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Ice Trails with "Le Commandant Charcot" for Load Assessment

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ABSTRACT

The Arctic Ocean is in a process of significant changes, which also raises the interest in exploring these changes. This also concerns the performance of ships and how different operational profiles together with climate change are affecting current and future designs. This paper presents ice trials with a PC2 ice classed ship during a Trans-Arctic voyage, where continuously data such as ice thickness and accelerations are measured. From these data the number of ice impacts is determined which is used in a probabilistic extreme ice load assessment. The probabilistic ice pressures are compared with the design pressures from the Polar Ice Classes. The results indicate a significant loading of the structure with a potential to exceed Ice Class values. The analysis and results contain uncertainties, as the applied state of the art needs to be updated with new measurements and data accounting for climate change. A detailed analysis during one ice trail with constant power indicated that ridges contribute significantly to the number of impacts, while recent research on Arctic survey indicates that the ice surface becomes smoother and the number of ridges reduce.

KEY WORDS: Ice; Trans-Arctic; Ship-borne measurements; Accelerations; Extreme load assessment

INTRODUCTION

The Arctic Ocean is in a process of significant changes with respect to climate, economic and geopolitical interests.

Ship operations in the Arctic require an understanding of the loads encountered, respectively, on how climate change affects the Arctic (Wei and Freris, 2025) and how this might reflect on the design of ships operating in ice (Cambos et al., 2019). Generally, the Polar Classes provide design loads for the hull (IACS UR I2, 2019), however when ships are operating with profiles that differ significantly from those commonly in service additional assessments might be used. The ship addressed in this paper is *"Le Commandant Charcot"* (*LCC*), which is an Arctic cruise and research vessel. She is built with ice class PC2 and has the unique operational profile sailing at least 50% of the time in ice and has in consequence significantly more encounters with ice than most other ships.

The design of local scantlings requires the assessment of local pressures. Jordaan et al. (1993) proposed in this context a probabilistic analysis of loads and later a probabilistic methodology for the design of Arctic ships (Ralph and Jordaan, 2013). The method is based on the analysis of measured pressures to which an extreme value distribution is fitted. In the design application of the method parameters such as exposure of the concerned plate (full or partly) and the number of impacts is to be included. An impact defines here a significant ice loading while e.g. Jordaan et al. (1993) uses the terminology hits. In operations, ramming often defines the loading (after backing out) when moving with relatively high velocity into a ridge. Such events also took place during this voyage and therefore both terms are referring to significant loading independent of the load origin. The term ramming is also used by Ralph (2016) for the interaction with ice floes and multi-year ice, but no further specifications are provided. The number of rams reflects that with an increasing number of interactions the probability of encountering higher loads increases. However, as the analysis in Tõns et al. (2015) indicates the number of rams/year is difficult to assess and consequently the number of was rams parametrically varied. Furthermore, it is not established how a ram is to be defined, respectively, what associated load increase should be counted as ram. Consequently, the state of the art is lacking an assessment how many hits a ship like *LCC* might encounter on a Trans-Arctic voyage respectively over a year. Also, the conditions causing an impact are undefined. This lack of information nearly prohibits the application of the probabilistic approach in the design process and this paper seeks to bridge this gap. Ralph (2016) stated that the Polar Classes PC4 - PC2 can be associated with multi-year ice impacts being: PC4: 10 impacts, PC3: 100 impacts and PC2: 1000 impacts.

Detailed load and pressure measurements usually require significant instrumentation, while the approach presented utilizes measured accelerations. During the Trans-Arctic voyage, a dynamic motion unit was mounted at the bow measuring accelerations in a higher frequency than pre-installed ship borne units. The presented approach compares probabilistic extreme pressure loads for the operational profile of *LCC* with design loads (IACS UR I2, 2019). Approach and results are discussed with respect to the state of the art, the transformation of the Arctic and future research needs.

SHIP AND ROUTE

The ship is *"Le Commandant Charcot"* (*LCC*) which is a cruise and research vessel with ice class PC2. She holds research laboratories and a hangar for larger equipment and enables research activities along the routes. Detailed information on hull and structure cannot be disclosed and are disguised in values. The investigations and measurements presented in this paper refer to a Trans-Arctic Cruise from Nome (Alaska, USA) to Longyearbyen (Svalbard, Norway). The cruise through geographic North Pole is displayed in Figure 1. The voyage took place in September 2024, which is the end of the Arctic summer and a refreezing of open leads and melt ponds took partly place already.

MEASUREMENTS

Ice Thickness Measurements

We have carried out continuous ice thickness data measurements with the so-called Sea Ice Monitoring System (SIMS), and electromagnetic induction (EM) ice thickness sensor (Haas et al., 1999; Haas, 1998). The SIMS was suspended from a horizontal boom extending from the ships bow, approximately 6 m ahead of the ship and 4 m above the ice. The EM sensor measures the height of the SIMS above the ice water interface, while its height above the surface of the ice is measured with a sonic echo sounder. Ice thickness is calculated from the difference between those two measurements, with an accuracy of approximately +/- 0.1 m over level ice.

Data were logged with a sampling frequency of 1 Hz, corresponding to a point spacing of approximately 4 m at a typical ship speed of 8 knots. Ice thicknesses were computed on the fly and displayed on the ships bridge in real time.

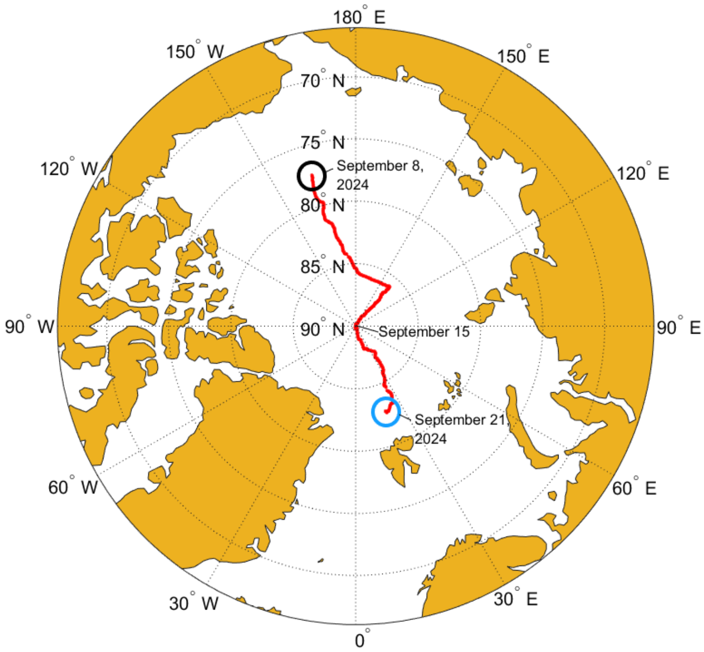

Figure 1: Route through the Arctic ice on the Trans-Arctic voyage September 2024 with start in Nome, Alaska, and destination Longyeardbyen, Svalbard.

Ice Property Measurements

The ice along the route varies between Nilas and partly 2.5 m thick second year sea ice. The encountered ice was post-decayed ice at the end of the summer season that started to re-freeze already. The properties are based on core-sample testing and for determining both compressive and flexural strength. Deatils are found in von Bock und Polach and Kubiczek (2025). The latter includes also some more information on the testing apparatus. For reference here, the properties at the geographic North Pole are stated Table *1*. All experiments are conducted at high loading rates in the brittle regime (strain rate around $10^{-1}s^{-1}$) at which ships interact with ice. The properties obtained indicate summer ice conditions despite the ice was already in the process of refreezing. For more details on the ice properties and comparisons with other semi-empirical formulas the interested reader is referred to von Bock und Polach and Kubiczek (2025).

Table 1: Ice properties measured at the North Pole in combination with flexural strength data from von Bock und Polach and Kubiczek (2025)

Thickness [m]	Bulk salinity [°%] / ppt	Thickness [m]	Mean temperature [C°]	Compressive strength [MPa]	Flexural strength [kPa]
1.8	2	1.8	-1.12	1.4	136

Acceleration and Motion Measurements

The Dynamic Motion Unit (DMU) VG400MB-100 from Crossbow is used to measure the ship's movements, see Figure *2*. This is a six-axis measuring system for measuring the linear acceleration along the three orthogonal axes x, y and z and the rotation rates for roll motions around the x-axis, pitch motions around the y-axis and yaw motions around the z-axis. The x-axis is oriented in the direction of the bow, the y-axis to port and the z-axis upwards. The system also has the option of calculating the roll and pitch angle using a Kalman filter algorithm in the firmware.

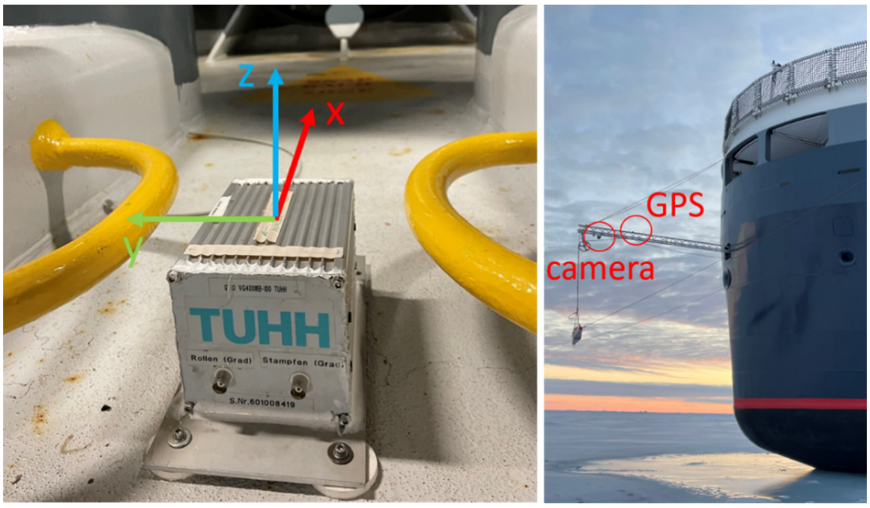

Figure 2: left) Orientation of DMU, right) Position of camera and GPS antenna

The measuring system is attached with four strong magnets to the mooring area, a particularly rigid structure in the bow area of the ship on deck 4 and is located approx. 76.46m in front of and 5.76m above the ship's center of gravity. In addition, a Reoling D4K23 16X LAN IP camera is mounted on a mast at the bow, which records the ice contact at the bow of the ship synchronized with time, as well as a GPS antenna for determining the position and time synchronization of the measurement data, see Figure *2*. The data is recorded at 100Hz for the accelerations and motions and at 2Hz for the camera time-synchronized on a Q.brixx-X station B SSD-1TB from Gantner Instruments.

The DMU was mounted on the forward winch deck from where the boom was put out in Figure *2*. The deck is of significant stiffness, but can be excited to vibrate also by impacts attacking in other locations than the bow.

ICE TRIALS AND MEASURED DATA

Trial settings and Conduction

The ice trials consist of two parts. One is the continuous measurement of accelerations and ice thickness during the entire voyage in ice and the second part are sections of constant power and straight heading. The auto-pilot is making minor adjustments keeping the course straight, when the ship is e.g. slightly deflected by a larger ice floe or non-symmetric breaking at the bow. These ice trials lasted between 20 min to 40 min and targeted for ice conditions as uniform as possible reducing the amount of variables in the analysis. The constant power sections are used for reference analysis.

Measured Data

Ice thickness and accelerations, respectively forces are measured continuously and their distributions are displayed in Figure *3*. Changes in accelerations (forces) are associated with changes in ice thickness and consequently, the total numbers for both cases are close to each other. For forces a bin size of $0.5*10^{-5}$ m/s² is chosen and for the ice thickness 0.5 m.

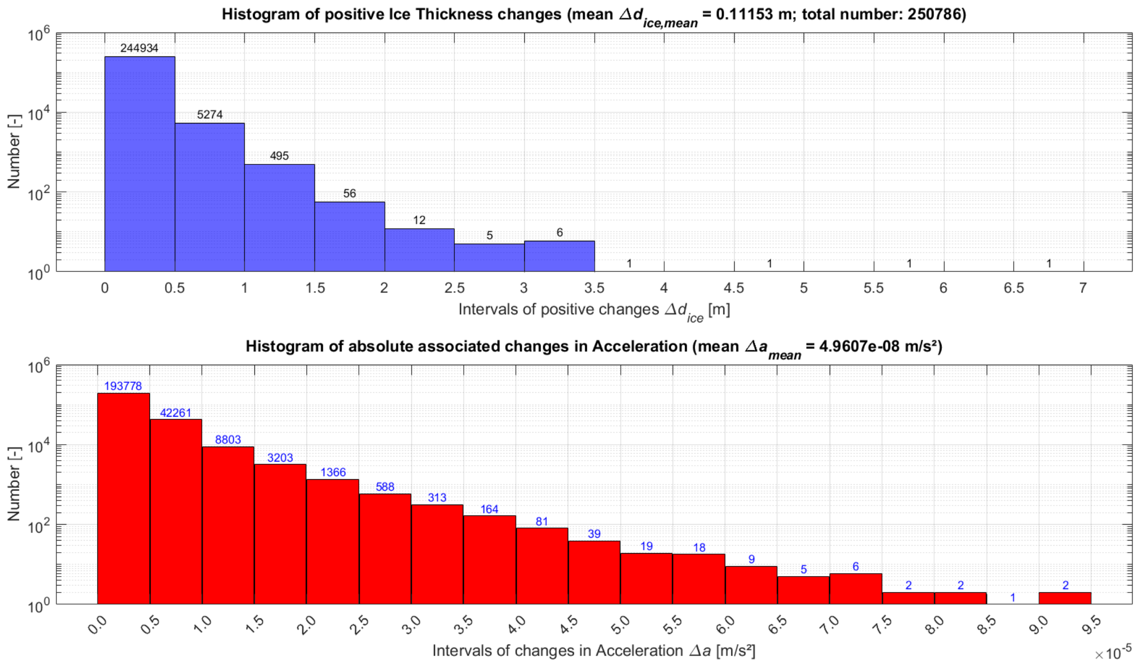

Figure 3: Number of recorded changes in ice thickness (top) and acceleration (bottom)

DATA ANALYSIS

The scope is the extraction of the number of impacts or rams from the data recorded in Figure *3*. Therefore, the data have to be filtered and processed which is described in the following. The measured horizontal accelerations are multiplied with the ship mass in order to obtain a force, respectively an amplification of the signal. The added mass for a ship in open water may be determined in a simplified fashion based on Lewis (1929), however various works (Isaacson and Cheung, 1988; von Bock und Polach and Ehlers, 2011) already indicated that the added mass is affected by the surrounding ice. As the added mass is related to the pressure field around the ship also the operational scenario and the ice conditions whether there are floes or level ice, are considered having an impact. This cannot be defined with the existing information and state of the art, while the presence of ice and the reflection of waves might even add an oscillatory character to the added mass (Li and Wu, 2021). Therefore, the use of the ship weight only, without the added mass, is applied here as a lower bound while acknowledging that actual load values might be higher as the added mass has to be integrated into absolute mass. The number of impact and ram counts is not affected.

The analysis is restricted to forces in the ship longitudinal x-direction (Figure *2*), as transvers (y-direction) accelerations are found to be co-dependent on ship motions. At this stage no approach is developed isolating transverse impact accelerations from transverse roll-motion accelerations. Therefore, the limitation to x-forces is believed providing a lower bound.

Extraction of Impact Events

The impact events in the recording need to be detected over the entire voyage and require an automatic method extracting the events. Figure *4* reflects this approach in an idealized example. A change in force must be associated with an increase in ice thickness and a simultaneous decrease in speed over the ramming process. As a ship is a response-control unit even with a set constant speed the response to the impact leads to a reduction in speed.

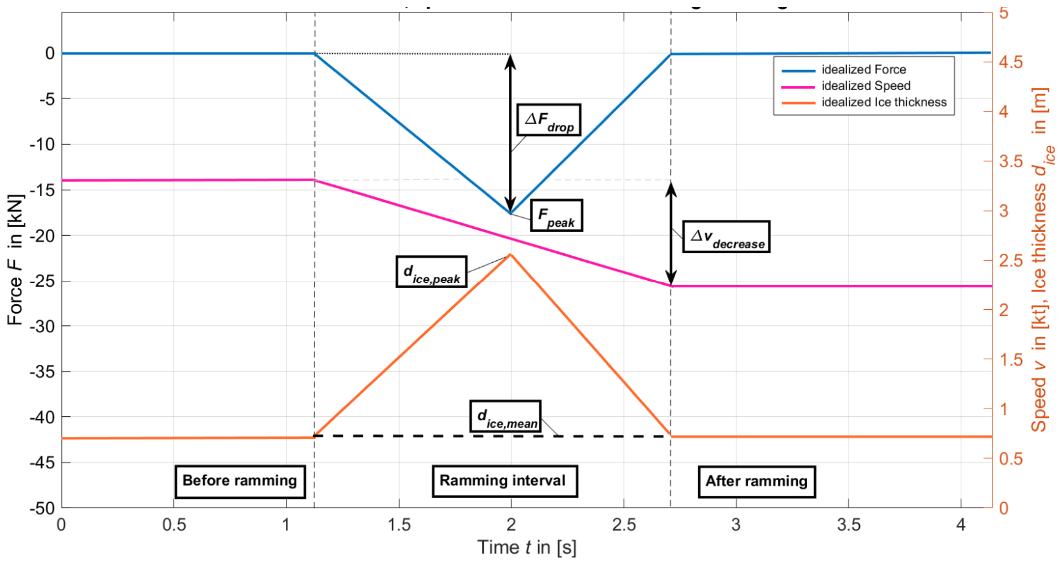

Figure 4: Criteria for ram detection with an idealized force, speed and ice thickness during ramming.

Filtering of Bow Impacts

The events of interest are those affecting at the bow on forward course. However, as the loading is measured not directly on a bow plate, but at the DMU (Figure *2*) the excitation may have multiple causes other than classic ice loading. Nevertheless, most impacts of relevant magnitude do originate from rams or impacts at the bow. While the other significant source of impact appears to be ice collisions with the azipod gondola or the propeller (pulling type). Both phenomenon and filtering approach is illustrated on Figure *5*d.

As the SIMS measuring the ice thickness is positioned ahead of the ship with a boom, an offset between ice thickness measurement and load measurement exists. This constant spatial offset is converted to a dynamic temporal offset as the velocity of the ship is continuously changing (see Figure *5*c). This adjustment is applied to the offset from the SIMS, to the bow stem as well as to the propulsion unit. Figure *5*b shows the relative position of the bow stem also indicating that the peak in thickness (probably a ridge) and the load peak are associated. Figure *5*b and d show that just before 13:30 UTC the ice thickness is zero, but still a load peak (Figure *5*d, green dashed line) is encountered. The green dashed line is the offset between the SIMS and the propulsion unit and shows in Figure *5*d when the ice encountered at the Time Frame will hit the azipod. The procedure in Figure *5* supports the exclusion of load peaks such as in Figure *5*d, green dashed line, as they are not associated with bow plate impacts.

Encountered Impacts

The number of impacts is used for the application of a probabilistic approach (Jordaan et al., 1993). The original paper uses the terminology hits with reference to non-zero pressure measurements, which is here used equivalent to impacts or rams. After the application of the impact detection and filtering process the number of rams reduces to 2506 from initial more than 240,000 load variations. Figure *6* displays the histogram of loads, where the impact or ram force is the absolute measured load.

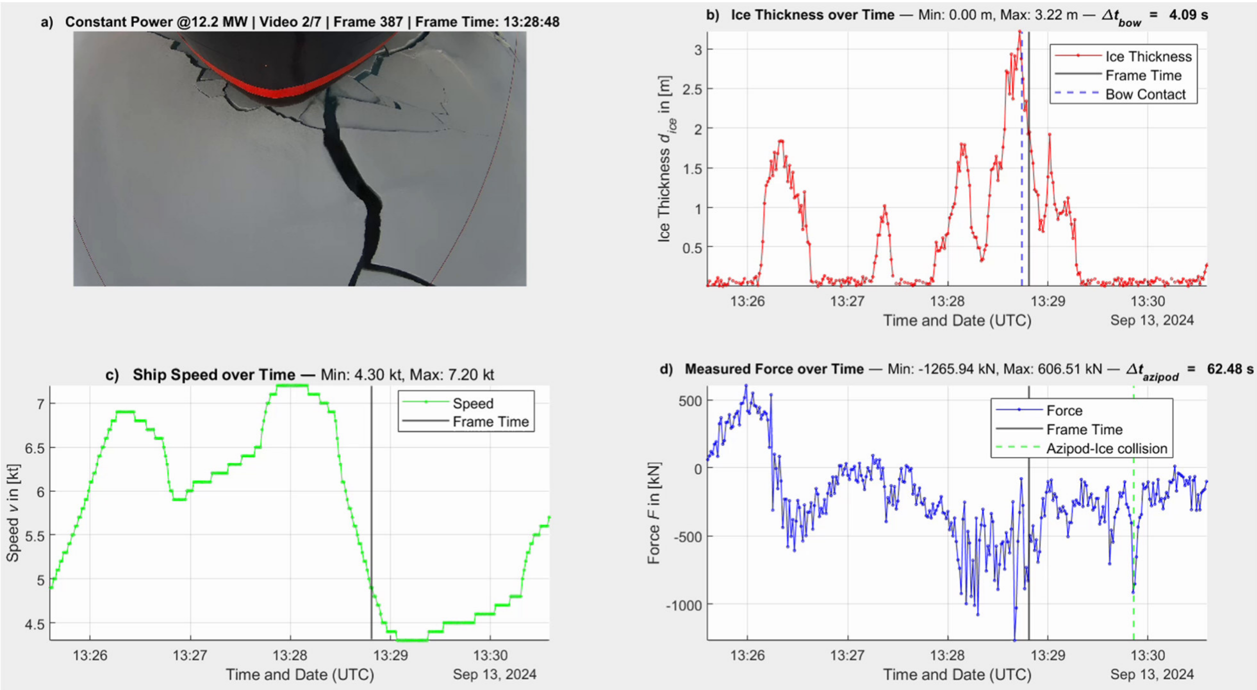

Figure 5: a) Displays the camera directed to the bow b) Ice thickness measurements with the reference time frame (SIMS) of the ice thickness measurement and the offset to the bow stem (contact with the ship). c) Speed over time with the reference time frame d) Force measurement with the reference Frame Time (SIMS) and the relative position of the propulsion unit (green dashed line).

Forces above -100 kN and force drops above 0 kN are excluded as they are of low significance and or fall within the measurement noise. Furthermore, only negative forces are associated with plate loads, while positive loads might be related to other excitations. This results in 2392 remaining ramming events according to Figure *4* for further analysis. The loads are found following a Weibull distribution in Figure *6*, which is considered best fit. The impact or ram force in direction of the ship motion on the horizontal axis refers to the absolute values recorded level at the impact.

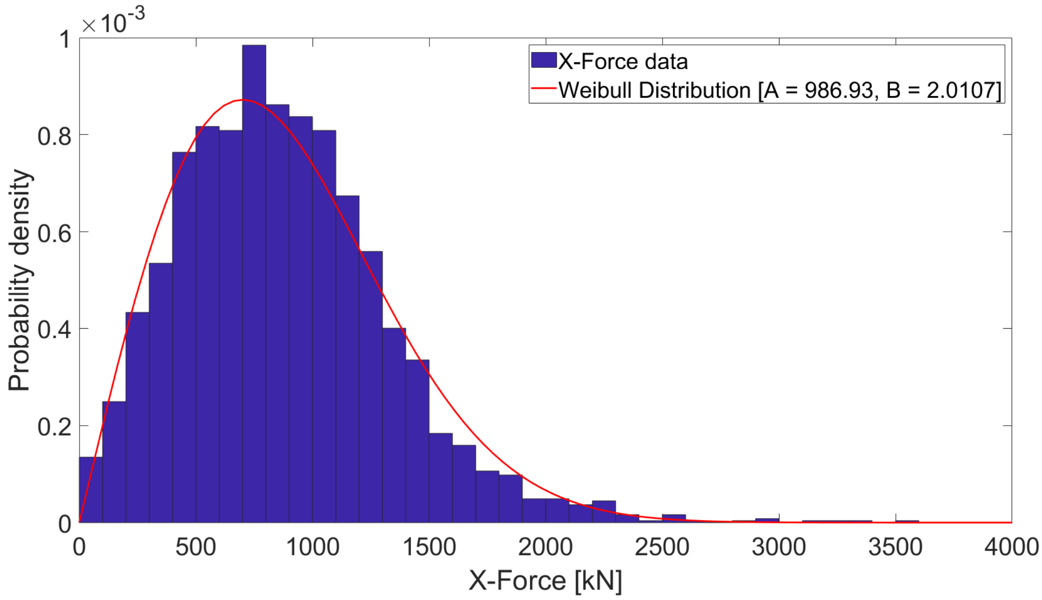

Figure 6: Histogram of 2392 impact or ram events with a fitted Weibull distribution.

CASE STUDY ON LOCAL PRESSURES AND COMPARISON WITH RULES

Jordaan et al. (1993) defined an extreme value distribution based on physical ramming measurements on instrumented panels. The probabilistic distribution is fit to the tail of the distribution of the recorded data. The here applied approach follows Jordaan et al. (1993) using the 1% exceedance, i.e. the "100-yr load", which is an extreme-level ice event for frequent environmental events associated with the Ultimate Limit State, ULS, . which is defined in Eqn. (1) as design pressure value $z_{0.01}$, with the definition of the parameters in Table *2*.

$$z_{0.01} = x_0 + \alpha(4.6 + \ln \nu + \ln r) \quad (1)$$

The parameter α is the pressure area relationship defined in Eqn. (2). These values are based on previous measurements on ships with instrumented plates or design values. These values are considered depending on the time of the year and region, e.g. Barents Sea in the Arctic summer (Tõns et al., 2015). C and D are these pressure area curve defining parameters, whereas a is the area under consideration. These values are selected based on measurements in the summer in the Beaufort Sea 1982 (Jordaan et al., 2007; Tõns et al., 2015), Table *2*. The data available for parameters C and D is limited and as the operating conditions are in decayed summer ice (Table *1*) the conditions selected are best fit.

$$\alpha = Ca^D \quad (2)$$

The number of impacts per voyage is 2392 according to Figure *6*. The proportion of impacts, *r*, is often taken as 1 (Tõns et al., 2015) or 0.5 (Jordaan et al., 2007) indicating a full hit of a plate with 1 equal 100 %. However, as the measured accelerations refer to global impacts, these need to be converted to local loads under the following assumptions:

- All impacts occur in the bow area from the width B/4 forward to the stem.

- An average plate width is used (between frames)
- The impacts are distributed equally over the bow panels

Based on the considerations above and the impact affected area (without disclosing structural details) $r = 0.017$ is determined, which is the inverse of the number of plates in the impact zone and it is assumed that in each impact each plate is fully hit..In Jordaan et al. (1993) $r$refers to a full hit of the plate for $r = 1$ and a miss $r = 0$, while a partial hit is anything in between. In the here presented measurements it is unknown if a certain impact hits a plate fully or neighboring plates in parts. Therefore, it is considered that in each impact every panel is affected partly based on the total number of plates in the bow.

The x-forces from the impacts and rams are converted to pressures, by assuming a uniform distribution over a single plate. Based on the Weibull distribution in Figure *6*, the pressure is plotted against the probability of exceedance, p_e, in full analogy to Jordaan et al; Ralph (1993; 2016). In analogy to Jordaan et al. (1993) an extreme value distribution is fitted to the tail of the data according to Eqn. ((3), with the x as the pressure data and the constants a and x_0, whereas x_0 is the pressure value at the intersection with the abscissa that is required in Eqn. (1). Data and the tail fitted extreme value distribution is shown in Figure *8*.

$$pe = \exp\left[-\frac{x - x_0}{a}\right] \tag{3}$$

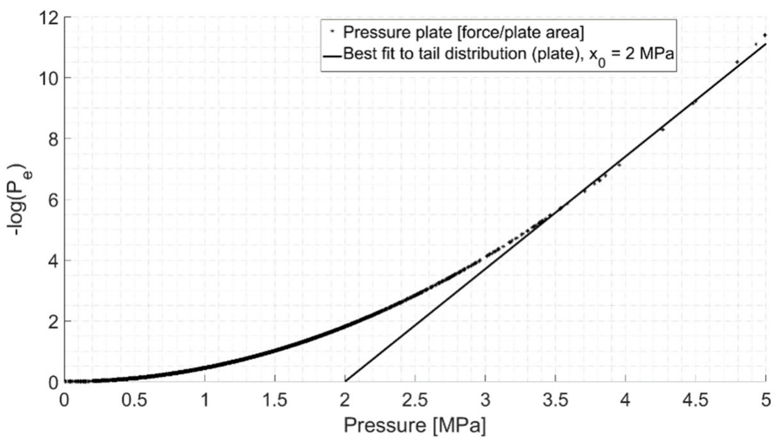

Figure 7: Probability of exceedance for the random pressure data based on the recorded impacts and rams together with a tail fit extreme value distribution.

Usually, the number of impacts per year are taken into consideration (Jordaan et al., 1993; Ralph and Jordaan, 2013; Tõns et al., 2015). The *LCC* operated on the Trans-Arctic voyage 21 days in Arctic summer conditions, which includes several days of open water operations. In the year 2025 the *LCC* operates from 17.04.2025 - 14.10.2025 in the Arctic, which is 187 days in the Arctic. For the annual number of impacts in the Arctic the counted impacts on the Trans-Arctic voyage is linearly scaled by factor 187/21 = 8.9 leading to 21300 annual impacts. Outside the time in the Arctic the *LCC* is transiting to Antarctica and sailing there, however currently no information on rams and operational profiles are available and therefore this is not regarded.

The calculated pressure loads are compared to design pressures of different ice classes according to the Polar Class Unified Requirements (IACS UR I2, 2019) for comparison for the bow area for which three locations are selected between B/4 and the stem. The calculation of design pressures require hull specifics, which cannot be shared and are therefore just stated as values in Figure *8*.

Table 2: Definition of parameters and values for Eqn. (1)

Parameter	Symbol	Value for *LCC*
Constant	C	0.53
Constant	D	-0.77
Number of impacts / unit time	ν	2392 / voyage
Proportion of impacts / fractural load on the plate. Values 0 to 1.	r	0.017
Threshold pressure [MPa]	x_0	2

The comparison of the methods for the probabilistic extremes loads and the polar ice load (IACS UR I2, 2019; Jordaan et al., 1993) is found in Figure 8. It indicates that the design load for ice class PC2 lies above the probabilistic 100-year extreme load / pressure for a single Trans-Arctic voyage, but below the corresponding pressure for an entire Arctic season. In the probabilistic approach the plate area can freely be varied, whereas in IACS UR I2, 2019 the plate area is dependent on pressure and location and consequently delivers discrete values.

The obtained extreme loads indicate that both the curves for the Trans-Arctic voyage as well as the Arctic season would exceed the design values for PC2, but stay below PC1. Based on limitations in the data and assumptions made the determined pressure area curves are considered as lower bound values and might be actually lie at even higher pressures.

DISCUSSION

Acceleration measurements aboard *LCC* are used determining the number of ice impacts onto the bow section from which a probabilistic 100-year extreme load is derived. Compared to other existing vessels *LCC* operates a significant number of days in the Arctic and is exposed to a significantly higher number of impacts than most existing vessels.

Based on the conducted measurements this paper presents a number of global impacts for a continuous icebreaking operation in the Arctic, which includes the interactions with all relevant ice features such as ridges and floes. An estimation of the number of impacts is generally not available and has to be estimated without reasonable basis or must be approach parametrically (Tõns et al., 2015). This study also indicates that the number of impacts is not associated to the number of icebreaking cycles, which are considered to be in the order of magnitude of the load variations (Figure *3*) of which the number of impacts is less than 1%.

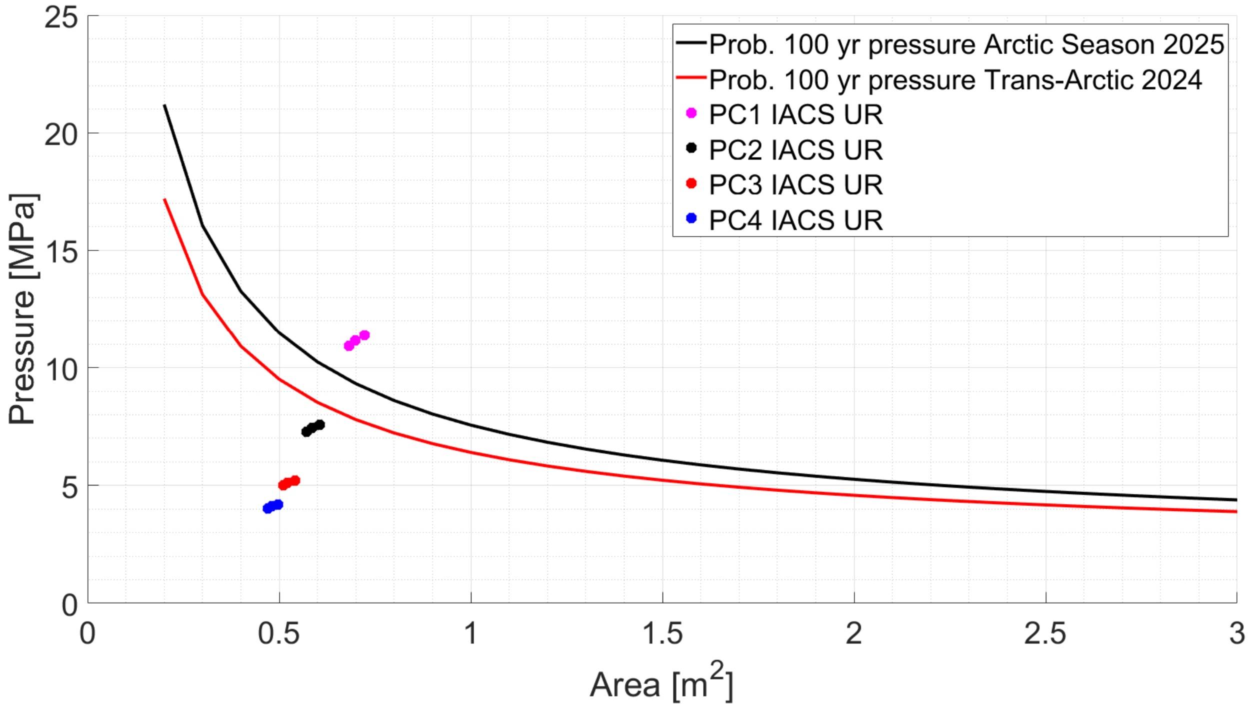

Figure 8: Pressure-area relationships comparing the probabilistic approach (Jordaan et al., 1993) with the design pressure values at the bow for different positions for Polar ice classes PC1 – PC4.

The sampling rate of the SIMS (ice thickness) is 1 Hz, while the accelerations are measured with 100 Hz. Both systems are synchronized by the GPS time. The variability of the load or acceleration is much higher than of the ice thickness due to its physical occurrence (Figure *9*). In the analysis of the ram or impact definition (Figure *4*) the ice thickness is linearly interpolated for alignment with the acceleration measurements. The sole display of measurement points in Figure *9* indicates loading events lasting several seconds so that the sampling rate of the ice thickness is considered to be a minor source of uncertainty.

The application of the probabilistic 100yr ice pressure includes some uncertainties as complementary data for analysis refer to data sets and methods derived from other ships and voyages. Limitations concern the following items: The applied pressure area relationship curve (Table *2*, Eqn. (2)) is based on experimental data from the summer season 1982. This is done due to a lack of more recent data. Due to the scarcity of data sets neither their scatter and uncertainty is known nor how well data from 40 years ago are applicable to current conditions under the aspect of climate change. Nevertheless, the ice property data (Table *1*) clearly indicate Arctic summer conditions. With respect to the annual Arctic operations ice property measurements from the beginning of April are needed in order to assess whether the conditions are relatable to summer conditions or rather winter conditions. With respect to the exposure of plates to impacts, a normal distribution over the bow is assumed, whereas it is unknown if the stem and areas close to it are proportionally exposed to more impacts than areas towards the shoulders. This can lead to an overestimation or underestimation of loads in certain areas. The selection of the threshold value, x_0, is based on the assumption that recorded loads exert pressure uniformly on a full plate work in analogy to Jordaan et al. (1993). The use of the values C and D are based on data from a very different ship in possibly similar conditions, which is however also limited as the only similarity is the same time of the year. This also introduces uncertainty into the outcome from Eqn. (2), but at the same time highlights the strong need for more research in this field.

The results displayed in Figure 8 indicate that the determined 100yr extreme loads exceed the design loads for PC2, despite some assumptions made that are lowering the calculated pressure values providing a lower bound. In this paper an attempt is made to classify impact or ram events counting more than 2000 impacts for the Trans-Arctic voyage, while Ralph (2016) stated that PC 1 refers to around 10 000 rams / year, while PC2 refers to around 1000 rams / year, which would already be exceeded on the Trans-Arctic voyage so that also the count of impacts appears to confirm the results in Figure 8.

One remaining question is whether the occurrence of impacts can be associated to certain ice features or conditions. A first attempt for an automatic detection of ridges (not presented here) turned out to be inconclusive and therefore one ice trial with constant power is analyzed with support of video footage. Figure *9* shows the identified impacts associated to ridges and ice floes as well as some impacts that cannot be associated to either of them. Nevertheless, this indicates that ridges, respectively deformed ice, might play a significant role in the loading of the structure. An automated feature detection of ridges and a more in depth analysis of the relationship between ridge occurrences and loads might be helpful with respect to future assessments and impact predictions as e.g. Krumpen et al. (2025) showed that in the progress of changing climate the number of ridges is reducing.

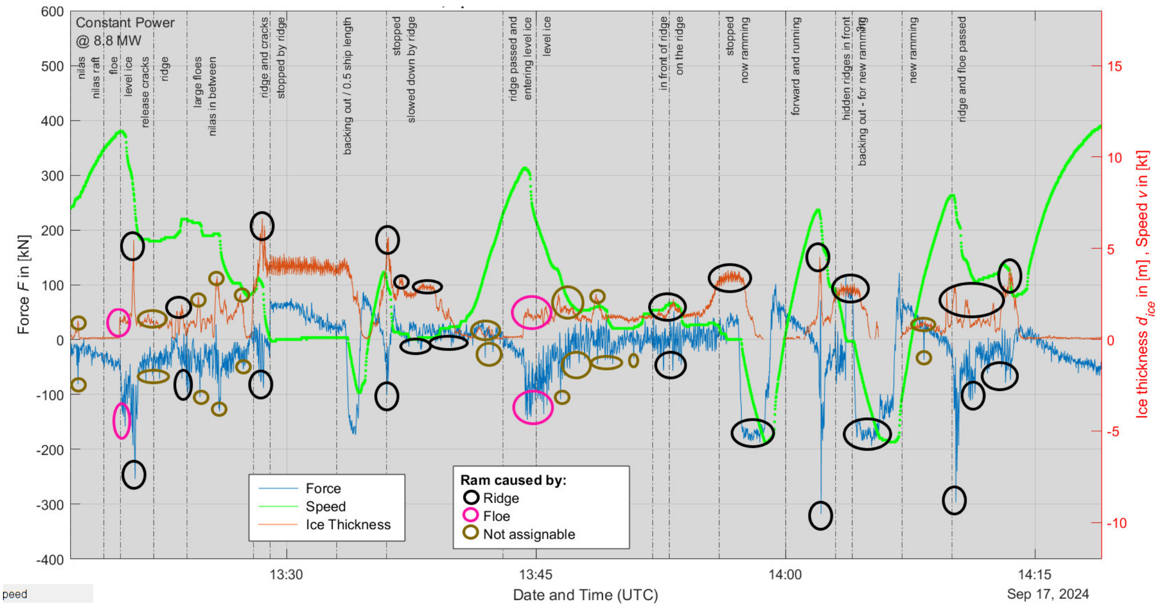

Figure 9: Detection of load peaks associated to ridges, ice floes and un-classified information

CONCLUSION

This paper presents acceleration measurements aboard the *LCC* during a Trans-Arctic voyage, which are used for the assessment of a probabilistic extreme load analysis. Despite of uncertainty in some of the data used and the assumptions made all are consistent towards obtaining a lower bound for values. Despite these assumptions the obtained pressure-area relationships indicate that for the Ultimate Limit State (ISO 19906:2019, 2019), the 100 yr loading, the design load of polar class PC2 is exceeded, due to the unique operational profile of *LCC* with much time in ice. In order to arrive at a conclusive statement whether this is a reasonable assessment or an over prediction of loading requires significantly more research in this field.

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