing.
- You understand that you are free to withdraw participation in the study without having to give a reason, and that doing so will not affect you now or in the future.
- You understand that if you choose to end your participation during data collection, any data collected from you up to that point will be destroyed.
- You understand that if you choose to withdraw after data collection has ended, your data can be removed from the study up to two weeks after your participation.

By signing this form, you do not give up your legal rights and do not release the researchers from their professional responsibilities.

Your Signature Confirms:

☐ I have read what this study is about and understood the risks and benefits. I have had adequate time to think about this and had the opportunity to ask questions and my questions have been answered.

☐ I agree to participate in the research project understanding the risks and contributions of my participation, that my participation is voluntary, and that I may end my participation.

☐ A copy of this Informed Consent Form has been given to me for my records.

Signature of Participant Date

Researcher's Signature:

I have explained this study to the best of my ability. I invited questions and gave answers. I believe that the participant fully understands what is involved in being in the study, any potential risks of the study and that they have freely chosen to be in the study.

Signature of Researcher Date

Participant Number: _______________
Date: _______________

Experience Questionnaire

Please answer the following questions but feel free to omit any that you do not wish to answer. If something is unclear, please ask the research coordinator. Your answers are confidential.

Question	Answer
1. What is your year of birth?	_________________________
2. What is your gender?	☐ Male ☐ Female ☐ Non-binary ☐ Prefer not to say Self-identify: ___________________
3. In what year of study are you enrolled?	☐ 1st year ☐ 2nd year ☐ 3rd year ☐ 4th year ☐ Over 4th year
4. Are you enrolled in a nautical science program?	☐ Yes ☐ No
5. What academic program are you enrolled in?	_________________________
6. Approximately how many months experience do you have at sea?	_________________________
7. On what types of vessels have you operated? (Select all that apply)	☐ OSV / AHTS ☐ Icebreaker ☐ Tanker / Bulk / Cargo ☐ Ferry / Coastal ☐ I have not spent time at sea
8. Have you ever operated in sea ice?	☐ Yes ☐ No

9. What types of operations did you perform while in ice? (Select all that apply)	☐ Watchkeeping during transit ☐ Maneuvering ship while being escorted ☐ Maneuvering ship to escort another vessel ☐ Ice management (open water) ☐ Ice management (confined water) ☐ Towing or emergency response ☐ I have only observed operations in ice ☐ I have not operated in ice

Participant Number: _______________

10. Where have you obtained your experience in operating in ice? (Select all that apply)	☐ Great lakes ☐ Gulf of St. Lawrence ☐ Coastal Newfoundland and Labrador ☐ Arctic (north of 60) ☐ Baltic Sea ☐ Caspian Sea ☐ Sea of Okhotsk ☐ Antarctic ☐ I have not operated in ice
11. Approximately how many years have you spent in the presence of sea ice?	________________________
12. What types of shore-based training have you taken for operating in ice? (Select all that apply)	☐ Basic training in ice operations ☐ Advanced training in ice operations ☐ Attendance at professional seminars discussing techniques and procedures relevant to ice operations ☐ I have never received training related to ice operations
13. Do you have any experience using a marine simulator? (Select all that apply)	☐ Training for navigation in open water ☐ Training for navigation in ice ☐ Research study ☐ I have no experience using a marine simulator

Participant Number: _______________ Date: _______________

Scenario: 1 / 2 / 3 / 4 / 5

Gauge: Y/N

Debriefing Questions

1. Rate your overall performance in completing the scenario. (1 is not very successful, 3 is somewhat successful, 5 is very successful)

1 2 3 4 5

2. What factors do you think were important for success in the scenario?

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3. What was the most challenging part of the scenario?

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4. Would you change anything about your strategy/approach in the scenario?

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5. Do feel like you were able to operate the ship safely?

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6. Other questions or comments about the scenario

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Participant Number: _______________

Scenario: 1 / 2 / 3 / 4 / 5

Gauge: Y/N

7. Do you feel the ice-load gauge assisted you in the scenario?

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8. Rate the performance of the ice-load gauge for helping you complete this scenario. (1 is not very successful, 3 is somewhat successful, 5 is very successful)

1 2 3 4 5

9. Did you modify your behaviour based on feedback from the gauge?

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10. How do you think your performance would have been different had the gauge not been available?

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11. Are there any changes you would make to the ice-load gauge to make it more helpful for you?

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12. Other questions or comments about the ice-load gauge

____
____
____

Participant Number: _______________ Date: ______________ Time: _____________

When: ☐ Before Habituation 1 ☐ After Habituation 3

☐ After Scenario 1 ☐ After Scenario 2 ☐ After Scenario 3

☐ After Scenario 4 ☐ After Scenario 5

--------------------------------PLEASE DO NOT WRITE ABOVE THIS LINE--------------------------------

Simulator Sickness Questionnaire

Please indicate the severity of symptoms that apply to you right now. Also note that there is no obligation to answer any or all questions if you do not wish to do so, but you must answer all questions in order to continue the study. There are no consequences for withdrawal from the study.

Symptom	**None (0)**	**Mild (1)**	**Moderate (2)**	**Severe (3)**
General discomfort				
Fatigue				
Headache				
Eyestrain				
Difficulty focusing				
Increased salivation				
Sweating				
Nausea				
Difficulty concentrating				
Fullness of head				
Blurred vision				
Dizziness (with eyes open)				
Dizziness (with eyes closed)				
Vertigo				
Stomach awareness				
Burping				

Kennedy, R. S., Lane, N. E., Berebaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

Recruitment Email: Volunteers Needed to Operate a Marine Simulator

Researchers at Memorial University are studying the effect of ice-load feedback on ice management performance in a simulator environment. The outcomes of the research will help to develop ice-load monitoring technology and could inform future ways of providing onboard training.

The Experiment:

- This research is being completed as part of a Master's Degree in Ocean and Naval Architectural Engineering under the supervision of Dr. Brian Veitch at Memorial University of Newfoundland.
- The research is being conducted using the Ice Management Simulator located in the Engineering and Applied Sciences (SJ Carew) building on Memorial University's St. John's campus.
- If you participate, you will be asked to attend 1 session (which could take up to 3-4 hours to complete).
- Refreshments and breaks will be provided.
- Exposure to simulators has been known to cause simulator-induced sickness. Researchers will monitor participants throughout the study for symptoms of simulator-induced sickness.
- Volunteers can withdraw from the study at any time and for any reason. There are no consequences for withdrawal from the study.

Who can participate?

- Post secondary students
- Ages 18 years of age or older
- Must have normal or corrected-to-normal vision
- Must have no prior experience with the MUN Ice Management Simulator

All participants will receive a $20 gift card for participating.

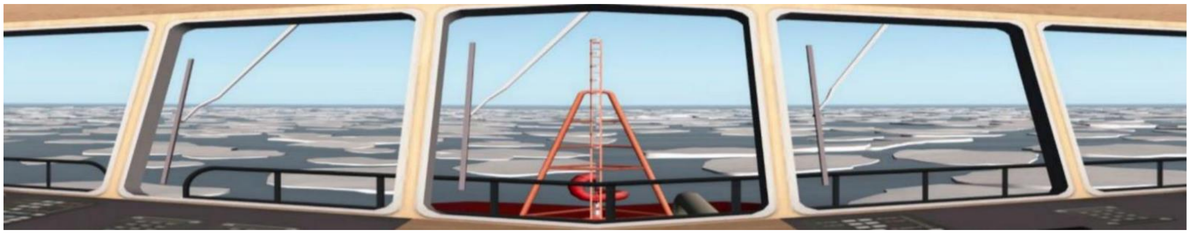
Participation in this study is not a program requirement, will not affect student grades, and will not be reported to instructors, other students, or school administrators.

If you are interested or have any questions, please contact:
Logan Miller
Email: lmiller21@mun.ca
Phone: (782) 370-1003

If you know anyone why may be interested in this study, please give them a copy of this information

The proposal for this research has been reviewed by the Interdisciplinary Committee on Ethics in Human Research and found to be in compliance with Memorial University's ethics policy. If you have ethical concerns about the research, such as your rights as a participant, you may contact the Chairperson of the ICEHR at icehr.chair@mun.ca or by telephone at 709-864-2861

Volunteers Needed to Operate a Marine Simulator



Researchers at Memorial University are studying the effect of ice-load feedback on ice management performance in a simulator environment. The outcomes of the research will help to develop ice-load monitoring technology and could inform future ways of providing onboard training.

The Experiment:

- This research is being completed as part of a Master's Degree in Ocean and Naval Architectural Engineering under the supervision of Dr. Brian Veitch at Memorial University of Newfoundland.
- The research is being conducted using the Ice Management Simulator located in the Engineering and Applied Sciences (SJ Carew) building on Memorial University's St. John's campus.
- If you participate, you will be asked to attend 1 session (which could take up to 2-3 hours to complete).
- Refreshments and breaks will be provided.
- Exposure to simulators has been known to cause simulator-induced sickness. Researchers will monitor participants throughout the study for symptoms of simulator-induced sickness.
- Volunteers can withdraw from the study at any time and for any reason. There are no consequences for withdrawal from the study.

Who can participate?

- Post secondary students
- Ages 18 years of age or older
- Must have normal or corrected-to-normal vision
- Must have no prior experience with the MUN Ice Management Simulator

All participants will receive a $20 gift card for participating.

Participation in this study is not a program requirement, will not effect student grades, and will not be reported to instructors, other students, or school administrators.

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