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Analysis of the event-maximum method for the prediction of local pressures on a ship's hull in the Antarctic ice

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ABSTRACT

The hull of a ship operating in ice might be exposed to significant ice loading, originating from a complex and stochastic interaction between the hull and the ice. In order to analyze such ice loading, statistical methods can be used. In this context, the estimation of the local ice pressures on various locations of a ship's hull is required. This study aims to analyze a semi-empirical method known as the event-maximum method, which estimates the maximum local pressures as a function of the contact area and the ice condition. To this end, this study uses the full-scale ice load measurements to determine a new set of curves describing the relationship between the contact area and the local pressures. The obtained curves are subsequently compared with corresponding curves determined in previous studies using different datasets. The results show that the curves obtained in this study are close to those obtained in previous studies. In addition, a sensitivity analysis is carried out to assess the sensitivity of the predicted local ice pressures to variations in the assumed load height. The sensitivity analysis shows that the predicted maximum local pressure is relatively insensitive to variations in the assumed load height. Furthermore, the study indicates that the event-maximum method might be overly conservative and discusses various approaches to overcome this challenge.

KEY WORDS: Ship-ice interaction; Probabilistic methods; Ice-induced loading; Local ice pressure; Event-maximum method.

1 INTRODUCTION

In recent years, the existence of potential natural resources of hydrocarbons and minerals in the Arctic and the possibility of a shorter shipping route through the Arctic seas increase the demand for ice class ships. Ship-ice interaction might cause significant ice loads, which can lead to elastic and plastic deformations on an ice class ship's hull. Thus, for designing safe and efficient Arctic ships to protect the human's life and the environment, the ice loading must be assessed.

The ice loading has a complex and stochastic nature, which is influenced by different variables such as the ice conditions, ice mechanical properties, relative speed between ship and ice, and the ice fracture mechanisms (Kujala & Vuorio, 1985). Thus, the ice loading on a ship's hull can be assessed through the statistical analysis of the full-scale ice load measurements. (Kujala & Vuorio, 1985)

The ice pressure is not uniformly distributed on the ship-ice interaction (nominal contact) area (Daley, et al., 1990). This might occur due to the fracture and flaking process, which result in reducing the nominal contact area and leaving a line-like feature in the area of interaction, where a high ice pressure is acting (Riska, 2010). The total force is transmitted into the hull of the ship through the High Pressure Zones (HPZs) existing in the local contact area, i.e., plates between the frames as shown in Figure 1 (Ralph, 2016). The local pressures on small contact areas can be significantly large and cause localized damages on the ship's hull. Thus, assessing the maximum local pressure with a low probability of exceedance is crucial for ship's hull structural design. For that purpose, Jordaan et al. (1993) develop the semi-empirical method known as the event-maximum method. However, few studies have been done for the evaluation of the proposed method. The availability of full-scale measurements form S.A. Agulhas II during the winters 2013-2014 in Antarctica enables further examine the method.

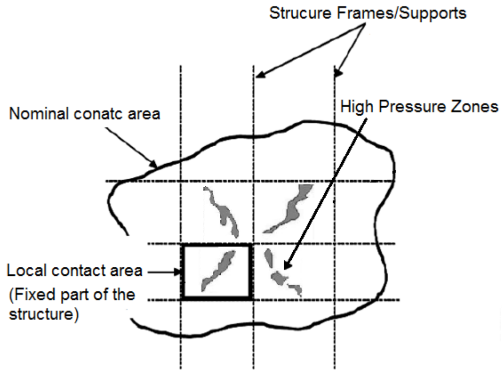

Figure 1. Representation of local contact area. (Ralph, 2016)

2 METHODS

This section will describe the methods that are used for estimating the maximum local pressures.

2.1 Identification of the ice load events

The time history of the ice loads on the ship's hull can be measured through the full-scale measurements. Then, ice load events (load amplitudes) can be specified from the ice load time history if the associated noises, i.e., open water wave loads are excluded from the data. For that purpose, the time-window method can be used. In this method, the time series as shown in Figure 2 are divided into the time windows of the same duration, i.e., 10 minutes, 30 minutes, or 1 hour. Thereafter, the maximum values of the time windows define the maximum load amplitudes of a certain period, i.e., ten-minute maximum ice loads.

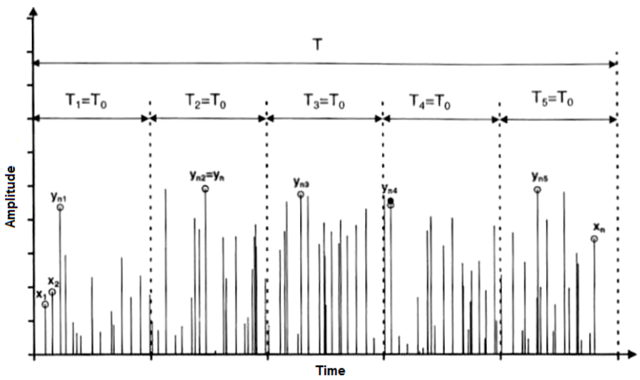

Figure 2. Determination of the ice load measured maxima (Hänninen, et al., 2001)

2.2 Ice pressure data

For assessing the maximum local pressure on a ship's hull, the ice pressure data are required. This study aims to define the ice pressure data from the full-scale ice load measurements. For that purpose, the maximum ice load is assumed to be connected with the maximum ice thickness for a certain period. In accordance with Finnish-Swedish Ice Class Rules (FSICR) for 1A super ice class, the load height (H) is assumed as 30% of the maximum ice thickness, corresponding to each ten-minute maximum ice load. The ten-minute maximum ice thicknesses are defined from the full-scale measurements. Furthermore, the load length (L) is considered as ship frame spacing at the location of interest. Thus, the contact areas (A) and the local ice pressures(P_l) are defined from Equation (1) and Equation (2) respectively.

$$A = L * H \tag{1}$$

$$P_l = \frac{F_{max}}{A} \tag{2}$$

where F_{max} is the maximum of the total force on the frame(s) of interest within specific period , i.e., ten-minute maximum ice load on two frames at the bow.

2.3 Event-maximum method

For assessing the maximum local ice pressure during a certain period, the event-maximum method is developed based on the extreme statistics by Jordaan et al (1993). The method implies that the local pressure on a specific contact area can be obtained from the fitting a linear line into the tail of the sorted pressures, which are plotted versus the natural logarithm of the probability of exceedance (P_e) (Jordaan, et al., 2005b). The fitted line is assumed to follow an exponential distribution as given in the Equation (3) (Jordaan, et al., 2005b).

$$F_X(x) = 1 - \exp\left(-\frac{x - x_0}{\alpha}\right) \tag{3}$$

where parameters of x_0 and α are constant values for the specific area. The parameter x is a random event that defines the pressure (Jordaan, et al., 2005b). As shown in Figure 3, parameter α is the inverse slope of the best fitting line and parameter x_0 is the intercept of the line with the abscissa (x axis) (Jordaan, et al., 2005b).

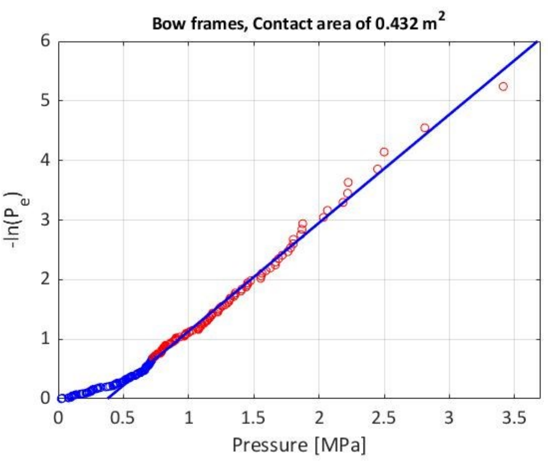

Figure 3. Representation of best fitting line to ten-minute maximum ice pressures at the tail (red dots) for two frames at the bow of S.A. Agulhas II, Antarctica 2013-2014

The maximum pressure, Z, that occurs at particular area of the hull for a specific period is defined as

$$Z = \max(X_1, X_2, \dots, X_N) \tag{4}$$

where X_i is the random quantity represents pressure and N is the total number of impacts (Jordaan, et al., 1993). Applying the extreme statistics to the Equation (3), defines the cumulative distribution function of the maximum local ice pressure for a particular area as

$$F_Z(z) = \exp\left\{-\exp\left(-\frac{(z - x_0 - x_1)}{\alpha}\right)\right\} \tag{5}$$

where, the parameter $x_1 = \alpha(ln\mu)$ and the parameter x_0 is a function of the area corresponding to the ice condition scenario (Taylor, et al., 2010). Jordaan et al. (1993) proposes that the parameter α is a function of area and can be represented by Equation (6), and parameter μ denotes the exposure (see section 2.4).

$$\alpha = Ca^D \tag{6}$$

The parameter a is the local contact area (see Figure 1) and parameters C and D are constant coefficients, which are connected with the ice type and ice condition (Jordaan, et al., 1993). Considering the α, x_0, and the exposure (μ), the maximum local pressure (z_e) corresponding to a specific probability of exceedance, i.e., 10^{-2} can be determined as given in the Equation (7) (Taylor, et al., 2010).

$$z_e = x_0 + \alpha\,\{-\ln[-\ln\ F_Z(z_e)] + \ln\mu\} \tag{7}$$

2.4 Exposure

For the evaluation of the maximum local pressure the ice exposure is required. The exposure for a certain period can be defined from the expected number of interactions (v) on a particular area of the hull based on the full-scale measurements using Equation (8). The proportion of the expected number of interactions on the exposed panel (r) also must be taken into account for design if the full-scale measurement is done on an instrumented panel contains several sub-panels (see Taylor et al. 2010). As in this study the full-scale measurement is done on instrumented frames instead of the sub-panels, the exposure is equal to the expected number of interactions ($r = 1$). The expected number of interaction for a certain period, usually one year for design, can be defined using Equation (9).

$$\mu = v * r \tag{8}$$

$$v = f * D_t \tag{9}$$

where, f is the impact frequency, i.e., per nautical mile (NM), and D_t is the total distance that ship operates in ice for a certain period. The frequency of the impacts can be defined based on full-scale measurements and the total distance can be either determined from ship ice trial data or simulation (Bergström, et al., 2016). In this study the frequency of the impacts and the total distance are defined based on full-scale ice load measurements.

3 Measurements

3.1 Full-scale ice load measurements

To obtain additional full-scale ice load measurements, a full-scale ice experiment was conducted on board of S.A. Agulhas II in the Antarctica. The voyage was started on 28th of the November 2013 and finished on 12th of the February 2014. During the ice trial, Kujala et al. (2014) carried out extensive measurements for different ice conditions. The measurements comprise the measurement of the ice loads on different areas of the hull of the ship, the visual observation of the ice condition, and the measurement of ice thickness. The ice thickness data used for this study were defined based on visual observations. Figure 4 represents the route that ship was operating during the voyage.

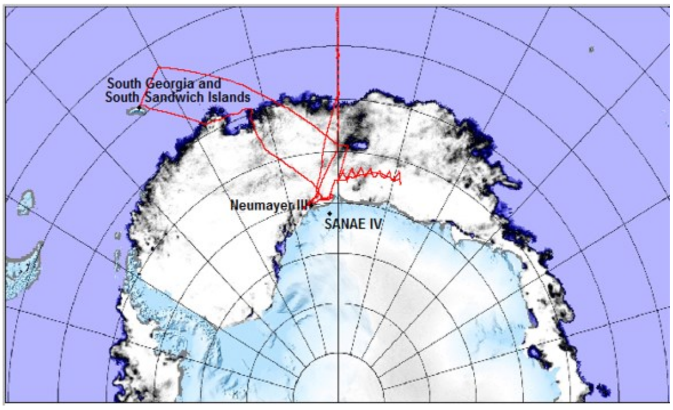

Figure 4. The voyage route (Kotilainen, et al., 2018)

3.2 Ship main dimensions and instrumentation set-up

S.A. Agulhas II was built by STX Finland in the Rauma shipyard in April 2012. The ship has Polar ice class PC 5 and propulsion power of 9 MW. The strength of the hull of ship is in accordance with DNV ICE-10. The main dimensions and parameters of the ship are listed in Table 1. (Kujala, et al., 2014)

Table 1. The main dimensions and parameters of the S.A. Agulhas II

Length, overall [m]	135.0
Length, between perpendiculars [m]	121.8
Breadth [m]	21.7
Draught, design [m]	7.65
Deadweight at design draught [t]	5,000
Service speed [kn]	14.0

For measuring the ice load the ship's hull was instrumented with the strain gauges on two frames at the bow (#134+400, and #134), three frames at the bow shoulder (#113, #112 1/2, and #112), and four frames at the stern shoulder (#41, #40 1/2, #40, and #39 1/2). Furthermore, ten strain gauges were installed on the hull plating for strain measurements. Figure 5 represents the setup of the strain gauges on the hull of S.A. Agulhas II.

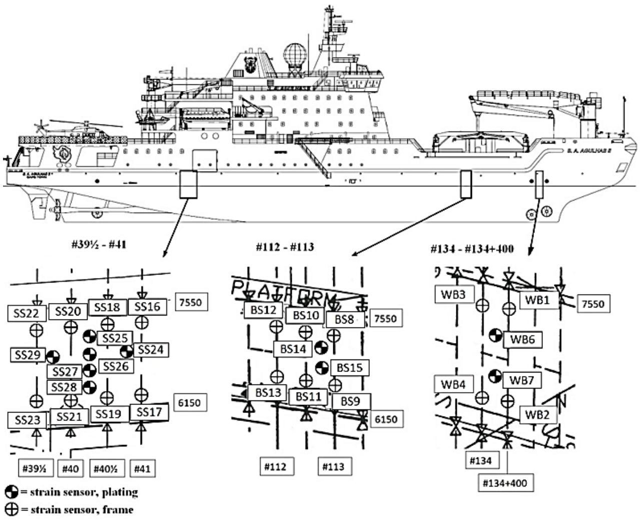

Figure 5. Representation of the setup of the strain gauges on the hull of the S.A. Agulhas II

4 Results and analysis

The following sections present some of the study results at different locations of the hull for single frames and the combination of two and three adjacent frames.

4.1 Ice load events

The ten-minute maximum ice loads on the frames of interest at different locations of hull are defined from the aforementioned full-scale measurements as represented in Figure 6. In addition, the threshold of 10 kN is applied for filtering the noises and effects of open water.

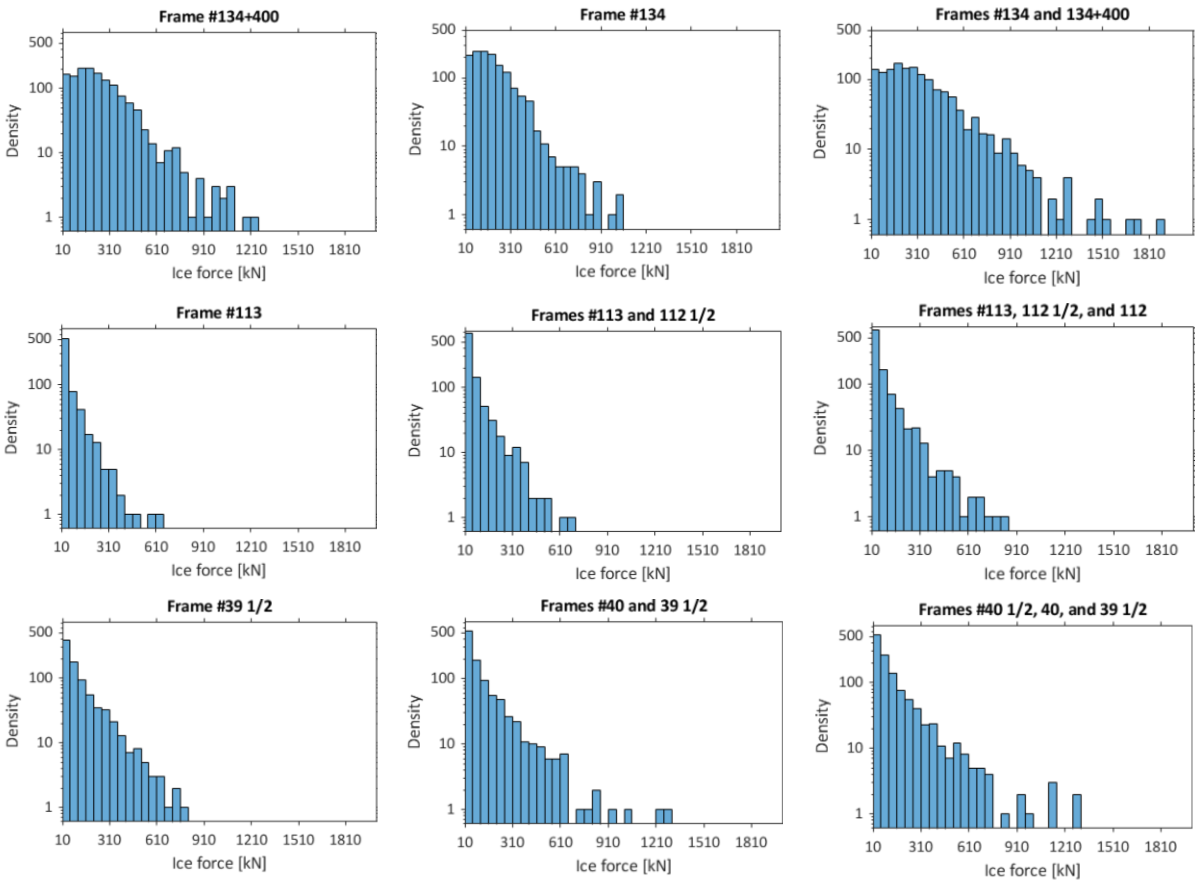

Figure 6. Ten-minute maximum ice loads on different locations of the hull

4.2 Determination of the ice thickness

The maximum ice thickness corresponding to ten-minute maximum ice load at different locations of the hull are determined based on ten-minute intervals visual observations. The ice thicknesses average of 2 meter and the standard deviation of 0.73 meter are obtained from the maximum ice thicknesses of ten-minute periods. Figure 7 represents the distribution of maximum ice thicknesses, which is obtained from the ten-minute period visual observations.

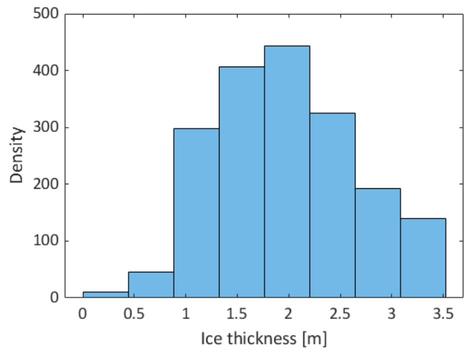

Figure 7. Histogram of maximum ice thicknesses of ten-minute periods

4.3 Determination of ice pressure data

The ten-minute maximum ice pressures on different locations of the hull are defined based on ten-minute maximum ice loads (Figure 6) and corresponding maximum ice thicknesses of ten-minute period (Figure 7) as explained in section 2.2. Figure 8 represents the ten-minute maximum ice pressures on different location of the hull.

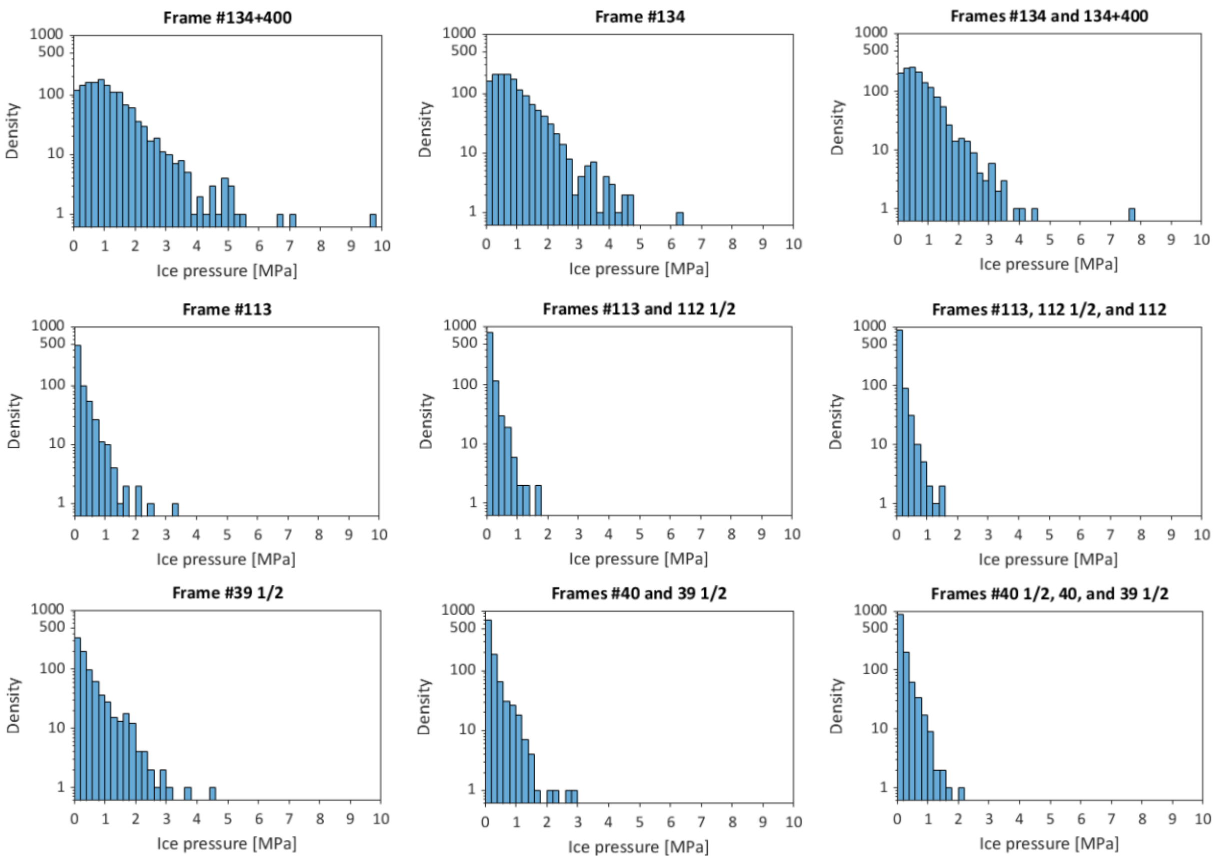

Figure 8. Ten-minute maximum ice pressures on different locations of the hull

4.4 Identification of α and x_0

For the evaluation of the maximum local pressures, the event-maximum method is applied to the ten-minute maximum ice pressures on different locations of hull. The parameters of α and x_0 are defined from the best-fitted lines to the peak pressures as illustrated in Figure 3. The peak pressures are determined as the ice pressures greater than the median. Furthermore, the parameters α and x_0 are plotted versus the contact area as shown in Figure 9 and Figure 10 respectively.

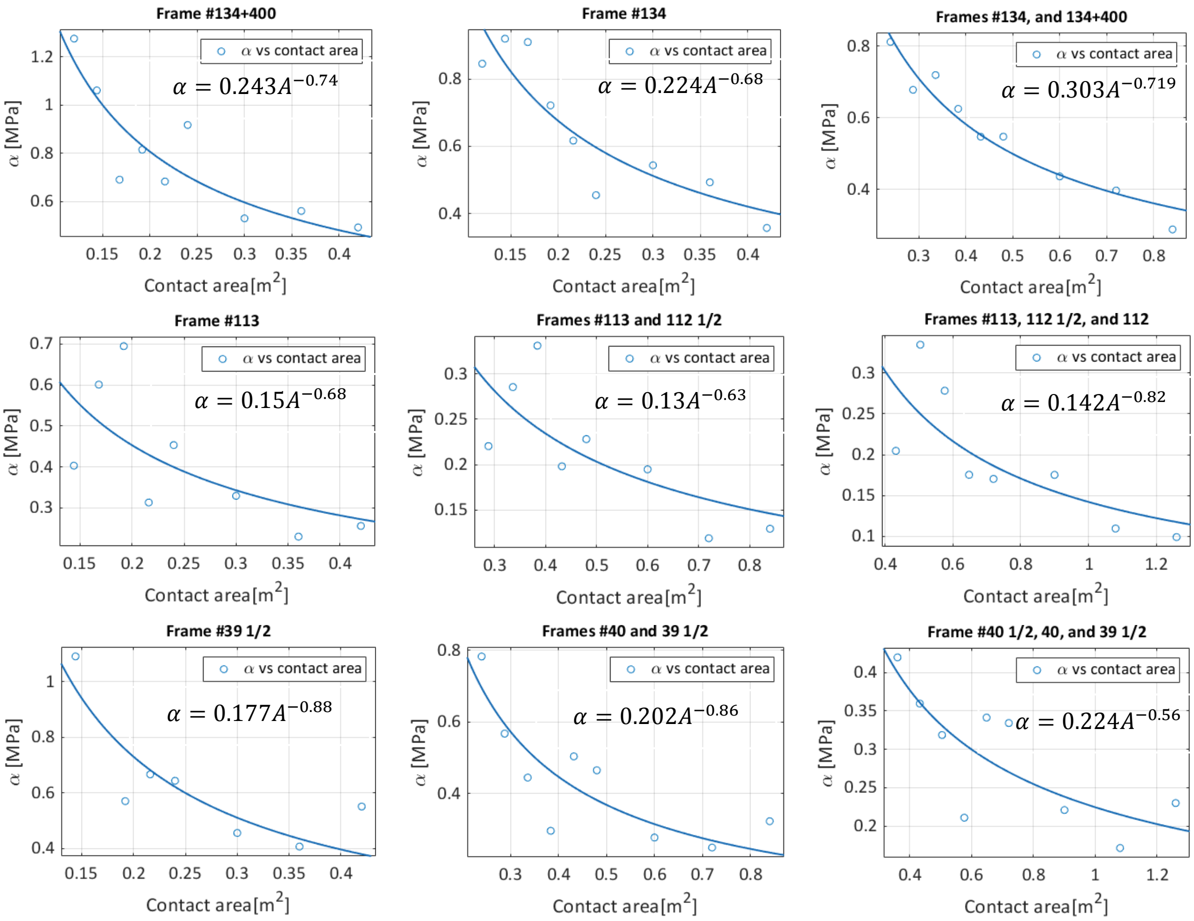

Figure 9. Representation of the α vs contact area at different locations of hull

The obtained α-area curves at different locations of hull are compared with the Jordaan et al. (1993) and ISO (2010) design curves. In addition, the obtained curves are compared with ones presented by Taylor et al. (2010) from the full-scale ice pressure measurements. Figure 11 represents the results of these comparisons.

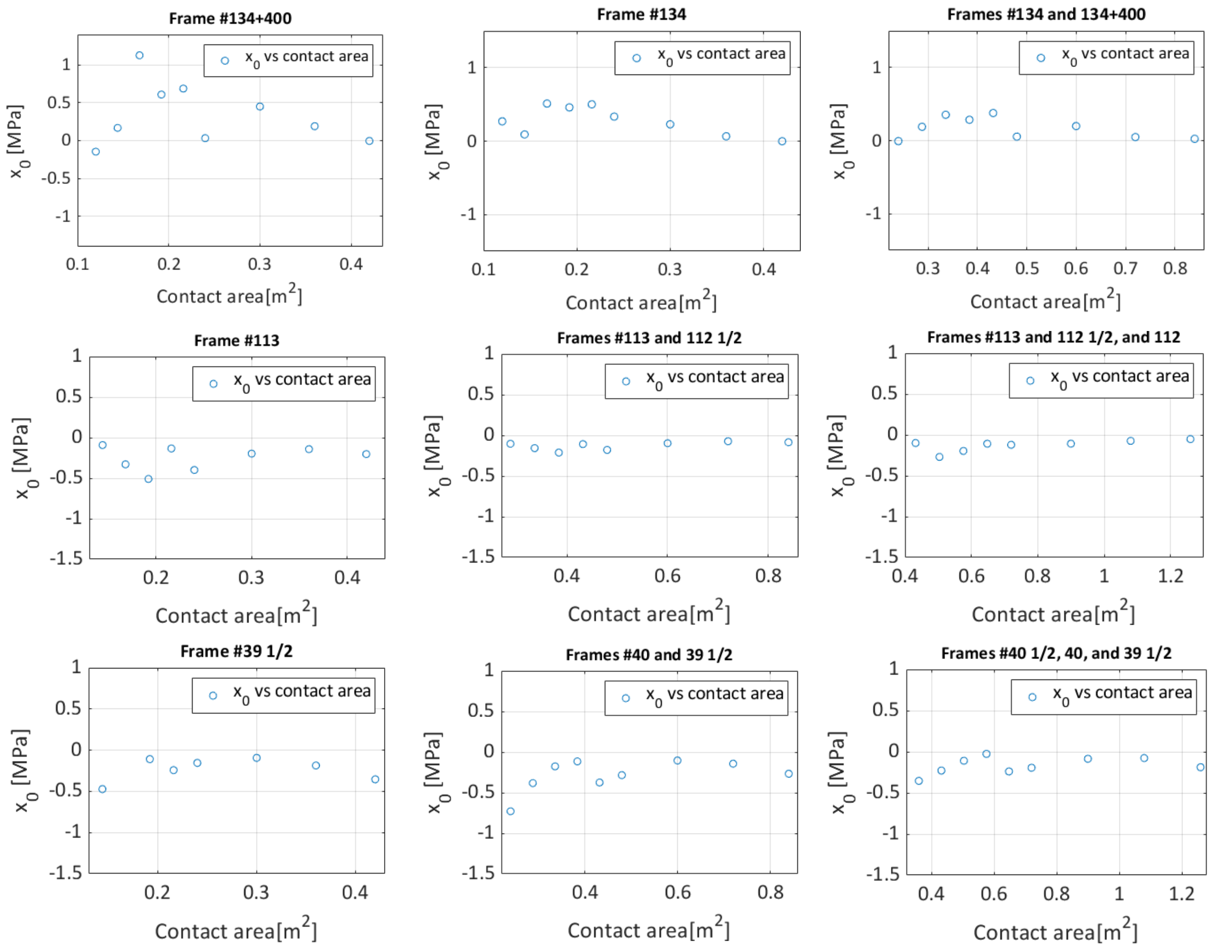

Figure 10. Representation of x_0 at different locations of hull

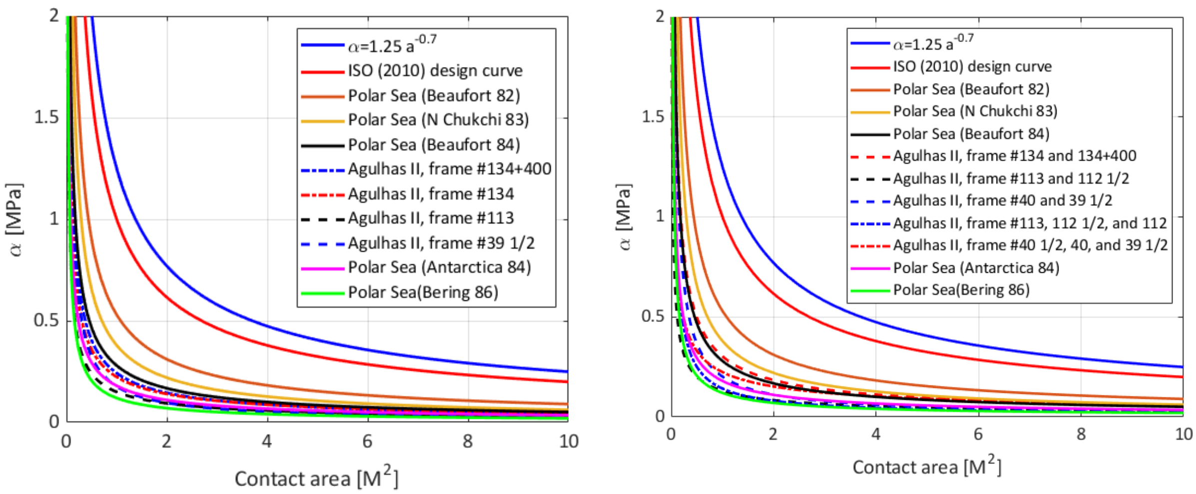

Figure 11. Comparison of the obtained α-area curves with the previous studies

4.5 Determination of exposure

The exposure at different locations of hull are defined directly from the ten-minute maximum ice loads. The total number of ten-minute maximum ice loads at the bow, bow shoulder, and the stern shoulder are defined as 1448, 675, and 878 respectively. However, the exposure can also be determined as explained in section 2.4. Similarly, the total distance that the ship was operating in ice is defined from the full-scale measurements as 1488 NM.

4.6 Evaluation of the maximum local pressures

The maximum local pressures on the contact area of 0.48 (m^2) for the combination of two frames at different locations of the hull are estimated using Equation (7). The results which correspond to certain probabilities of exceedance (P_e) for duration of one year are presented in Table 2. The obtained maximum local pressures are compared with ones resulted from using the α-area curve proposed by Jordaan et al. (1993) and the ice exposure according to Polar Class Rules. In accordance with the ice class PC5, the ice exposure is considered as one exposure to Multi-Year Ice (MYI) per year.

Table 2. Maximum local pressure at different locations of hull

Hull location	Max. local pressure $(P_e = 10^{-2})$	Max. local pressure $(P_e = 10^{-4})$
Bow	6.16	8.53
Bow shoulder	2.52	3.47
Stern shoulder	4.77	6.52
Bow, bow shoulder and stern shoulder[1]	9.61	19.24

4.7 Sensitivity analysis

In current study, a sensitivity analysis is carried out to assess the sensitivity of the estimated local ice pressures to variations in the assumed load height. As the bow of ship is more exposed to the ice floes, the sensitivity analysis is only performed for the combination of two frames at the bow and on the contact area of 0.48 m^2. In this respect, the assumed load height is varied from 20% to 50% of maximum ice thickness with the increment of 10%. Furthermore, for assessing the sensitivity of the results to variation of the assumed load height, the coefficient of variation is also evaluated. The coefficient of variation defines as the ratio of the standard deviation to the mean. Table 3 represents the sensitivity analysis results.

Table 3. Effect of variation of assumed load heigth on maximum local pressure

Description	Max. local pressure [MPa] $P_e = 10^{-2}$	Max. local pressure [MPa] $P_e = 10^{-4}$
Load height as 20 % of max. ice thickness	6.91	9.57
Load height as 30 % of max. ice thickness	6.16	8.53
Load height as 40 % of max. ice thickness	5.86	8.05
Load height as 50 % of max. ice thickness	5.41	7.46
Mean	6.08	8.40
Standard deviation	0.63	0.89
Coefficient of variation (%)	10.3	10.6

[1] The design curve proposed by Jordaan et al. (1993) with $t_k = 1$, $t = 1$, and $r = 1$

5 Discussion and conclusion

This study analyzed the event-maximum method, which is a semi-empirical method for estimating the maximum local pressures on a ship's hull. As the measured local ice pressures are not available, the study used the full-scale ice load measurements for calculating the ice pressures. This study results are then compared with the previous studies.

The study outcomes indicate that the event-maximum method is suitable to estimate the maximum local pressures at ship's hull using the full-scale ice load measurements. Moreover, the results of this study indicate that the obtained α-area curves at all the locations of hull are close to the curves presented by Taylor et al. (2010), which were obtained from full-scale measurements. In addition, the coefficient D for the α-area curves at the bow and bow shoulder are in the range recommended by Jordaan et al. (1993). Furthermore, the study results agreed with the results of the previous study presented by Taylor et al. (2010), which show that the x_0 values at all the locations of the hull tends to zero as the contact area increases.

The study indicates that the use of design curve presented by Jordaan et al. (1993) results in conservative maximum local pressures estimation. One possibility for this overestimation is the safety margins that are taken into account for the design curves. Furthermore, this might occur as this design curve is defined from considerably heavier ice condition compared to this study. Thus, using the appropriate design curve, which is derived from the ice condition similar to the one that is intended to be used for design, is recommended.

The results of sensitivity analysis indicate that the variation of the load height has relatively small effect on α-area curves and estimated local pressures at the bow. In addition, variation of the load height only causes small changes in coefficient C while coefficient D remains constant. The result of sensitivity analysis and the similarity between the obtained α-area curves and the curves presented by Taylor et al. (2010) indicates that the assumption made in this study for defining the load height can be a valid approach.

The study results indicate that the exposure is connected with the location of ship-ice interaction. This means that a conservative design can obtain if the exposure value at bow is used for the evaluation of maximum local pressures at the bow shoulder and stern shoulder. Thus, for designing a safe and efficient ice class ship's hull structure, defining various ice exposures for different locations of hull is recommended.

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