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Estimation of model ice properties in ice tank operations with numerical models

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ABSTRACT

Conducting model ice tests is still the state of the art in predicting the performance of ships and structures in ice. This is also valid for other occurrences such as waves in ice or ice feature formation processes. In an ice tank ice properties such as the flexural strengths and the thickness usually formulate the target properties towards which the ice production process is adjusted. This also means that prior to testing the properties are measured and in case target properties are not yet met additional tempering or cooling is done until target conditions are met. Conducting cantilever beam tests for the flexural strength and plate deflection tests for the elastic modulus is time consuming in the time critical ice production process. The plate deflection tests itself can take up to an hour including all preparation

This paper presents a method that reduces the time needed to conduct property tests in the ice tank, while providing deeper insight into the ice properties. The first method uses a parametric finite element model, which reproduces the cantilever beam tests. With an iterative routine, the elastic or strain modulus of the ice is determined as well as the nominal stress at failure (flexural stress), the elastic stress at the root corners and the buoyancy force. Especially, the latter is in some cases of particular interest and it has been for decades under debate whether this can be read from the force recordings of the cantilever beam tests.

The method increases the amount of information of the ice sheet properties significantly and reduces the time spent on ice property testing. The methods are applied and tested for different ice sheets and measurements from the Hamburg Ship Model Basin (HSVA). It is shown that the elastic modulus can be determined with a good agreement (better than 4% for regular model ice of around 30 mm thickness) to the plate deflection tests. Furthermore, the effective strain modulus and the buoyancy force is delivered as result.

KEY WORDS: Model ice, Cantilever beam tests, Finite Element Modeling, Experiments; Ice Tank Operations

INTRODUCTION

Ice model tests are still the state of the art method for performance predictions of ships and structures in ice as no numerical method is yet established. Additionally, ice tank tests gain increasing significance for the investigation of wave-ice interaction (Dolatshah et al., 2017; Klein et al., 2021; Marchenko et al., 2021; Passerotti et al., 2022), which is relevant for oceanographic research and the decay of polar ice sheets in the course of the changing climate.

In all the disciplines mentioned, the scaling of the acting forces and ice properties is of high importance in order to arrive at meaningful and representative results. Ship-ice interaction is commonly based on the maintenance of Froude and Cauchy similitude (Schwarz, 1977; von Bock und Polach, Ettema, Gralher, Kellner, & Stender, 2019; Zufelt & Ettema, 1996), while for wave-ice interaction similitudes or non-dimensional criteria might differ in dependence on the scope (Fox, 2001; Voermans et al., 2020; von Bock und Polach, Klein, & Hartmann, 2021). It must be acknowledged that model ice is commonly not a perfectly scaled surrogate of sea ice and that certain areas that still require development (von Bock und Polach & Molyneux, 2017) and therefore scaling and production methods might be adjusted from case to case (von Bock und Polach et al., 2020). This means for example that the flexural strength is adjusted and scaled for ships breaking ice (Schwarz, 1977), whereas for the compressive failure at vertical structures the compressive strength is adjusted and a less compliant ice is generated (Ziemer, 2018).

In each model test the properties of the generated ice is measured in the process assessing whether target properties are met and whether additional measures in terms of cooling or tempering need to be taken to re-adjust the current properties. The ice property measurements conducted are standardized in the guidelines of the International Towing Tank Conference (ITTC, 2014).

In most ice model tests conducted the flexural strength and the flexural rigidity are the parameters of most interest. The flexural rigidity refers usually to the elastic modulus and at times to the corresponding strain modulus if the deformation was not fully elastic (von Bock und Polach, 2015).

The challenge in these measurements is their fast and accurate conduction. The time-sensitivity is related to the limited control of the dynamics of the ice properties and the time spent on conducting the experiments. Generally, ice properties are tried to be kept steady once target properties are reached, however certain dynamics sometimes cannot be avoided so that properties are subjected to a certain drift. In this regard measuring the elastic modulus with the deflection of an infinite plate requires around 60 minutes and cannot be conducted in thin ice with insufficient bearing capacity of the ice. The flexural strength tests require around 30 minutes and are conducted three to four times
In order to overcome this, a numerical method based on the finite element analysis of the flexural strength tests is presented which does not require separate experiments for the elastic modulus. Furthermore, the method is able to provide both the elastic modulus and the overall effective strain modulus as well as the buoyancy force of the beam.

This method has been tested successfully in an early stage of development and its practical relevance proven during ice model tests (von Bock und Polach et al., 2021). In this test, the elastic modulus was very important for the wave properties, but the thickness too thin so that plate deflection tests were impossible to conduct.

METHODS

Experiments

The experiments consist of flexural strength measurements that are conducted with cantilever beam tests and elastic modulus tests by deflecting an infinite plate. Tests are conducted in three different ice sheets and in ice sheet 2 and 3 two sets of flexural strength measurements are analyzed. The experimental procedures follow the recommendation of ITTC (2014) and the time difference between plate deflection tests and flexural strength tests is maximum around one hour. . The elastic modulus is determined with non-destructive plate deflection tests and leave the ice sheet intact for the later experiments. Thickness measurements are taken from the cantilever beam tests and ice density measurements are taken from samples of the same location as the cantilever beams following the procedure of ITTC (2014). A compilation of the three ice sheets and their measured properties is found in Table 1.

Table 1. Mechanical properties of the analyzed ice sheets. In total three ice sheets are analyzed, with two sets of flexural strength measurements in ice sheet 2 and 3.

Ice sheet	Average thickness, h, [mm]	Density, ρ_{ice}, [kg/m³]	Measured elastic modulus, E, [MPa]	Average flexural strength, σ_f, [kPa]	No. cantilever beam measurements	Time elapsed between σ_f and E measurement [min]
01	28	830*	10.7	36.3	3	35
02-1	29.3	875	14	32.6	2	-54
02-2	29.7			36.2	3	-66
03-1	64.2	885	98	29.6	3	-49
03-2	66.1			31.3	3	-66

*estimate based on a similar ice sheet generated before

Analysis of the force-displacement data from cantilever beam tests

The measurements of the flexural strength, i.e. the force-displacement plots, need to be analyzed to define the elastic limit and the maximum forces for the numerical analysis. As the model-ice shows distinct non-linear behavior in the force-displacement curves (von Bock und Polach, 2015; von Bock und Polach et al., 2019) the distinct points need to be identified. In tank operations these points are defined manually and depend significantly on the experience of the operator, which introduces bias.
The elastic limit is defined as the point where the linear relationship between force and displacement ends as displayed in Figure 1. In order to detect slope changes the oscillations introduced by the driving electric motor of the original measurements are removed by applying a moving mean of 50 points.

The end of the elastic range, i.e. the onset of non-linear behavior, is defined by a change in slope from the initial linear elastic slope (von Bock und Polach, 2015; von Bock und Polach et al., 2019).

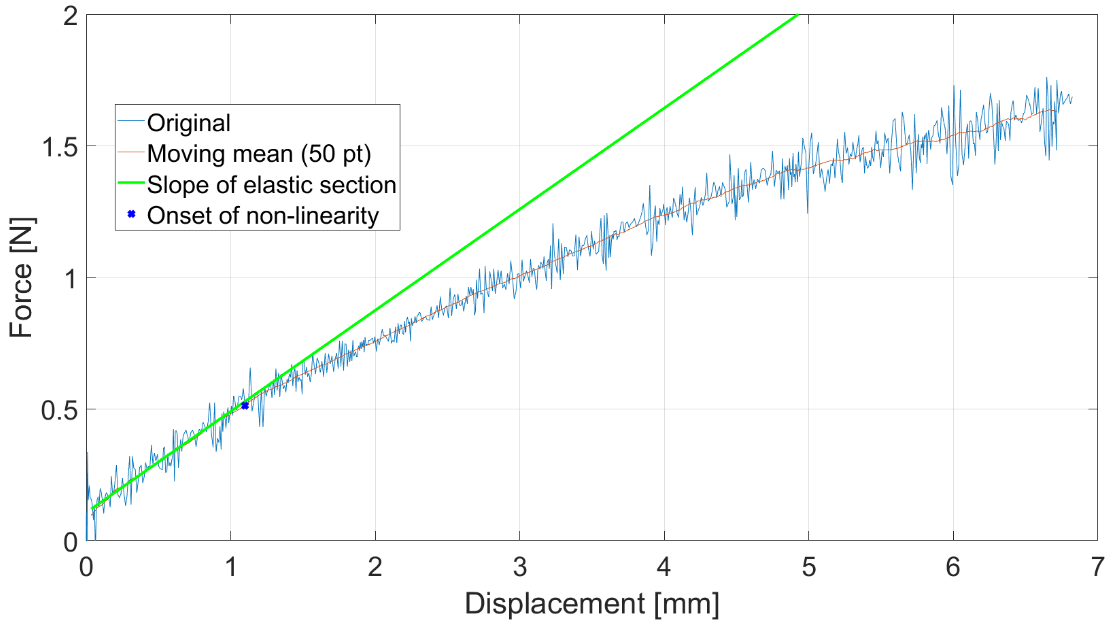

Figure 1: Example of a force-displacement curve from cantilever beam tests with lines indicating the section-wise linear force-displacement relationships. The measurement is taken from ice sheet 2 conducted within around 1.5 seconds.

The elastic section is a slope that is fit over the first 100 samples in all analyzed experiments. In order to balance some oscillations from the onset of the load application onto the ice and the build-up of the load the first point is the average of the samples 20 to 50 and the second one the average of the samples 50 to 100 of the smoothed curve.

The onset of non-linearity respectively the elastic limit is defined once the slope of the elastic section and deviates by 2% of the moving mean of the measurement. The 2% is an arbitrary selected value, but proved to be insensitive to minor variations and small enough to detect the onset on non-linearity. This process is running automatically, but all results are visually cross-checked. Limitations are found in the section DISCUSSION.

For the interaction with marine structures also the stiffness at the point of global failure is of interest. This peak force value (maximum load) is also used for the flexural strength and used to determine in the later calculations the global strain modulus, S. This modulus assumes a linear material behavior from load application to maximum load. Please refer to von Bock und Polach et al. (2019) for more details.

Finite Element Model

The finite element model is parametric and built in ANSYS. Therefore, the model can be built fast for the individual dimensions of each cantilever beam. In addition to the beam dimensions, the ice density and the load is needed and requires the measured thickness and accounts for the radii at the transition between cantilever beam and ice sheet The model is made of solids and at the ends of the parent ice sheet (three sides) all degrees of freedom (DOF) are constrained. The dimensions of the adjacent (parent) ice sheet are defined being half the beam length, L, and three times the beam width, b, to avoid the boundary conditions influencing the vertical deflection of the beam root (Figure 2).

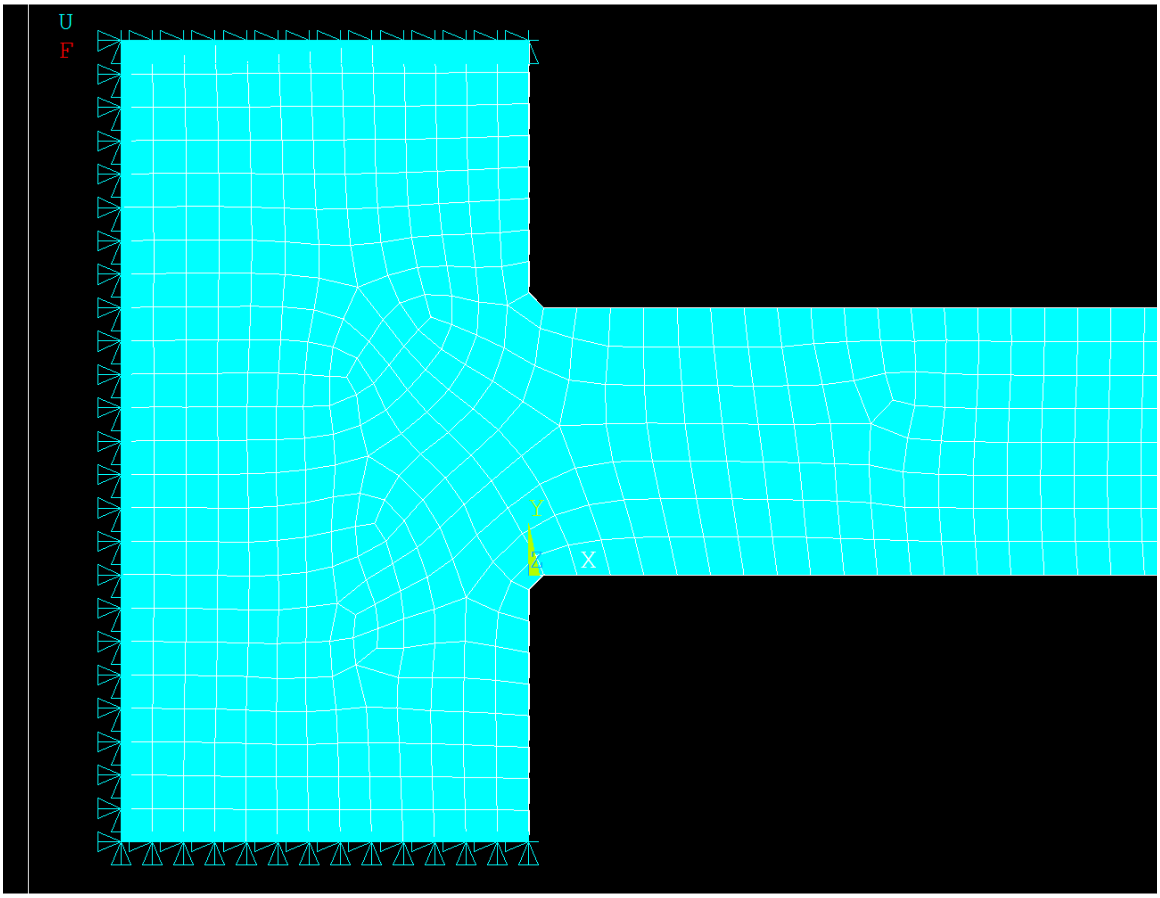

Figure 2: Applied boundary conditions at the edges of the adjacent ice sheet

The buoyancy is modeled with nonlinear springs (COMBIN39). In the model the resting condition is considered as equilibrium of weight and buoyancy in which no forces are acting. Once vertical displacement is initiated and the beam is pushed into the water the spring force increases linearly with the vertical displacement. Once the vertical displacement equals the freeboard and top flooding occurs the maximum buoyancy force for this section is reached and the buoyancy force is set constant. The area over which each spring represents the buoyancy force is determined by the area of the bottom nodes divided by the number of nodes. As this approach requires a regular mesh, the root radii and the nodes further away from the beam do not have a spring. This is acceptable, because the vertical deformation is small in this region and the contribution to the buoyancy is neglected. The global buoyancy force is determined from the difference between the applied vertical force and the vertical reaction forces at the boundary conditions.

Figure 3 shows the impact on the determined elastic modulus if the adjacent ice sheet dimensions are reduced in length and width. The size of the adjacent ice sheet is determined as a function of the cantilever beam length, L, and its width, b. Figure 3 also indicated the sensitivity of results on the number of elements over thickness. In the guidelines of (ITTC, 2014) the thickness is used as reference dimension as hence the number of elements is also defined depending on the thickness. Furthermore, this introduces a certain flexibility and numerical efficiency in tank operations for any thickness. Based upon the sensitivity study it was decided that 4 elements of over thickness is a reasonable selection. Principally, the number of elements must be high enough to adequately reflect compliance of the ice sheets and must be low enough to provide results as fast as possible.

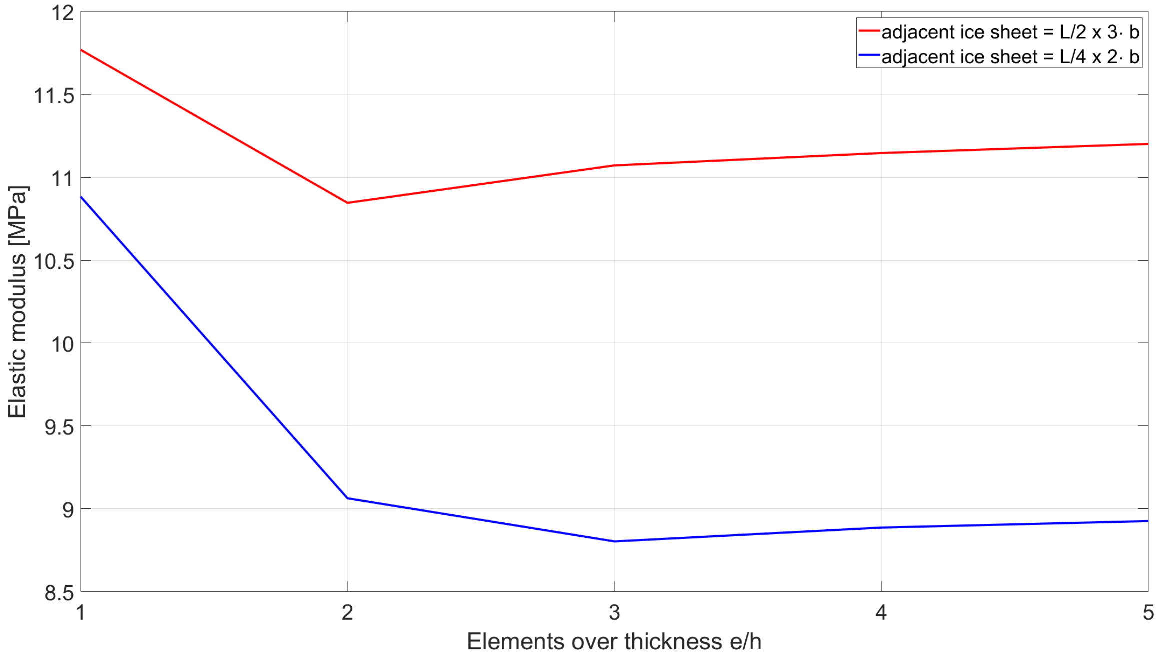

Figure 3: Sensitivity of the elastic modulus calculation on the number of elements over thickness and the size of the adjacent ice sheet.

RESULTS

Elastic modulus

The elastic modulus determined with the numerical model and the data determined from the experiments as described in Figure *1*. Figure 4 shows the measured vs. modelled elastic modulii for the examined three ice sheets. The results for the ice sheets 1 and 2 show a good agreement with the elastic modulus measured from the plate deflection tests, i.e. a deviation of maximum 4%. The simulation results for ice sheet 3 shows a high scatter around the measured elastic modulus (Figure 4). The deviation is in average around 18 %. The automated detection of the slope change is working for the less strong ice sheets 1 and 2 of around 30 mm thickness. For ice sheet 3 (65 mm thick) the loading curve shows several oscillations (Figure 5) and the elastic range is not defined by a gradual slope change, but by a local load peak and subsequent unloading. For ice sheet 3 the selection of the range is done manually and it is found that the selection of the load initiation point holds a high sensitivity to the results.

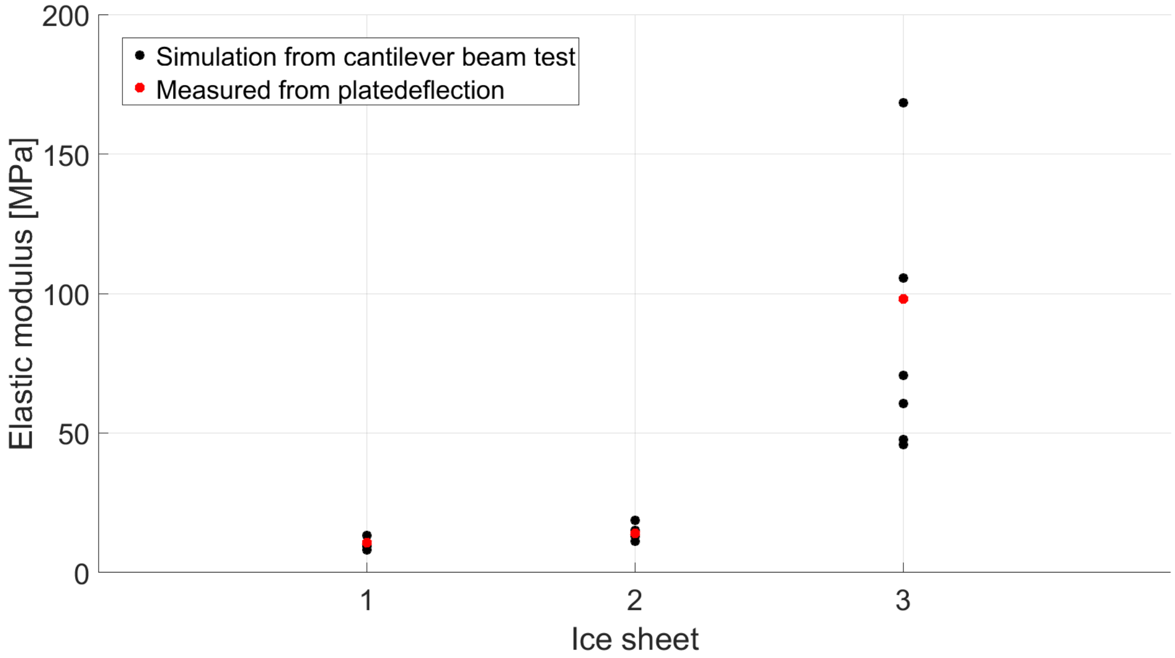

Figure 4. Simulated elastic moduli form cantilever beam tests and measured from plate deflection tests.

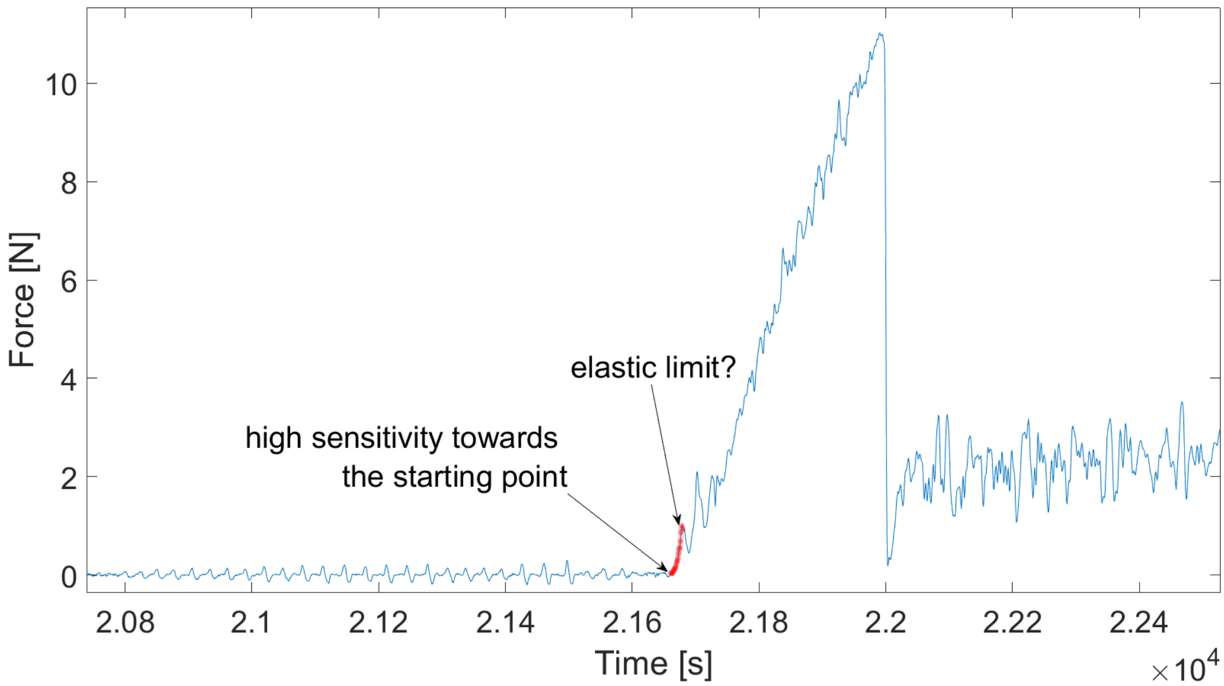

Figure 5. Loading curve of thick (65 mm) (ice sheet 3). The load shows several oscillations, but no gradual slope change as the thinner model ice. This curve is a representative sample for all other measurements in ice sheet 3.

Effective strain modulus and buoyancy force

The effective strain modulus is the stiffness that can represent the point of maximum load and displacement with a linear elastic calculation. This is the stiffness a marine structure, such as a ship model, experiences when it bends the ice downward. Table *2* shows the average results for the ice sheets investigated. The variation is reflected by the standard deviation, std. The variation in the effective strain modulus is small for the ice sheets 1 and 2, while it is relatively significant for the thick and strong ice sheet 3.

Table 2. Simulated results of effective strain modulus and buoyancy force

Ice sheet	Average effective strain modulus, S, [MPa]	std (S) [MPa]	Average Buoyancy force, F_b, [N]	std(F_b)
01	3.92	0.63	0.24	0.01
02	7.04	0.64	0.34	0.04
03	37.48	9.96	0.56	0.08

In ice tank operations the buoyancy is usually estimated from the force when the broken (free floating) cantilever beam is resting on the plunger connected to the load cell. In some cases, this is of interest in order to deduct the buoyancy force from the peak load for the flexural strength calculations. Figure *6* shows results from one of the thinner ice sheets, where the calculated buoyancy force can be approximated as the residual force of the broken ice beam, as is often done. Figure *7* shows the same for the thick ice sheet 3, where there is no obvious force reading equivalent to the buoyancy force.

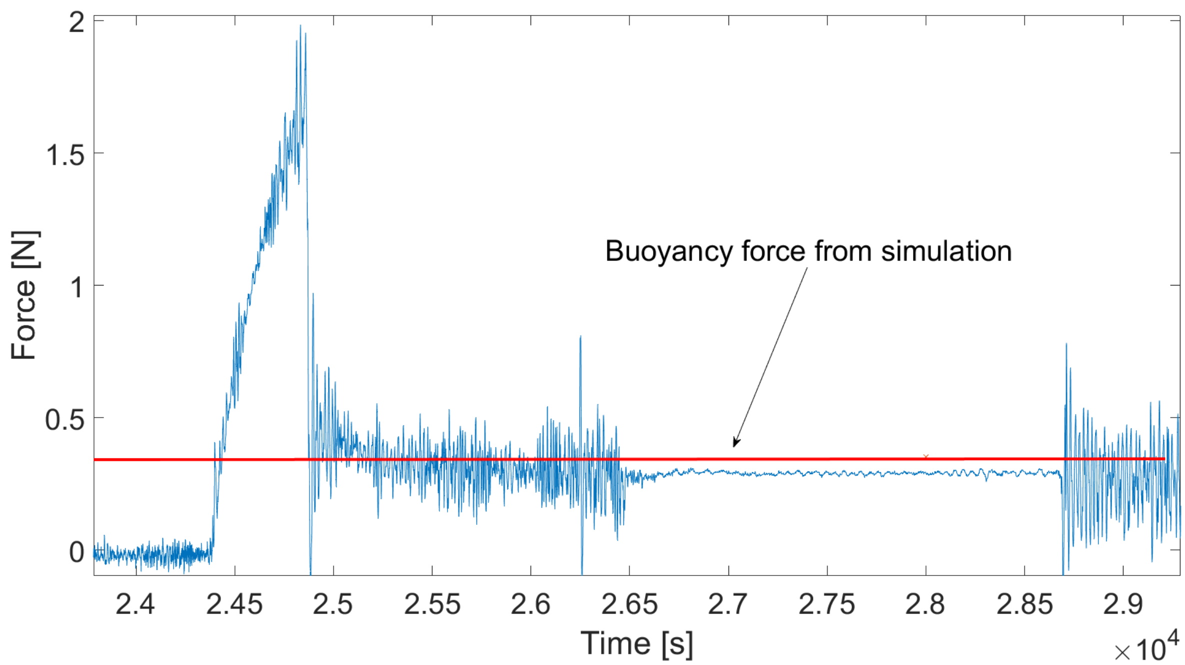

Figure 6. Loading curve of ice sheet 2 with the calculated buoyancy force

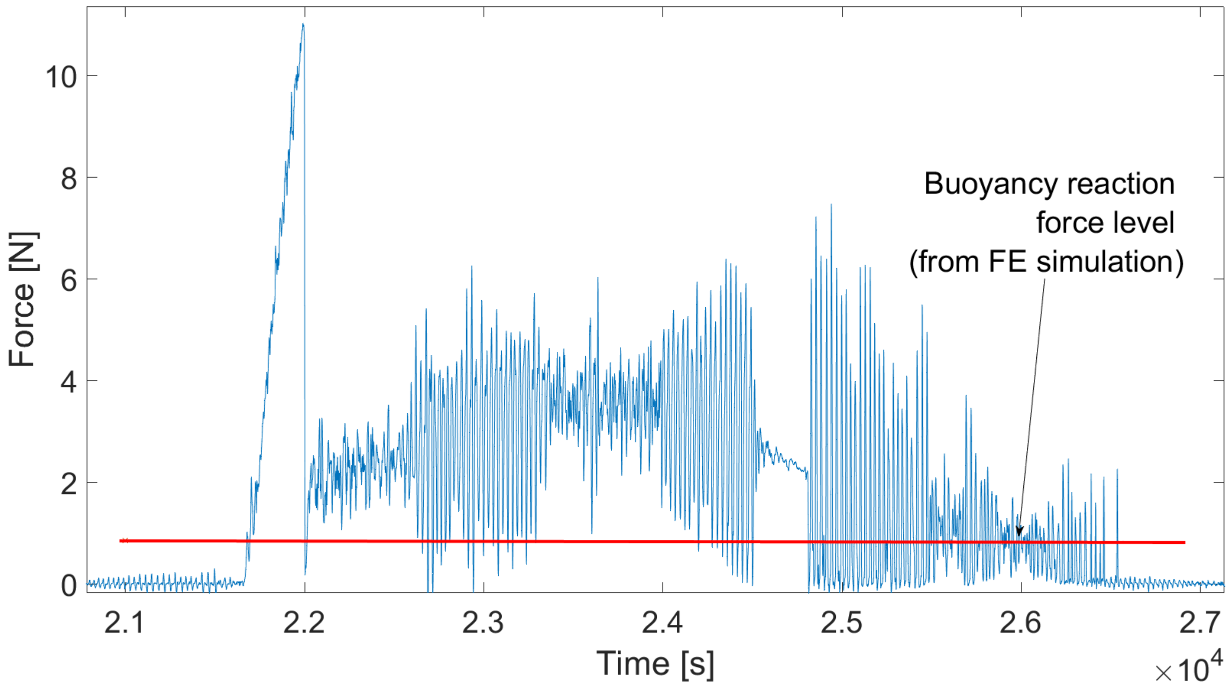

Figure 7. Loading curve of ice sheet 3 with the calculated buoyancy force

DISCUSSION

The properties of the model ice are subjected to a certain variation over the length and the width of the tank. This concerns both strength and thickness. The cantilever beam tests are conducted close to the tank wall to minimize an impact on the later tests, such as unwanted crack developments. The elastic modulus is tested in the middle of the tank in a certain distance to the cut out cantilever beams in order to comply with the boundary condition of an infinite plate. Already, these spatial differences in the experiments might limit an exact match of properties. Additionally, ice properties are subjected to a temporal dynamic and as cantilever beam tests and elastic modulus tests are not conducted simultaneously this is potentially another cause for differences between the values measured from the plate deflection test and the calculated values based on the flexural strength tests.

Measurement Accuracies and Tank Procedures

In the tank operations and the flexural strength tests the length of the broken cantilever beam is reported. This procedure might be sufficient for the flexural strength, but for the presented modelling approach the intact beam length is required which is often identical to the broken beam, but not always. Additionally, the distance between the beam tip and the load application point needs to be determined accurately. It is usually assumed that the beam is loaded at the tip, but already due to practical constraints the loading location needs to have a small offset from the tip. For the example analysis presented in Figure 3 an offset of 9 mm from the beam tip changed the effective strain modulus by 8%. This indicates the impact of inaccuracies in the offset and uncovers one possible reason for the scattered results.

Irregularities in Measurements

The automated method works well as long as no irregularities such as force oscillations due to smaller cracks occur. In this case a discontinuity is generated, that causes a drop in the filtered signal which leads to a misinterpretation of the linear range and of the elastic limit. Furthermore, for stronger ice and larger response forces the oscillation of the force signal is significantly reduced and the filtering of the signal can be adjusted, which underlines once more the difficulty of generalizing the settings of the analysis with respect to the high variability in the experiments.

Improvements in Future

The methods discussed in this paper are considered proof-of-concept based upon results from ice tank operations demonstrating the approach to be useful for adjusting model ice properties prior to, and during testing. Results from cantilever beam experiments in ice sheets of different strengths and thicknesses reflect different phenomena, some of which are not yet fully understood. Consequently, the data analysis method may need future adjustments. While it has been working well for the 30 mm ice sheets manual analysis was required for the thick ice sheet 3.

CONCLUSION

The method presented comprises of a finite element model of a cantilever beam with distinct boundary conditions and an automated approach for the analysis of flexural strength load measurements. The method was shown to provide reasonable estimated of the elastic modulus, the effective strain modulus and the buoyancy force. The generation of input data with thick ice deems to be challenging since it appears that the deformation behavior is different compare to thinner ice. The method has the capacity to provide significant support in tank operations by providing more insight into the ice properties and critical tank time can be saved when measurements of the elastic modulus with plate deflection measurements can be skipped. As ice property measurements belong usually to the preparation before the actual tests the method presented can provide more time for actual tests and reduce tank operation time, where one hour of saved time can be beneficial also concerning the fatigue of the tank crew.

Additional development of the method with respect to the analysis of measurement data is needed in order to fully automate the process.

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