EXPERIMENT-BASED RELATIONS BETWEEN LEVEL ICE LOADS AND MANAGED ICE LOADS ON AN ARCTIC JACK-UP STRUCTURE

J.S. Hoving[1], R. Vermeulen[1], A.W. Mesu[1], A.B. Cammaert[1]
[1]Delft University of Technology, Delft, THE NETHERLANDS

ABSTRACT
Jack-ups have been constructed for numerous ocean environments, but to date there has been no operating experience under Arctic sea ice conditions. The current state of jack-up technology does not allow working outside the ice-free season and thus ice management will be needed to extend the drilling season. Currently, ice load calculations are reasonably well defined for level ice, while the ice loads due to managed ice are not known evenly well. In order to extend the drilling season for multi-legged jack-up structures by means of ice management, a better understanding of managed ice loads is required. To this purpose, the relation between level ice loads and managed ice loads on a multi-legged jack-up structure is investigated.

Experiments for a 4-leg jack-up model were carried out in the ice tank of the Hamburgische Schiffbau-Versuchsanstalt (HSVA) in Germany, at a scaling ratio of 1:32. Two ice thicknesses (0.5 m and 1.0 m full scale) and three model orientations (0°, 22.5° and 45°) were tested. Additionally, ice concentration (level ice, $8/10^{th}$ and $6/10^{th}$) and ice velocity (0.5 m/s and 1.0 m/s full scale) were varied.

This paper reports on the model tests and the corresponding parametric study that was carried out with a focus on managed ice parameters. The relation between the observed level ice loads and the observed managed ice loads is quantified and discussed for varying orientations, ice velocities and ice thicknesses. Video and time series analyses were used to correlate ice loads to in-situ failure modes, and the results of these are summarised.

INTRODUCTION
Jack-ups have been designed and constructed to perform drilling operations in numerous ocean environments, but to date there has been no operating experience under Arctic sea ice conditions. Because of their relatively slender member sizes, this class of structures are not sufficiently robust in severe ice environments in order to withstand the high ice loads involved. On the other hand, there is considerable experience with jack-ups and other multi-leg offshore structures used for production in subarctic ice environments, such as the Bohai Sea and Cook Inlet (Cammaert et al, 2011), as well as offshore Sakhalin Island, where the ice conditions are less critical and the platform designs are more massive. To make the use of jack-ups viable for drilling operations in the Arctic, their operational window should be extended outside the ice-free season. This can be done using ice management, but how much ice management do we need, and under what conditions?

As outlined in Croasdale *et al*, 2009, managed ice is the term given to ice that has been broken ahead of a platform or an anchored vessel in order to reduce ice loads or other effects of ice interaction such as rubble build up. Ice features which would create loads greater than the resistance or strength of the stationary platform or vessel are broken into small pieces to reduce the ice loads. This is usually done with several icebreakers; one or more breaking ice in the far field and one or more breaking ice in the near field. Although there is some experience on how much management is required to reduce design loads, Croasdale *et al* state that the "present methods for managed ice loads are empirical and rely on expert judgement".

In order to extend the drilling season for jack-up structures by means of ice management, a better understanding of managed ice loads is required. To this purpose, the relation between level ice loads and managed ice loads on a jack-up structure is investigated as ice load calculations are reasonably well defined for level ice, while the ice loads due to managed ice are not known evenly well. Finding the ratio between managed ice and level ice loads therefore yields an estimation of the managed ice loads and thereby allows us to determine the viability of using jack-ups for drilling operations in the Arctic. Additionally, for situations where ice management is not necessarily required, the relation between the load on one platform leg and the global load on all four legs needs further investigation.

Previous experimental and numerical studies have also attempted to investigate the magnitude and distribution of ice loads on multi-leg structures. In an experimental study Timco, 1986, noted that the back (sheltered) leg of a structure experienced lower loads because the broken ice encountered these legs fails in bending or shearing rather than crushing, and these failure modes give a lower load than crushing. Similar observations have also been witnessed in the present series of tests. Shkhinek *et al,* 2009, investigated the ice loads on a structure with four legs by means of a finite difference model, during which leg sheltering, non-simultaneous load peaks in the leg and jamming of ice rubble in between the legs were witnessed. Karulin *et al*, 2012, also investigated the ice loads on a multi-leg semisubmersible structure.

In the following, we will first discuss the model configuration and the test set-up, as well as the schedule of the test campaign. Before presenting the results of the data analysis, we will assess the measurements done to determine which test series should be accounted for in the data analysis, including a validation and verification of the data obtained during the test runs. Subsequently, the analysed data is discussed and compared to observations, before giving the conclusions and recommendations.

TEST DESCRIPTION

The campaign to experimentally determine the interaction of ice with a 4-leg jack-up model was carried out in the ice tank of the Hamburgische Schiffbau-Versuchsanstalt (HSVA) in Hamburg, Germany. Due to the impracticability of moving ice toward and through a stationary structure model, the interaction between the jack-up model and the ice is simulated by suspending the jack-up model from a towing carriage and then pulling the jack-up model through the ice by moving the towing carriage over the stationary cover.

The model tests were divided over 6 test-days spread over a time span of 3 weeks. Every test-day is identified as a single test-series as shown in Table 1. As we have considered 2 ice thicknesses and 3 model orientations, every test-series, and therefore each day of testing, represents 1 out of the 6 possible combinations of ice thickness and model orientation. The tested model and full scale ice thicknesses, as well as the model orientations are given per test-series in Table 1.

During each test day, 6 experiments were performed, starting with a passage over the tank where the jack-up model was pulled through a new level ice sheet with the specifications given in Table 1. After the first passage through the tank, 20% of the ice was cut from the level ice sheet and disposed off. Subsequently, the remaining level ice was cut into rectangular pieces of various sizes to approximate a typical managed ice field according to the work done at HSVA by Van der Werff (2012). Here, the largest ice floes were chosen such that they would not jam between the jack-up legs on their own, which is a valid assumption when managed ice is considered. After evenly distributing the remaining ice floes over the length of the ice tank, an 8/10th ice concentration was obtained, allowing for a second passage through the tank. For the third passage through the tank a 6/10th ice concentration was obtained by disposing of 25% of the ice floes that remained after the second passage. Figure 1 shows the three different ice concentrations in the ice tank prior to the test-runs. Note here that only level ice and managed ice conditions are simulated and that ridge ice loads are thus not considered.

Additionally, during each passage through the ice tank the velocity of the towing carriage was varied. Starting with a velocity of 0.09 m/s, which corresponds to a full scale velocity of 0.5 m/s, the towing carriage accelerated at 1/3rd of the tank length to a velocity of 0.018 m/s, i.e. a full scale velocity of 1.0 m/s. By doubling the velocity at 1/3rd of the tank length, the duration of the ice-structure-interaction was chosen to be equal for both velocities. Thus, considering 3 different ice concentrations and 2 different ice velocities yields the 6 test-runs per test-series given in Table 2.

Model dimensions
The model constructed for the tests is based on an Arctic jack-up design concept for use in early-winter ice conditions in the Chukchi Sea. Instead of the truss-legs that are common for jack-ups operating in open water, the Arctic jack-up is fitted with 4 enclosed cylindrical legs with a full scale diameter of 7 m and a 50 m centre-to-centre leg spacing. When choosing the

Table 1. Ice thickness and model orientation per test-series.

Test-series	**Description**	**Parameters**		
		Ice thickness [m]		**Model orientation**
		Model scale	*Full scale*	
10000	*1st test day - 14/09*	0.033	1.1	0.0 °
20000	*2nd test day - 17/09*	0.033	1.1	22.5 °
30000	*3rd test day - 19/09*	0.016	0.5	22.5 °
40000	*4th test day - 21/09*	0.016	0.5	45.0 °
50000	*5th test day - 25/09*	0.033	1.1	45.0 °
60000	*6th test day - 28/09*	0.016	0.5	0.0 °

Table 2. Carriage velocity and ice concentration per test-run.

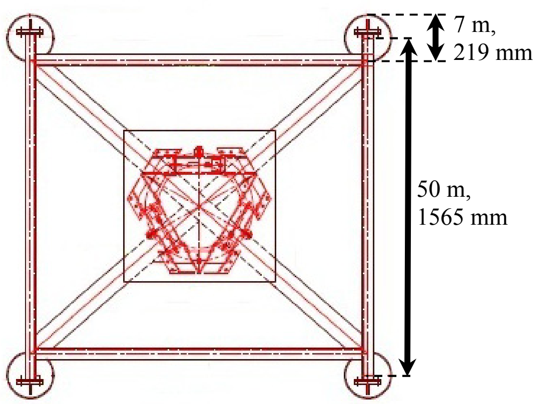
Test-runs	**Description**	**Parameters**		
		Velocity [m/s]		**Ice concentration**
		Model scale	*Full scale*	
x1010	*Level ice, 1/2*	0.09	0.5	level ice
x1020	*Level ice, 2/2*	0.18	1.0	level ice
x1011	*Managed ice, 1/4*	0.09	0.5	8/10th
x1012	*Managed ice, 2/4*	0.18	1.0	8/10th
x1021	*Managed ice, 3/4*	0.09	0.5	6/10th
x1022	*Managed ice, 4/4*	0.18	1.0	6/10th

Figure 1. Ice concentrations in the ice tank: level ice, 8/10th and 6/10th.

geometric scaling factor of the Arctic jack-up model, several practical issues were taken into account, such as the bearing capacity of the towing carriage and the capacity of measurement equipment. Additionally, the influence of the ice tank boundaries should be minimized. As such, the intentional geometrical model to full scale ratio was chosen as 1:30. As the structural elements and steel tubes used for the jack-up model were only available in certain standard dimensions, the geometrical scaling factor of the scaling model was ultimately chosen as 31.949. Consequently, the jack-up model has a leg diameter of 219 mm and a centre-to-centre leg spacing of 1565 mm as depicted in Figure 2a.

Measurement equipment
Each of the four legs was equipped with a tri-axial load cell, with a maximum capacity of 500 N, that was bolted to the model frame at one side and to the cylindrical leg on the other, thus connecting the jack-up legs with the model frame. To ensure that the load cell and the jack-up leg were connected well, the tri-axial load cells were given the same diameter as the cylindrical jack-up legs at their interface. Figure 3a shows one of the tri-axial load cells bolted to the model frame with a cylindrical face. Furthermore, the complete jack-up model was connected with the carriage by means of a 6-component load cell, measuring the total loading on the jack-up model. In addition, the top of the model was equipped with a dual axial accelerometer. All tests were documented by 2 high-definition and 1 regular video cameras above water, 2 underwater cameras and 2 photo cameras. The measurement equipment was calibrated through open water tests.

ICE PROPERTIES
As we are looking to extend the drilling season for jack-ups in the Arctic, the ice properties were chosen to represent early-winter ice conditions in the Chukchi Sea as this is a location in the Arctic that is a viable candidate for the use of jack-ups. A target crushing strength of 60



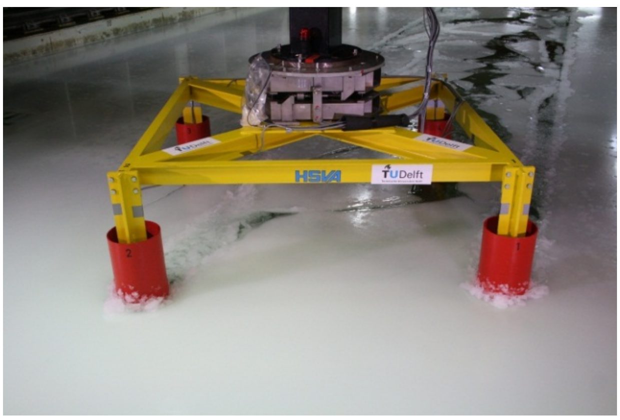


Figure 2. a) Dimensions of the jack-up in full scale and in model scale.
b) The jack-up model at 22.5° orientation in level ice.

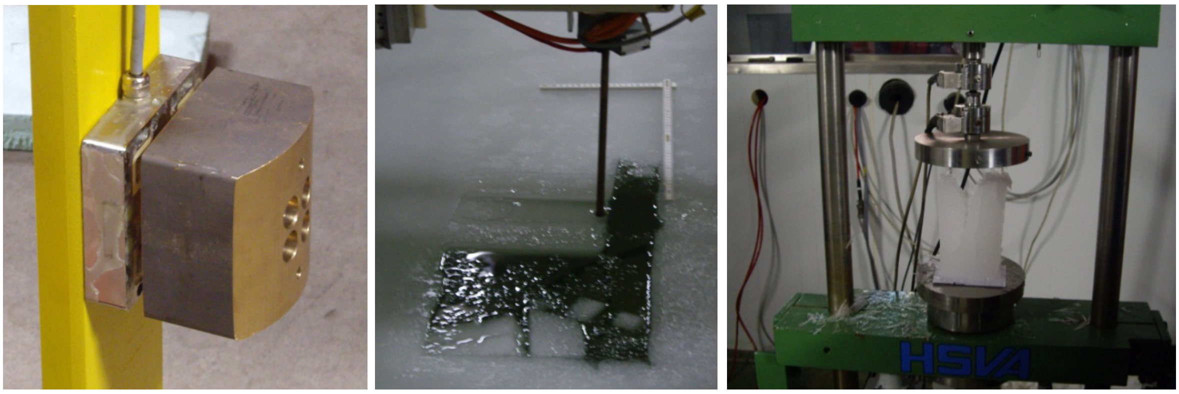


Figure 3. a) Tri-axial load cell for the jack-up legs attached to the jack-up model frame.
b) In-situ bending test. c) Compression test.

kPa was chosen to represent a full scale ice strength of 1.8 MPa, which typically corresponds to early-season ice conditions in the Arctic and normal conditions in temperate areas.

During the test-runs the properties of the ice were determined by doing measurements on several ice samples taken from the level ice sheet at different locations along the length of the ice tank. The flexural strength of the ice was determined by measuring the required force to break the ice from in-situ bending tests along the level ice sheet. Next to measuring the flexural strength in-situ, a sample of ice was extracted from the ice sheet to measure its compressive strength. Unfortunately however, the compressive strength could only be measured for the thick ice sheets, i.e. the ice sheet with a model scale ice thickness of 0.033 m, as the thin ice with a model scale ice thickness of 0.016 m was simply too thin to be placed in the compression test equipment. The ice thickness was measured from the track behind the jack-up model that remained after the first passage of the jack-up model through the ice sheet. Finally, the ice density was determined from measuring the weight and volume of pieces of the level ice sheet that were discarded after the level ice runs to obtain the $8/10^{th}$ ice concentration. The measured ice properties are shown in Table 3 per test-series, where the given values for the different ice properties are the averages of the measurements done along the length of the basin per test-series.

Before commencing the first passage of the jack-up model through the level ice sheet, the ice strength was determined from flexural strength tests; Generally it is expected for ice in the ice tank that its compressive strength can be found by multiplying the flexural strength with a factor 1.5. Therefore, a suitable ice strength was considered reached when the flexural strength was 40 kPa. As can be seen from the measured ice properties in Table 3, the factor between the measured compressive and flexural strengths for the thick ice sheet proves to be between 1.1 and 1.2 instead. As the compressive strengths could not be measured for the thin

Table 3. Measured ice properties per Test-series.

Test-series	**Mean ice thickness [mm]**	**Mean ice density [kg/m^3]**	**Compressive strength [kPa]**	**Flexural strength [kPa]**
10000	32.6	914.8	60.3	51.2
20000	34.5	n/a	57.7	50.9
30000	17.9	893.2	n/a	28.6
40000	17.8	896.0	n/a	38.8
50000	31.0	889.7	47.5	43.5
60000	16.5	866.1	n/a	39.6

ice sheet and were therefore derived from the measured flexural strengths, it is unclear whether or not the thin ice sheets were at the target compressive strength before commencing the test-runs. Consequently, it is doubtful whether the ice properties used in these tests do actually represent the early-winter ice conditions for the Chukchi Sea. To check its influence, the occurrence of unwanted failure modes has been investigated.

Failure modes

During most of the tests it was observed that the ice sheets had a distinct failure mode which dominated the run, however incidental alternation with another failure mode occurred. For the first two ice sheets, the predominant failure mode was crushing. In the third, fourth and sixth sheet bending was predominant and for the fifth sheet buckling was the predominant failure mode, however for these four sheets crushing occurred as well. Mixed failure modes were also experienced by Kato and Sodhi (1983a, b). They stated that the probability of mixed failure modes is higher than occurrence of “pure” failure modes.

Comparing our ice properties to the failure map by Timco (1986), it appears that our ice has been modelled erroneously. Timco uses the aspect ratio and strain rate as governing factors for modelling, which in our case leads to different failure modes when comparing the full and model scales. Blanchet et al. (1989) stated that not only the aspect ratio, but also the ice thickness itself has an influence on the failure mode. Additionally, from the ISO19906 code it appears that the flexural strength of the ice is an important aspect for scale modelling. Comparing the measured ice properties from Table 1 with the observed failure modes shows that the flexural strength and the ice thickness influence the occurring failure mode. Considering the above it appears that other failure modes besides crushing can be avoided by increasing the flexural strength of the model ice by lowering the ice temperature and thus the brine volume, according to Timco and O’Brien (1994).

Scaling of ice properties influences level ice loads, while its effect on managed ice loads is minimal due to a difference in load limiting mechanisms. Consequently, also the ratios between the loads due to level ice and those due to managed ice are influenced by the applied scaling. Thus, we have to take the possibly incorrect scaling of the level ice into account when considering the ratios between the loads due to level ice and those due to managed ice that follow from the test results.

ASSESSMENT OF THE TEST DATA

For each test-run, the measurements were recorded through a total of 20 channels; 12 channels for the forces on each of the 4 legs in x-, y- and z-direction, 6 channels for the 6 component load cell and 2 channels for the accelerometers in x- and y-direction. The measurement data that was gathered by a computer on-board the towing carriage with a sampling frequency of 50 Hz. Before commencing with the presentation and analysis of the obtained test data, we should first identify which test data is fit for analysis and whether any test-runs, or segments of test-runs are to be neglected.

Verification of the test data

First, the raw measurements have been considered separately per test-run. Some of the obtained data proved to be erroneous due to malfunctions of the tri-axial load cells in the jack-up legs. Typical issues that were met consisted of not recording any data in one of the three directions, offsets in the measurements, as well as drifting measurements, which was apparent due to the loads not returning to their equilibrium state after the test runs. Offsets and linear drifts were corrected a-posteriori by subtracting the offsets or trends from the original data.

Finally, to verify the resulting data, we have compared the loads measured by the 6-component load cell to the total load that follows from the summation of the loads measured by the tri-axial load cells in the jack-up legs for different runs. After comparing the 2 data-sets, we find a minor, yet increasing offset between the two equivalent total loads on the jack-up. A thorough investigation of the test-data shows that this offset follows from a small drift in 2 of the tri-axial load cells in the jack-up legs. As this drift is approximately linear, the drift can be easily removed from the measurement data. (See Figure 4b)

Validation of the test data

For some of the tests the measurement equipment failed, however due to the symmetry and comparison to the 6-component load cell it was possible to determine the missing data. Most failures in the load cells occurred in the out-of-plane z-axis, however the loads in this direction were not taken into account in this paper.

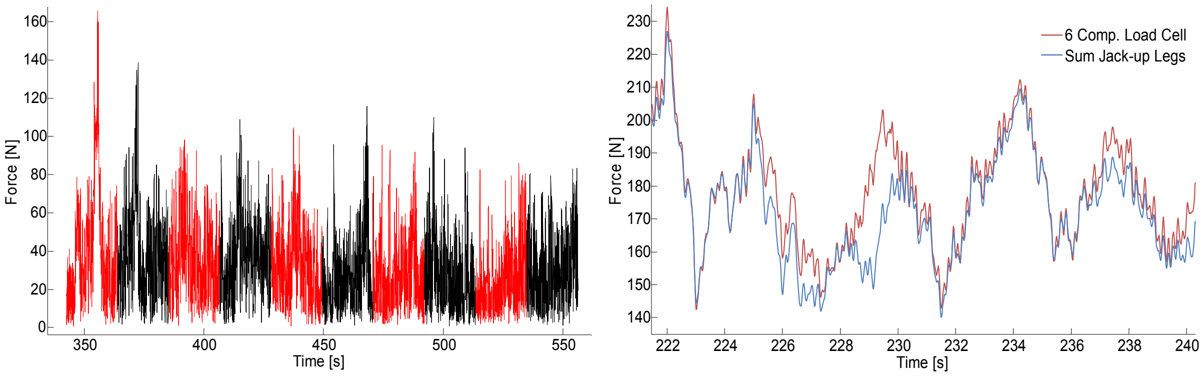


Figure 4. a) The resultant load on a front leg for test-run 11012 divided in 10 segments.
b) Comparison: 6-component load cell versus the sum of the tri-axial load cells in the legs

To determine the valid parts of each test run, and investigate if there are any start-up or end-issues due to the basins boundaries, we have separated each run into several parts and determined the probability density functions (PDFs) for each part of the structure. Consequently, we have identified the influence of the initial conditions for the low velocity data sets, the influence of the velocity increase, as well as the influence of the ice tank boundaries. For the data here presented, we have disregarded the first segment of all test runs, as there was a significant influence of the initial conditions and the velocity jumps.

DISCUSSION AND PRESENTATION OF THE TEST DATA

To show the differences between ice loads due to level ice and those due to managed ice, we will first present PDFs for the resultant load on the so-called design leg as well as probability density functions for the total resultant load on the complete structure. The design leg here refers to the particular jack-up leg that endures the highest loads during the test runs. For the 0° orientation, the 2 front legs should endure similar load conditions and the data corresponding to these 2 legs is therefore combined into a single PDF. For the 22.5° and the 45° orientation, the highest loads were expected at the front jack-up legs. This was confirmed by the measurements. Figures 5, 6 and 7 compare the resulting PDFs for respectively level ice, $8/10^{th}$ and $6/10^{th}$ ice concentration for several test-runs. As was to be expected, the lowest ice loads were found for $6/10^{th}$ ice concentration, while the highest loads were found for the level ice runs. Additionally, the PDFs for the full structure show a clearer distinction between the loads for level ice, $8/10^{th}$ and $6/10^{th}$ ice concentration than the PDFs for the design legs. This can be explained by the fact that the differences between the leg loads are smaller for managed ice than for level ice.

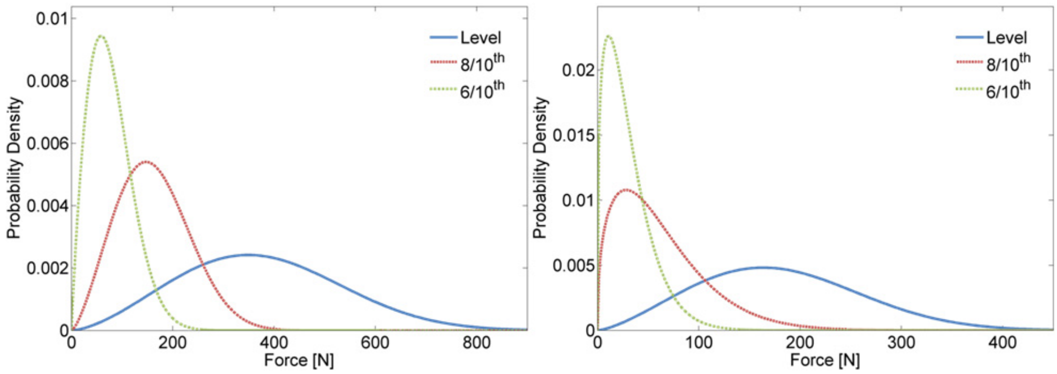


Figure 5. PDFs for 33 mm ice thickness, 0° orientation, a) full structure. b) design leg.

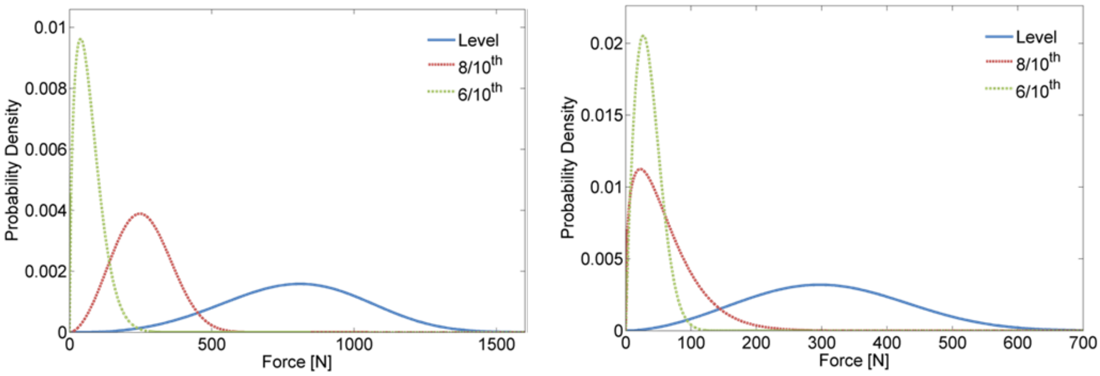


Figure 6. PDFs for 33 mm ice thickness, 22.5° orientation, a) full structure. b) design leg.

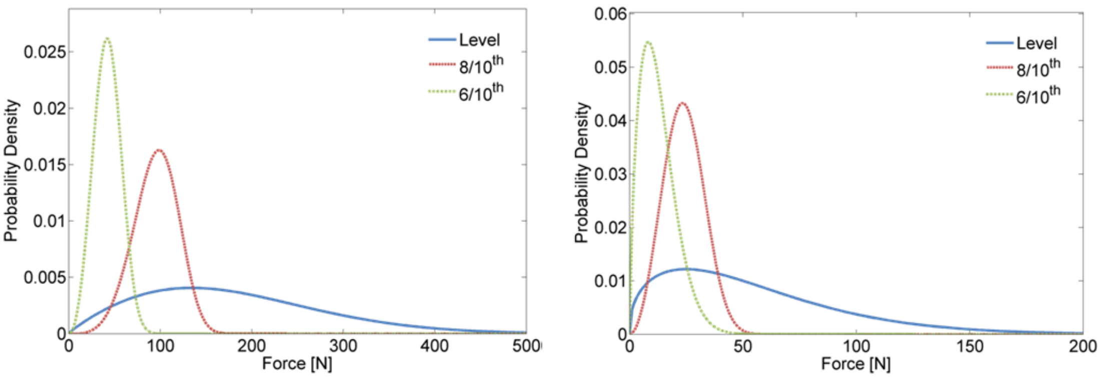


Figure 7. PDFs for 16 mm ice thickness, 45° orientation, a) full structure. b) design leg.

In Figures 8 and 9, the load ratios are given for the mean ice loads on respectively the full structure and the design leg in relation to the level ice loads. Consequently, the level ice loads must always have a load ratio of 1, while the 8/10th and 6/10th managed ice load have load ratios smaller than 1. It follows from the presented load ratios that the mean ice loads on the jack-up in 8/10th managed ice of 1.1 m thickness are roughly 40% of the mean ice loads on the jack-up in level ice. For the same ice thickness, the mean ice loads on the jack-up in 6/10th managed ice are roughly 20% of the level ice loads. When the thinner ice sheet is considered, i.e. the ice sheet with a full scale thickness of 0.5 m, the 8/10th managed mean ice loads may approach 80% of the level ice loads, while the 6/10th managed mean ice loads are approximately 30% of the level ice loads. Figures 10 and 11 show the standard deviation of the ice loads and correspond to the mean values given in Figures 8 and 9. From Figures 8 to 11 it is seen that the mean load ratios and the standard deviation of the corresponding ice loads are similar for the full structure and the design leg.

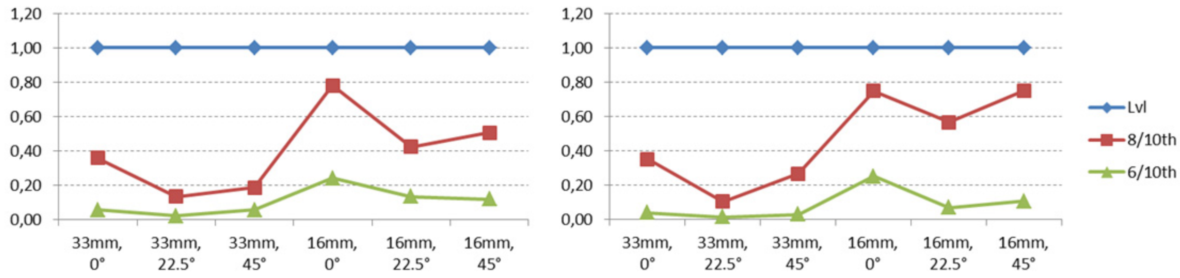


Figure 8. Mean load ratios for full scale velocity 0.5 m/s a) full structure. b) design leg

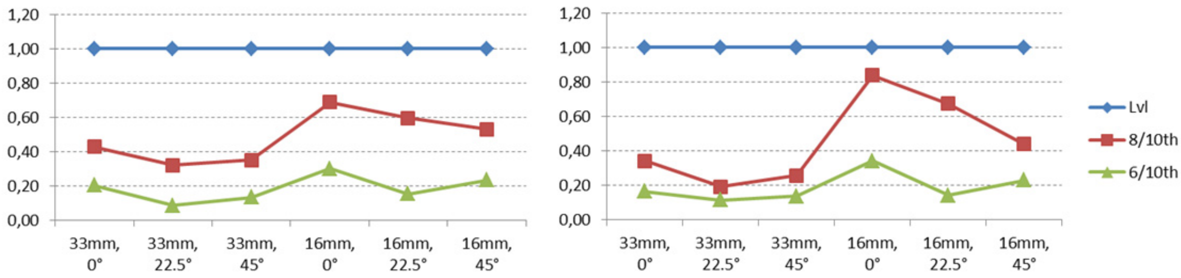


Figure 9. Mean load ratios for full scale velocity 1.0 m/s a) full structure. b) design leg

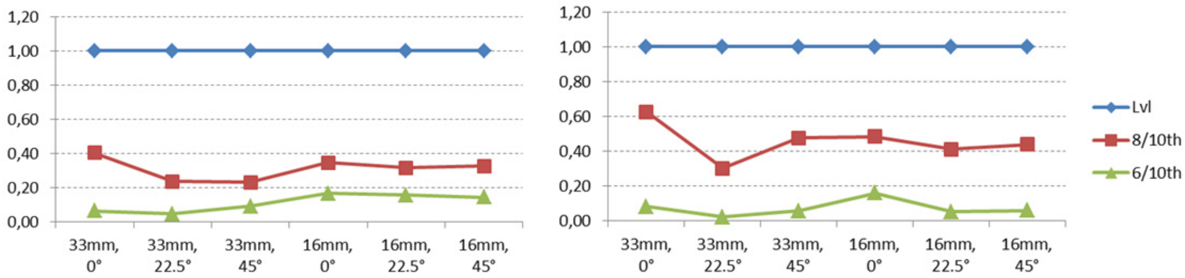


Figure 10. Ratios standard dev. for full scale velocity 0.5 m/s a) full structure. b) design leg.

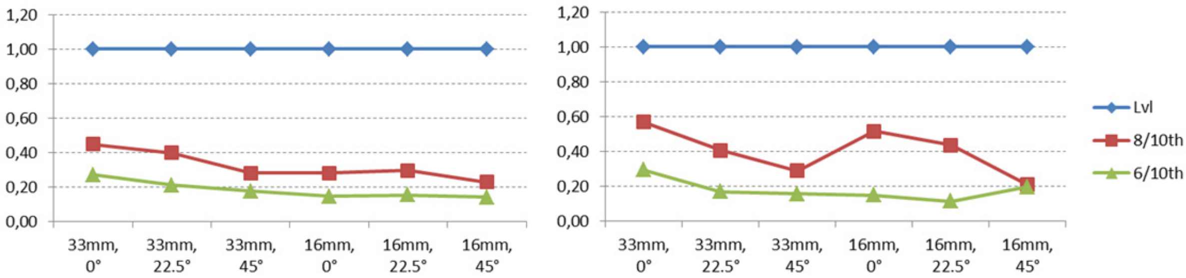


Figure 11. Ratios standard dev. for full scale velocity 1.0 m/s a) full structure. b) design leg.

CONCLUSION & RECOMMENDATIONS

The presented data shows a clear distinction between measured ice loads due to level ice and measured ice loads due to managed ice; additionally a first estimate is given of the actual ratios between these loads. Notably, we find that the ratios between level ice loads and managed ice loads are larger than the ratios found for the thinner ice sheets.

It is here emphasized that the data analysis is currently still on-going and that the results presented in this paper are preliminary. Additional planned data analysis consists of a probabilistic determination of the corresponding design loads, as well as Fourier and Wavelet analysis.

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