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THE MEASURED LINE LOAD AS A FUNCTION OF THE LOAD LENGTH IN THE ANTARCTIC WATERS

Mikko Suominen, Pentti Kujala
Aalto University, School of Engineering, Department of Applied Mechanics, Espoo, FINLAND

ABSTRACT
The sea ice in the Antarctic waters consists of first and multi-year ice. In order to secure the safety at sea, knowledge on the ice-induced loads on the ship hull is required. From the structural point of view, the knowledge on the load length and magnitude is needed. Earlier measurements have shown that the magnitude of the ice-induced line load is decreasing as a function of the loading length. However, only a few full-scale measurement campaigns have been conducted in the Antarctic waters. In order to increase the knowledge on ice-induced loads on the ship hull, PSRV S.A. Agulhas II was instrumented with strain sensors when she was under construction. Two full-scale expeditions were conducted on board S.A. Agulhas II in the Antarctic waters during the austral summers 2012/2013 and 2013/2014. During these campaigns, the ice-induced loading on the ship hull was recorded continuously at three hull areas.

This paper studies the measured maximum line load as a function of the loading length. The results are compared to the earlier studies that have employed the data gathered in the Baltic Sea. The study shows that the Gumbel I asymptotic distribution gives a good representation of the measured 1-hour maxima for the bow and 12-hour maxima for the stern. Furthermore, it is shown that the magnitude of the expected maximum line load is significantly greater in the Antarctic waters in comparison to the Baltic Sea.

INTRODUCTION
From the structural point of view, the amplitude of the loading as a function of the area is of the interest. Thus, knowledge on the ice-induced loads is required for the design of the vessels to be operating in the Southern Ocean. However, only a few full-scale measurements have been conducted in the Southern Ocean. In order to increase the knowledge on ice-induced loading on the ship hull, PSRV S.A. Agulhas II was instrumented for full-scale measurements when she was under construction. PSRV S.A. Agulhas II conducts annual voyages to Antarctica within South African National Antarctic Expedition during the austral summers. The full-scale ice-induced load measurements have been conducted since she was delivered to South Africa 2012.

This paper focuses on the magnitude of the ice-induced line loads as a function of the load length. The study utilizes the 1-hour, and 12-hour measured maximum ice-induced line loads measured during the voyages in 2012/2013 and 2013/2014. The measured maxima are presented as a function of the load length and Gumbel I asymptotic distributions are fitted to the measured maxima. The Gumbel I asymptotic distribution is chosen as it has shown a good fit to the measured maxima in the earlier studies (Kujala, 1994) and the extreme values of the exponential type distributions approach Gumbel I distribution (Gumbel, 1958). After fitting the distributions to the measurements data, the expected maximum line loads with a return period of 1, 10, 100, and 1000 days are presented as a function of the load length. Lastly, the results are compared to the measurements on board IB Sisu and MS Arcturus. The study utilizes the data measured at the bow and stern shoulder area of S.A. Agulhas II. Thus, the data collected from the bow shoulder is left outside the data.

DESCRIPTION OF THE SHIP AND INSTRUMENTATION

The main dimensions of PSRV S.A. Agulhas II are presented in Table 1. She was built into the Polar ice class PC5 and the hull was constructed in accordance with DNV ICE-10. Three areas of the starboard side of the hull were instrumented with strain gauges when she was under construction in 2011/2012. The upper and lower parts of the frame were instrumented with V-shaped strain gauges, which measured the shear strains occurring in the frame. The instrumentation consists of two, three and four adjacent frames at the bow, bow shoulder and stern shoulder respectively, see Figure 1. In addition, the hull plating was instrumented with strain gauges in these areas. See Suominen et al. (2013) for more detailed description of the instrumentation.

Table 1. The main dimensions of the ship.

Length, bpp.	121.8 m
Breath, mould.	21.7 m
Draught, design	7.65 m
Deadweight at design displacement	5000 t
Speed, service	14.0 kn

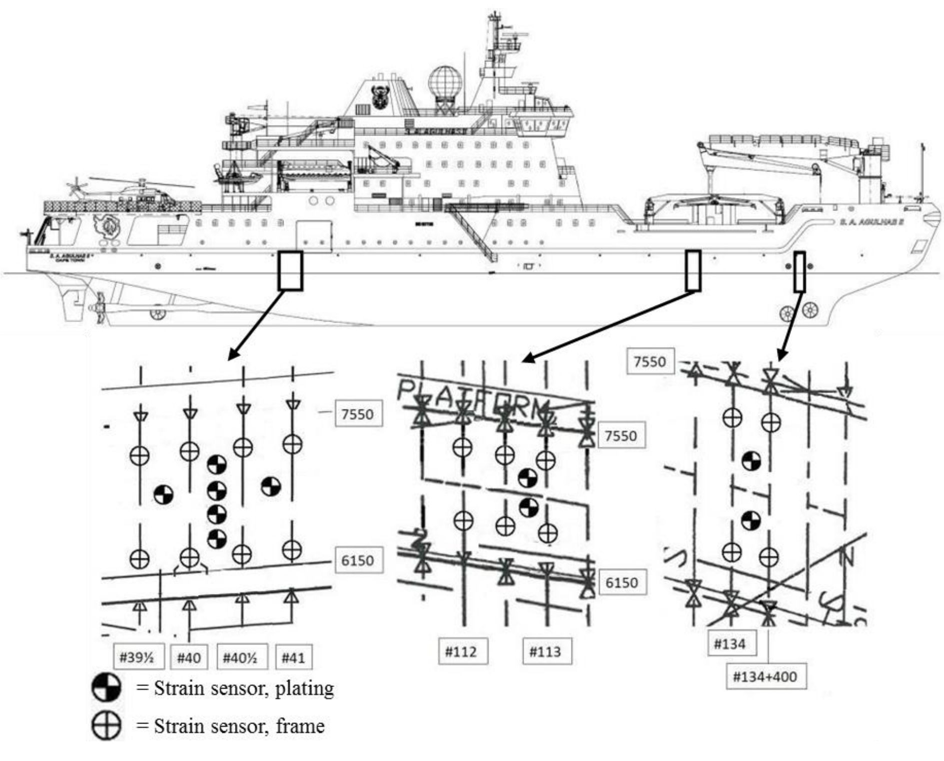

Figure 1. The instrumented areas at the bow, bow shoulder and stern shoulder indicated with black squares (after Suominen et al., 2013).

DATA PROCESSING

The ice-induced loading on a frame is calculated from the measured difference in the shear strains between the upper and lower part of the frame by employing an influence coefficient matrix. The influence coefficient matrix was determined for the bow shoulder and stern shoulder with the calibration pulls, see Suominen et al. (2015) for a detailed description of the calibration pulls and the method. The influence coefficient matrix for the bow area was determined employing the FEM model of the area.

The line loads are determined from the measured loading by dividing the measured loading with the frame spacing, which is 0.4 meters in all instrumented areas. The line load affecting over one frame spacing is determined by dividing the measured loading on one frame with the frame spacing. The line loading affecting over two frame spacing is calculated by adding up the measured loading on two adjacent frames and dividing the sum with the length of two frame spacing. The line loads affecting over three and four frame spacing is determined with the same principle. The line loads for the bow are determined taking into account the measurements on frames #134½ and #134 and the line loads for the stern are determined from the frames #41, #40½, #40 and #39½.

This study considers 1-hour and 12-hour maximum line loads. Thus, the two voyages were divided into one and twelve hour time periods and the maximum line loads over different load lengths were determined for each period for the bow and stern. As the instrumentation at the bow consists of two frames, two load lengths were considered, one and two frame spacing. The instrumentation at the stern consists of four adjacent frames. Thus, four different load lengths were considered, one, two, three and four frame spacing. The measured 1-hour maximum line loads affecting over one frame spacing at the bow and stern during the voyages are presented in Figure 2. The measured 1-hour maximum line loads as a function of the load length are presented in Figure 3. After the measured maxima were defined for each time period, the maxima were organized into histograms with 10 kN/m bin size. The threshold was set to 50 kN/m which corresponds, on average, 20 kN loading on each frame.

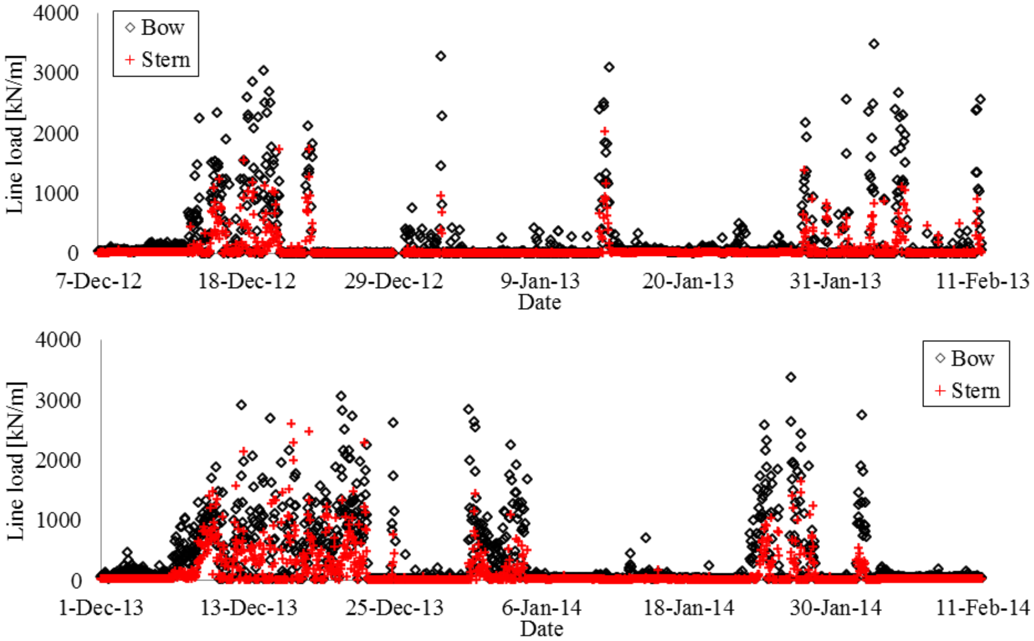

Figure 2. The measured 1-hour maximum line loads for one frame spacing at the bow (black squares) and stern (red crosses).

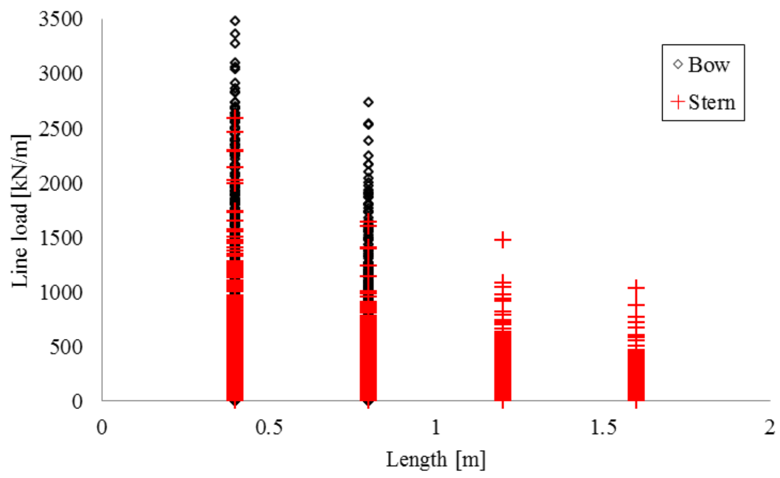

Figure 3. The measured 1-hour maximum line loads at the bow and stern as a function of the load length.

ANALYSING METHODS

The cumulative probability, p_e, of the measured maxima is presented by applying the Weibull plotting position

$$p_e = \frac{m}{N+1} \quad (1)$$

where m is the cumulative number of the maxima in the classes and N is the total number of ice-induced loads. The cumulative distribution function of the Gumbel I probability distribution is given as (Gumbel, 1958)

$$G(x) = e^{-e^{-\beta(x-u)}} \quad (2)$$

where β and u are the parameters of the Gumbel I distribution, which are defined from the measured mean value, μ, and standard deviation, σ, of the sample as follows

$$\beta = \frac{\pi}{\sigma\sqrt{6}}, \qquad u = \mu - \gamma_{E-M}\beta^{-1} \quad (3)$$

γ_{E-M} is the Euler-Mascheroni constant which equals 0.5772. The load range is incomplete due to the threshold. Thus, a truncated cumulative function $G_t(x)$, is derived for the Gumbel I distribution, G(x),

$$G_t(x) = \frac{G(x) - G(x_t)}{1 - G(x_t)}, x_t \leq x \quad (4)$$

where x_t is the chosen threshold. The return period of maximum line loads, T(x), is determined from the cumulative probability, F(x),

$$T(x) = \frac{1}{1 - F(x)} \quad (5)$$

RESULTS

The measured and predicted maximum line loads

The measurement data was processed into 1-hour and 12-hour maxima as described in the data processing chapter. After the data processing, the mean values and standard deviations of the 1- and 12-hour maximum line loads for the bow and stern were determined and the Gumbel I parameters were calculated with Equation (3), see Table 2 and 3. After the parameters were defined, the return period of time of the maximum ice-induced line loads were determined from the measurements utilizing Equations (1) and (5) and with the Gumbel I distribution employing Equations (2), (4), and (5). The results for the bow and stern are presented in Figure 4 and Figure 5, respectively.

Table 2. The measured mean value and standard deviation of the 1- and 12-hour maximum line loads and the determined Gumbel I parameters for the bow.

	Bow, L=0.4 m		Bow, L=0.8 m	
	1 h	12 h	1 h	12 h
Mean value, μ, [kN/m]	588.8	880.6	433.6	644.4
Standard deviation, σ, [kN/m]	640.1	939.9	436.5	661.6
Gumbel I parameter, β, [m/kN]	0.0020	0.0014	0.0029	0.0019
Gumbel I parameter, u, [kN/m]	300.7	457.6	237.2	346.6

Table 3. The measured mean value and standard deviation of the 1- and 12-hour maximum line loads and the determined Gumbel I parameters for the stern.

	Stern, L=0.4 m		Stern, L=0.8 m		Stern, L=1.2 m		Stern, L=1.6 m	
	1 h	12 h	1 h	12 h	1 h	12 h	1 h	12 h
Mean value, μ, [kN/m]	451.5	789.7	298.2	556.3	230.5	417.2	184.1	315.7
Standard deviation, σ, [kN/m]	388.9	596.2	234.4	343.9	172.3	252.0	126.2	180.7
Gumbel I parameter, β, [m/kN]	0.0033	0.0022	0.0055	0.0037	0.0074	0.0051	0.0102	0.0071
Gumbel I parameter, u, [kN/m]	276.4	521.4	192.7	401.5	152.9	303.8	127.3	234.4

Figure 4 shows better correspondence for the bow between the measured and predicted maxima when the 1-hour maximum ice-induced line loads are utilized in the study in comparison to the 12-hour maxima. The highest measured line loads having the load length of 0.4 m are clearly overestimated by the Gumbel I distribution. However, the Gumbel I distribution follows the measured line loads closely in the shorter return periods of time. In addition, with a load length of 0.8 meters the Gumbel I distribution gives a good correspondence to the measured line loads through the whole time range.

A similar comparison with the stern data shows that the Gumbel I distribution underestimates the highest measured line loads when the 1-hour maximum ice-induced line loads are utilized. However, the correspondence between the Gumbel I distributions and the measured maxima is good for all the load lengths when the 12-hour maxima are employed. The only measured line load clearly deviating from the Gumbel I distribution is the highest measured maxima with a load length of 1.2 meters.

As the 1-hour maxima showed better correspondence between the measured maxima and the Gumbel I distribution at the bow, the expected maximum line loads with a return period of 1, 10, 100, and 1000 days for the bow were determined utilizing 1-hour maxima. Respectively, the 12-hour maxima were employed when the expected maximum line loads with a return period of 1, 10, 100, and 1000 days were determined for the stern. The results are presented in Figure 6.

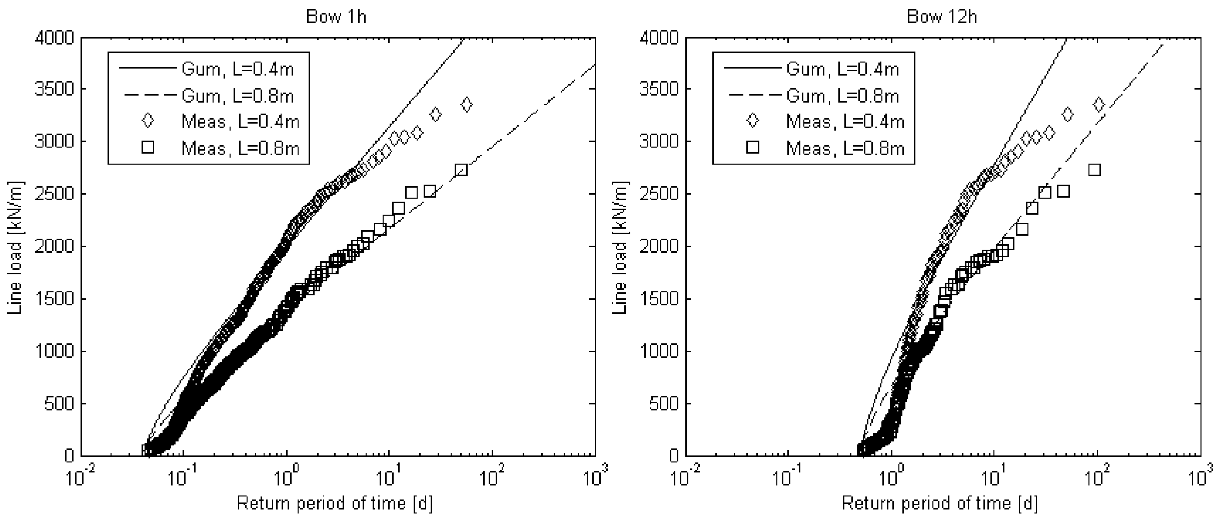

Figure 4. The return period of time of the 1-hour and 12-hour maximum line loads at the bow.

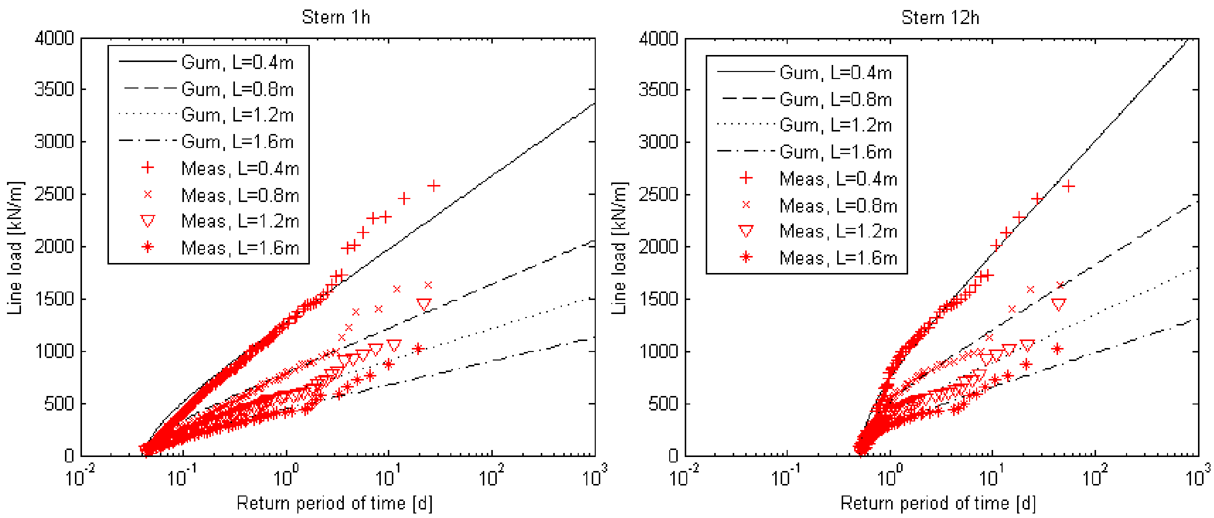

Figure 5. The return period of time of the 1-hour and 12-hour maximum line loads at the stern.

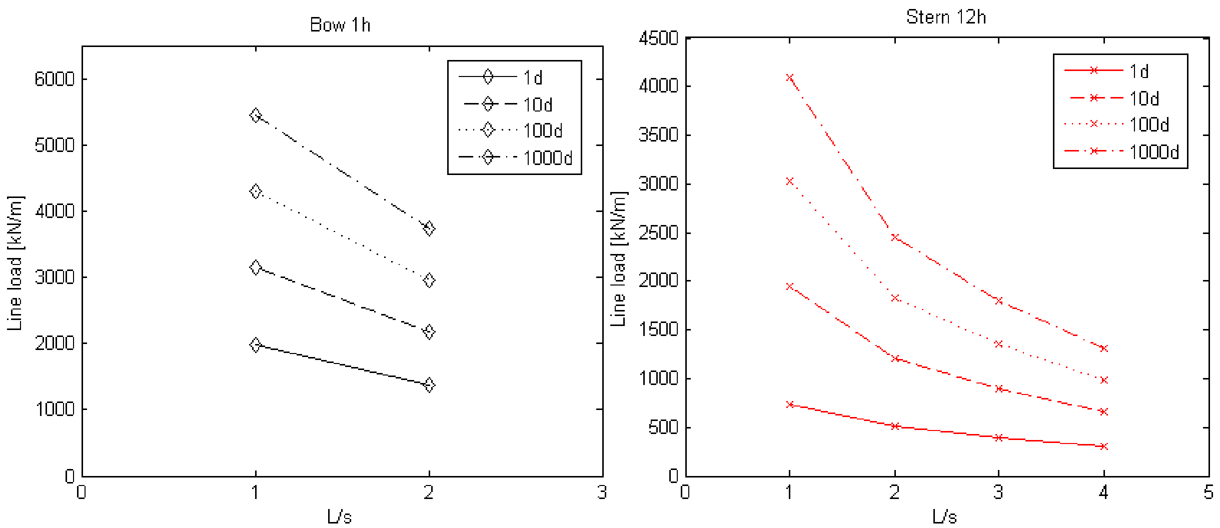

Figure 6. The expected 1, 10, 100, and 1000 days maximum line load as a function of the relation between the load length, L, and frame spacing, s, at the bow and stern.

Comparison to other full-scale measurements

Here, the results obtained in this study are compared to the measurements on board IB Sisu and MS Arcturus, as reported by Kujala and Arughadhoss (2012). The main dimensions of the ships are presented in Table 4. The full-scale measurements on board IB Sisu were performed in the Baltic Sea in the boreal winters from 1978 to 1985 (Kujala and Vuorio, 1986). IB Sisu was instrumented with 31 strain gauges and 4 ice pressure gauges. The instrumentation included five adjacent frames (FFR6 to FFR10), which enables the ice-induced loading to be studied as a function of the load length (Kujala and Arughadhoss, 2012) similar to the study performed in this paper. The measurements on board MS Arcturus were conducted in the Baltic Sea during the boreal winters from 1983 to 1987. The instrumentation on board MS Arcturus consisted of ten frames in total, five frames in two different areas (Sukselainen and Nyman, 1988). Thus, the ice-induced loading as a function of the load length can be studied.

Table 4. The main dimensions of IB Sisu and MS Arcturus.

	IB Sisu	MS Arcturus
Length [m]	106.6 (oa)	155
Breadth [m]	23.8	25
Draught [m]	8.3	8.3
Displacement [t]	9660	12 000
Speed, ow [kn]	19	17

Kujala and Vuorio (1986) fitted Gumbel I distribution to the measured long-term and short-term measurement data on board IB Sisu and estimated the return period of maximum ice-induced loads. Following the same principle, Sukselainen and Nyman (1988) fitted an extreme value distribution to the measured 12-hour maximum ice-induced loads measured during the winters from 1985 to 1987 in the Gulf of Finland and estimated the return period of maximum ice-induced loads. The results for the return period of 10 days taken from these two studies are presented in Table 5.

Table 5. The extrapolated load values with return period of 10 days in full scale for IB Sisu (Kujala and Vuorio, 1986) and for MS Arcturus (Sukselainen and Nyman, 1988), reproduced from Kujala and Arughadhoss (2012).

Number of frames	Line load [kN/m]	
	IB Sisu	MS Arcturus
1	1291	836
2	965	612
3	814	510
4	721	448
5	657	405

Kujala and Arughadhoss (2012) studied the magnitude of the line load, q, as a function of the load length by fitting a curve to the measurement data which was of the form

$$q = C\left(\frac{l_C}{s}\right)^{-a} \quad (6)$$

where s is the frame spacing, l_C is the load length and C and a are unknown parameters. The unknown parameters were determined with the non-linear least square method by fitting the curve to the measurement data presented in Table 5. Following this method, the parameter C is 1291 kN/m, s is 0.434 m and a (the exponent) is 0.42 for IB Sisu and 836 kN/m, 0.35, and 0.45 for MS Arcturus, respectively (Kujala and Arughadhoss, 2012). Applying the same method to the S.A. Agulhas II data with s equals 0.4 meter, the C parameter obtains a value of 1989 kN/m and a (the exponent) is 0.733 for the stern and for the bow C and a obtain values of 3150 kN/m and 0.538, respectively. It should be noted that the bow data recorded on board S.A. Agulhas II contain only two data points. Figure 7 presents the curves fitted on the Sisu, Arcturus and S.A. Agulhas II data.

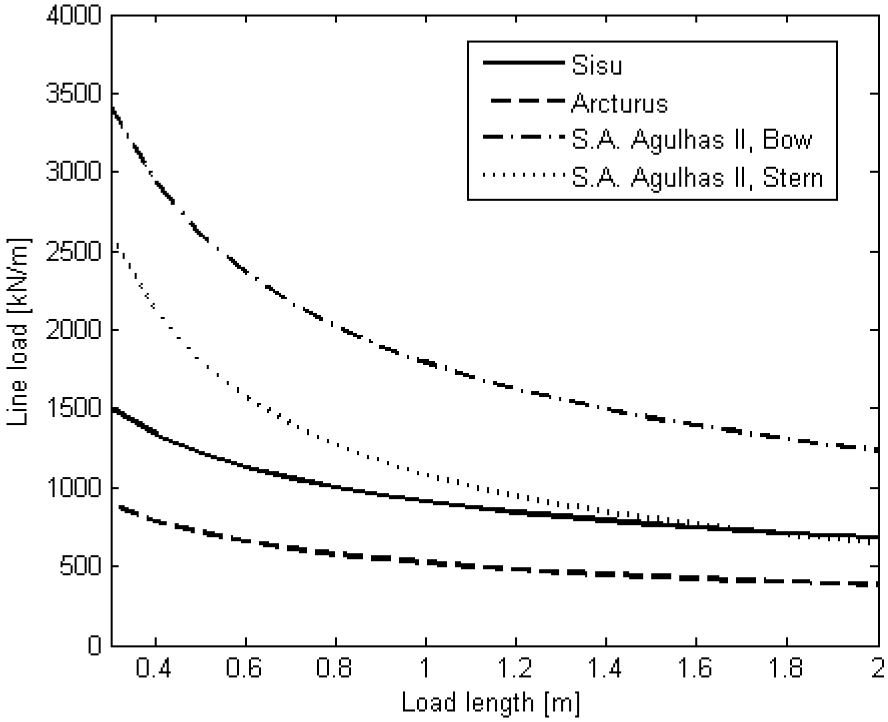

Figure 7. The comparison of the line loads determined from the full scale measurements on board IB Sisu, MS Arcturus and PSRV S.A. Agulhas II as a function of the load length. The presented line loads are the expected maximum line loads with the return period of 10 days.

The magnitude of the 10 days expected maximum line load determined from the S.A. Agulhas II bow measurements is significantly higher in comparison to the corresponding line loads on Sisu and Arcturus, see Figure 7. In addition, the magnitude is significantly higher in comparison to Sisu and Arcturus when the 10 days expected maximum line load is determined from the S.A. Agulhas II stern data for the length of the loading smaller than 1 meter, see Figure 7. The difference between Sisu and S.A. Agulhas II stern diminishes as a function of the load length and is equal with a load length of 1.7 meters. This indicates that greater ice-induced line loads occur in Antarctic waters in comparison to the operations in the Baltic Sea, which is expected due to much thicker ice and multi-year ice inclusions.

DISCUSSION

As can be noted from the return period of time study, the results differ whether 1- or 12-hour maxima are employed when the return period of time is determined. This is considered to be due to the amount of ice encountered and the number of minor ice-induced loads. When 12-hour maxima are employed, the number of smaller loads is reduced as only the highest load from the period is accounted. The longer time period increases the probability of the higher ice-induced loads, thus, decreasing the number of smaller ice-induced loads.

In addition, the 12-hour maxima account more open water in the measurements in comparison to the 1-hour maxima if the operational time in ice is determined based on the loading exceeding a certain threshold (as was done in this study). In this study, it was considered that the ship was operating in ice conditions if a load level of 50 kN/m was exceeded during the observation period. This affects, especially, to the determined return period of the highest measured line load. As an example, when the measured return period for a load length of 0.4 m at the bow is determined from 1-hour maxima, the return period of the measured 3360 kN/m line load is 56 days, whereas it is 103 days when the return period is determined based on 12-hour maxima. Therefore, the employed time period affects the results significantly and should be noted when lifetime maximum line loads are studied.

The study showed that the Gumbel I distribution gives a good correspondence to the 1-hour maxima for the bow and 12-hour maxima for the stern. With a load length of 0.4 m for the bow, a difference between the measured and the Gumbel I distribution occurs when the return period of time exceeds 10 day. The difference increases if 12-hour maxima are employed. The difference between the measured maxima and the Gumbel I distribution for a load length of 0.4 m can be reduced if maxima of a shorter time period are employed (such as 15-minutes maxima), but then the difference between the measured and Gumbel I distribution increases for the load length of 0.8 m. The optimization of the time period and a detailed study on this matter is left for the future work.

The effect of the threshold was not studied in this paper. However, it is recognized that the threshold has an effect on the results. As an ice-induced load histogram is of the exponential type, an increase in the threshold decreases the number of the ice-induced loads effectively. A reduction in the number of smaller loadings directly affects the Gumbel I parameters through the mean value and standard deviation of the sample and to the determined return period of time through the number of ice-induced loads. The effect of the threshold should be studied in details in future.

CONCLUSIONS

The beginning of the paper presented the instrumentation on board PSRV S.A. Agulhas II, the measured 1-hour maxima from the two Antarctic expeditions and the data processing of the measurements. Afterwards, the probabilistic methods were presented and applied to the measurement data. Lastly, the results were compared to the earlier full-scale measurements. The study showed that the Gumbel I asymptotic probability distribution gives a good fit to the measured 1-hour maximum line loads at the bow and a good fit to the measured 12-hour maxima for the stern.

The comparison of the bow and stern maxima pointed out that the measured line loads are higher at the bow and the return period of higher line loads is shorter at for the bow. The comparison of the 10-day expected maximum line loads showed that the line loads at the bow and stern are significantly higher in the Antarctic waters than in the Baltic Sea when the length of the loading is less than 1 meter. However, the difference for the stern data decreases as a function of the load length and the difference is insignificant for the line loads wider than 1.4 meters.

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