

STYRELSEN FÖR
VINTERSJÖFARTSFORSKNING
WINTER NAVIGATION RESEARCH BOARD

Research Report No 91

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**AZIMUTHING THRUSTER ICE LOAD CALCULATION AND SIMPLIFIED ICE CONTACT
LOAD FORMULATION**

Finnish Transport Safety Agency

Finnish Transport Agency

Finland

Swedish Maritime Administration

Swedish Transport Agency

Sweden

Talvimerenkulun tutkimusraportit — Winter Navigation Research Reports
ISSN 2342-4303
ISBN 978-952-311-162-2

FOREWORD

In this report no 91, the Winter Navigation Research Board presents the results of the research project Azirule2014. The aim of the project was to develop simplified load formulae for ice loads experienced by azimuthing thrusters for the development of the Finnish-Swedish ice class rules.

The report presents the relevant load scenarios and ice load calculation methods as well validation of the methods. The load scenarios are ice-thruster interaction during ridge penetration and ice block impact to azimuthing thruster. The methods give results in the correct range and good correlation with experimental data. The formulae for ice loads are presented for validation by industry and classification societies.

The Winter Navigation Research Board warmly thanks Mr. Aki Kinnunen, Mr. Juha Kurkela and Mr. Pekka Juuti for this report.

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October 2016

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Azimuthing thruster ice load calculation and simplified ice contact load formulation

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Confidentiality: Public

Report's title Azimuthing thruster ice load calculation and simplified ice contact load formulation		
Customer, contact person, address Finnish Transport Safety Agency Jorma Kämäräinen PO Box 320, FI-00101 Helsinki, Finland		Order reference W14-1 AZIRULE2014 Dno TRAFI /737/02.03.01/2014
Project name Azirule2014		Project number/Short name 86099 / Azirule2014
Author(s) Aki Kinnunen, Juha Kurkela, Pekka Juuti		Pages 50
Keywords Ice load, ice structure interaction, contact, dynamic model, measurement, ice class rules		Report identification code VTT-R-00258-15
<p>Summary</p> <p>The approach for the development of Finnish-Swedish ice class rules for azimuthing thruster is to determine ice load scenarios and load cases to be included in the ice class rules. The ice loads will be calculated with sophisticated models and models will be verified with full scale measurement data from ice breaker Fennica. Simplified load formulae will be developed based on advanced ice load models and measurement data. The results will be combined to form the technical draft of Finnish-Swedish Ice Class Rules for azimuthing propulsion units.</p> <p>In this document, the work done up to and including 2014 is documented. The relevant load scenarios and applicable ice load calculation methods are presented, example cases selected and ice loads calculated for these example cases with different methods.</p> <p>The relevant ice load scenarios were identified to be ice block impact to azimuthing thruster and the thruster-ice interaction when going through ice ridge.</p> <p>Regarding the ice block impact to azimuthing thruster load scenario, a conclusion can be made that the developed dynamic impact load model gives contact loads that are at a correct range for full scale and correspond well to small scale experiment on sea ice. A parameter study was done with dynamic impact load model and based on the results, a simplified impact load formulation is suggested. The suggested formulation is currently for review only, it is to be validated by industry and other classification societies.</p> <p>The ridge penetration load case was studied with FE-model showing a good correlation in thruster total loads with the full scale measurements and a proposal of the simplified load model for ice class rules is presented. The simplification proposal is based on parameter study with FE-model. Simplified formulation is suggested for azimuthing thruster total load when ship is going through ice ridge. This simplification still needs further testing and verification, and is provided for industry and classification societies review.</p>		
Confidentiality	Public	
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1. Introduction

The Finnish Transport Safety Agency (Trafi) initiated ice class rule development project for azimuthing thrusters in 2010. Finnish-Swedish ice class rules do not have at the moment specific (ice class) rules for azimuthing thrusters. Into the project steering group were invited representatives from classification societies and azimuthing thruster manufacturing industry in order to get the ice class rule development work onto right track right from the start. VTT Technical Research Centre of Finland is responsible of the actual development work, following the guideline frames set by the steering group. A project kick-off meeting was held in June 2010 in Helsinki, with a very good attendance from the invited classification societies and industry partners. The initiative meeting was followed by participator survey regarding what to study in this project.

The work progress was followed up in steering group meetings, held annually in 2011, 2012, 2013 and 2014.

In this document the research activities and key results achieved during and up to 2014 are presented. Simplified load formulas are suggested for the studied load cases, namely ice block impact to azimuthing thruster and ice ridge interaction with ship and azimuthing thruster.

2. Goal

The ice class rule development is aimed to create technical background to renew Finnish Swedish Ice class rules to be harmonized with international ice class rule work. The approach is to determine ice load scenarios and load cases to be included in the ice class rules. The ice loads will be calculated with sophisticated models and models will be verified with measurement data. Simplified load formulae will be developed based on ice load models and measurement data. The results will be combined to form the technical draft of Finnish-Swedish Ice Class Rules for azimuthing propulsion units.

For 2014, goal was to

- Use the previously implemented ship and thruster geometry for ridge penetration FEM modelling and run a parametric study for thruster-ridge interaction loads, including variation of ship size, thruster size, thruster steering angle and ridge geometry, in order to establish idea of simplified thruster load model for ridge penetration case.
- Use available full scale data for validation purposes; measurements from ice breaker Fennica and Botnica were available, Fennica results were considered primary validation data.
- Ice block impact model was to be further developed and validated, improve ice-structure contact force model functionality and, with a controlled test setup, to evaluate the model accuracy in load calculation and dynamic magnification in impact.

3. Ice load scenarios

The relevant ice load scenarios for ice structure interaction are shortly described here. Further details for ice load calculation for each scenario are documented in the ice load model and calculation chapters.

3.1 Ice impact

The main parameters when an individual ice block impacts to the propulsion structure are the affecting ice mass m (kg) and initial relative velocity v (knots) between the ice and structure. Relevant scenarios include at least impact to propeller hub and 'rear end of propulsion unit'. The relevant load calculation models include at least: VTT, ABS and DNV ice load models. Following figure illustrates the load scenario.

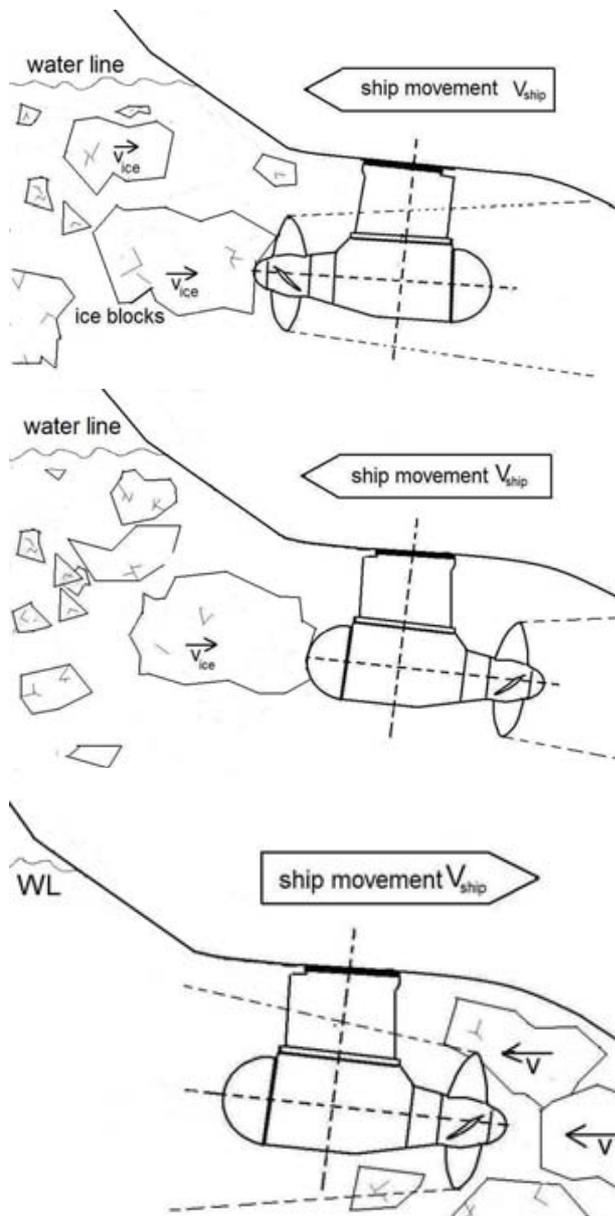


Figure 1. Ice impact load scenario

3.2 Ridge penetration

Ice ridges are common features in ice-covered sea areas. They are formed when sea ice is compressed or sheared under the action of wind and currents. A ridge contains a large number of ice pieces of varying sizes and shapes that are piled arbitrarily. Rubble above the water line is called a sail and the rubble below the water line is called a keel. Between them, close to the waterline, is the re-frozen solid ice zone called a consolidated layer, Figure 2. First-year ridges are often a key consideration from an engineering perspective.

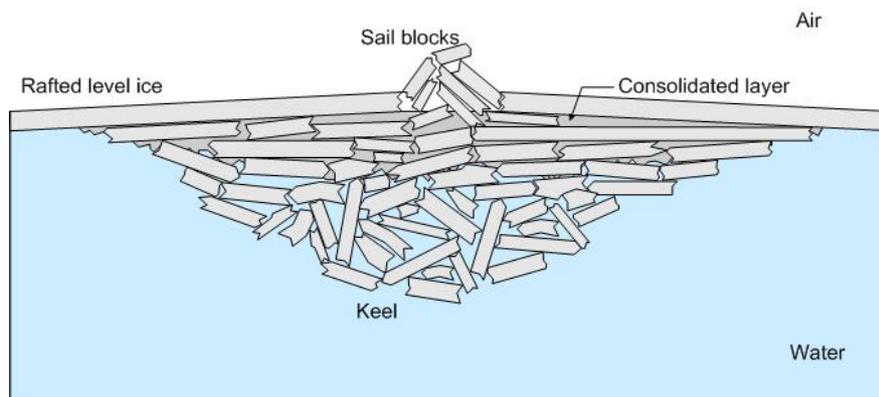


Figure 2. Principal sketch of ice ridge.

The relevant load calculation methods include finite element simulations (FEM) and corresponding ice load predictions according to DNV. Even though the FEM simulation with advanced ice failure model requires very intensive computation and is fairly complicated to use, it gives basic understanding of failure mechanisms of ice and of ice load development during ice-thruster interaction. This approach can then be further utilized for instance to develop a simplified ice pressure distribution model.

The worst scenario to introduce the highest loads on the thruster body was assumed, when the thruster was turned sideways before interacting with an ice ridge (see Fig. 3). The other steering angles can be straightforwardly studied by the FEM-analysis.

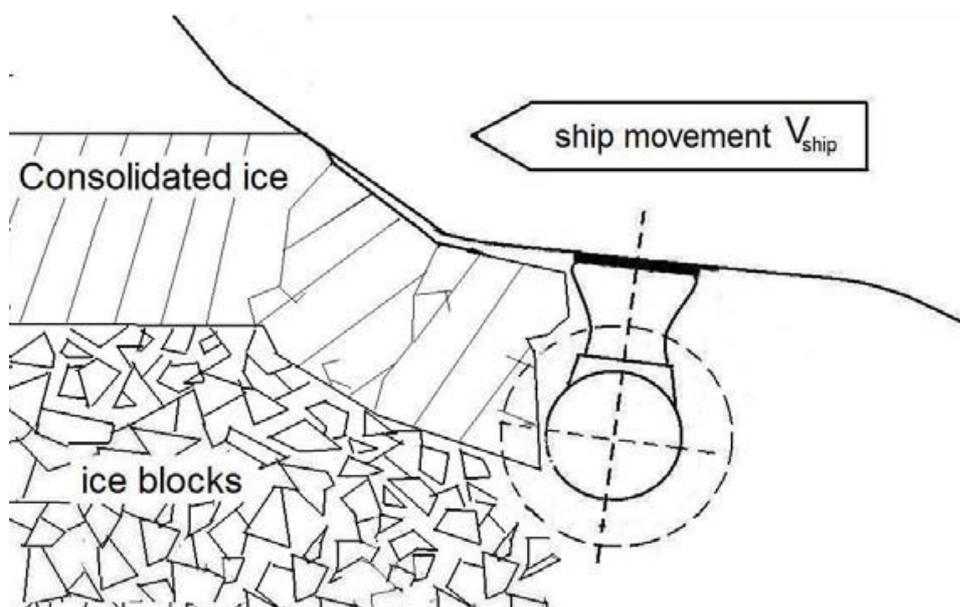


Figure 3. Ridge penetration load scenario.

4. Impact load model development and validation experiments

4.1 Impact model development

The previously used two-mass (thruster and ice) [1] impact model was revised to use three mass system, i.e. model includes ship mass (m_s), flexible connection between thruster and ship (k), thruster mass (m_t), contact model between ice and thruster (F_c) and ice mass (m_i). Principle is shown in Figure 4.

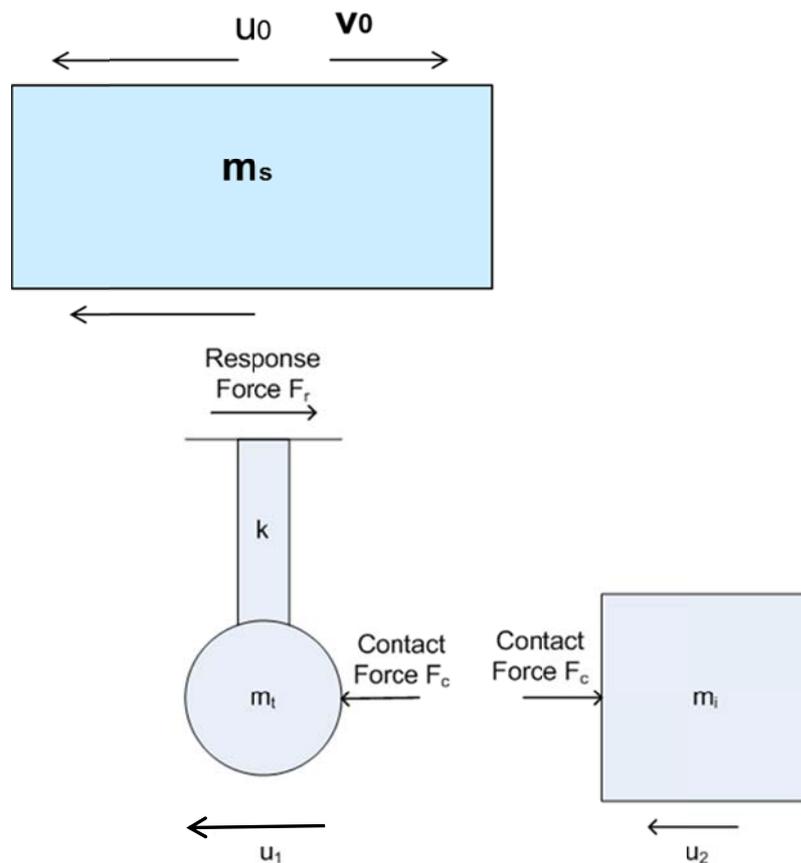


Figure 4. Impact model principle.

The motions of equation can be derived for the three mass system as follows.

4.1.1 Indentation pressure

The contact area grows when thruster structure penetration into ice goes further. This means that the contact force grows according to equation (1) because contact area grows faster than indentation pressure p is decreasing. Contact force F_c is based on indentation pressure and is determined by equation

$$F_c = Ap_0 \sqrt{\frac{A_0}{A}}, \quad (1)$$

where A_0 is a reference area and p_0 is a reference pressure. For Baltic Sea ice 1 m^2 and 3 MPa can be used. The reference pressure can be set to the uniaxial compression strength of ice if it is known. This reference pressure value is the way to control the ice strength parameter in the contact model. Design curve for the indentation pressure and some full scale data points are shown in the Figure 5. Some full scale data points are from m/s Aatos (Huovinen, 1990) and rest of the data is collected from different sources by Bjerkås (2007)

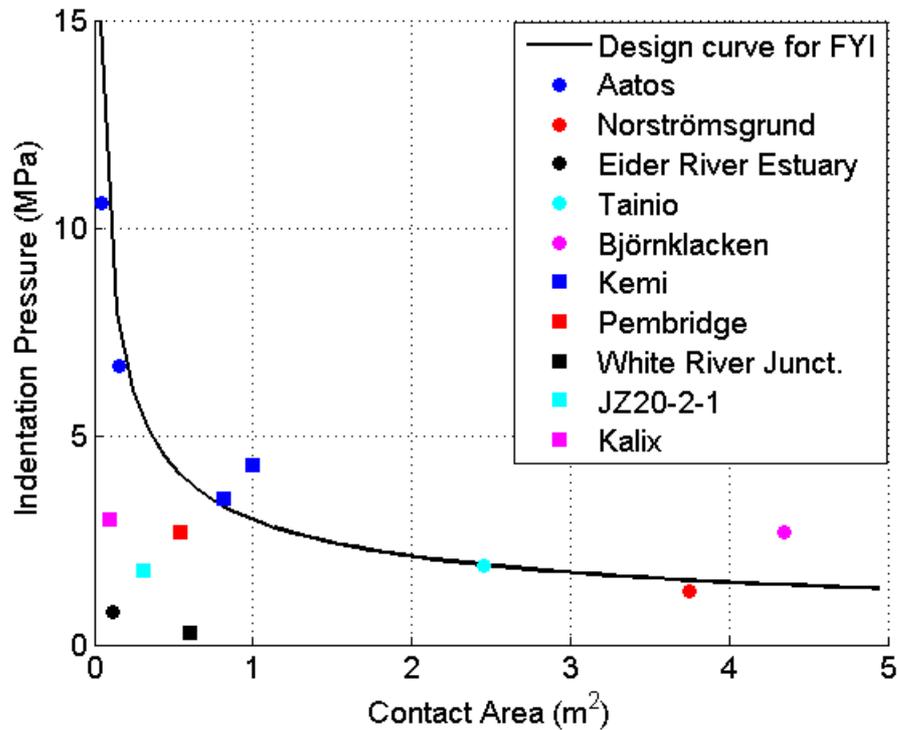


Figure 5. Indentation pressure as a function of contact area.

In the conducted laboratory scale tests on sea ice, a maximum pressure limit for small area contacts is used in the form

$$p_0 \sqrt{\frac{A_0}{A}} \leq p_{lim} \quad (2)$$

The behavior of this limit is presented in principle in Figure 6. The area relationship exponent has also effect on the load behaviour and values of $\frac{1}{2}$ and $\frac{1}{3}$ are also shown.

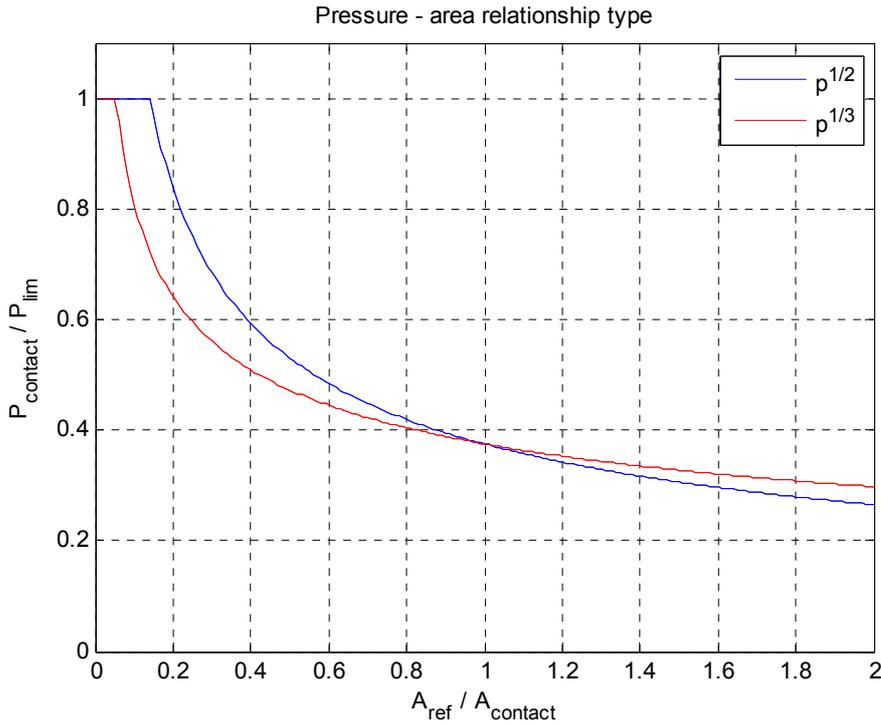


Figure 6. Principle of contact pressure limit for small contact areas.

4.1.2 Description of model

The contact is assumed to take place between a hemispherical section of thruster body ('head') or equally hemispherical propeller hub. For this approach the contact area A is the current contact area, defined by

$$A = \pi(r^2 - (r - u_2 - u_1)^2), \quad (3)$$

where r is radius of curvature of the thruster housing / propeller hub.

During the impact, contact force F_c and response force F_r are defined by equations

$$\begin{aligned} -F_r &= m_s \ddot{u}_0 \\ F_r - F_c &= m_t \ddot{u}_1 + c_1(\dot{u}_1 - \dot{u}_0) + k(u_1 - u_0) \\ -F_c &= m_i \ddot{u}_2 + c_2(\dot{u}_2 - \dot{u}_1) \end{aligned} \quad (4)$$

$$F_c = Ap_0 \sqrt{\frac{A_0}{A}}$$

where m_s is mass of a ship, m_t is mass of the thruster, m_i is mass of the impacting ice block and u_0 , u_1 and u_2 are displacements as shown in Figure 4.

Response force F_r is determined with connection stiffness k and damping c as follows

$$\begin{aligned} F_r &= kx_1 + c\dot{x}_1 \\ x_1 &= u_1 - u_0 \\ \dot{x}_1 &= \dot{u}_1 - \dot{u}_0 \end{aligned} \quad (5)$$

Then, the equations of motion are solved with difference method in direct time domain solution, with the initial conditions for displacement (zero) and velocity v_0 for ship and thruster

$$\begin{aligned}
 u_0(0) &= 0 \\
 u_1(0) &= 0 \\
 u_2(0) &= 0 \\
 \dot{u}_0(0) &= v_0 \\
 \dot{u}_1(0) &= v_0 \\
 \dot{u}_2(0) &= 0
 \end{aligned}
 \tag{6}$$

4.2 Impact experiments purpose and principle

The test setup was done to facilitate controlled impacts to ice for impact model validation. The principle of test is to use a pendulum mass to impact a controlled impact with steel structure into ice. Principle is shown in Figure 7.

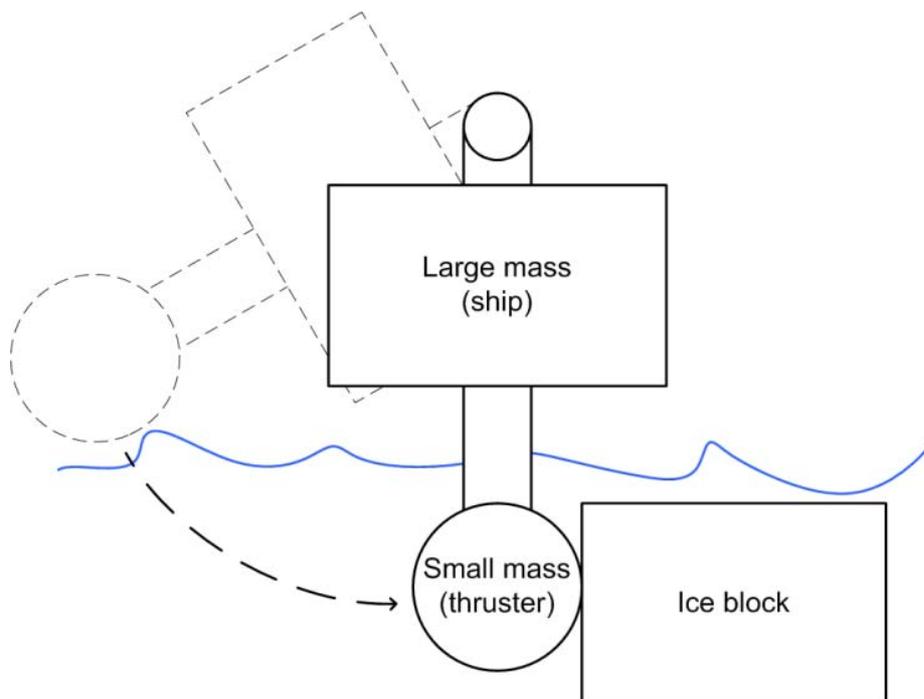


Figure 7. First sketch for impact testing principle.

Measured quantities in the test were ice contact load, acceleration of impact mass and acceleration of ice.

Goal for the test arrangement is to achieve direct information from steel impact to ice, for comparison with calculation model and further development of the model. The test was done in real environment, on sea ice and impact point was submerged, to get all the elements included in test that are acting in real ship application.

4.3 Testing limitations

The limitations known during the testing are

- limited number of impact repetitions at each test condition, thus statistically these results are limited.
- Acceleration sensors on ice and impactor mass indicate contact velocities and displacements through integration of the measured acceleration signal. This is not completely accurate.

4.4 Impact test method

4.4.1 Test rig design and construction

The impact test rig shown in Figure 8 was designed at VTT, manufactured from rectangular section tubing, parts connected with bolt joints. The same test rig was used on field tests in winter 2013 in Espoo as well.

Pendulum impactor is constructed of center plate and additional mass plates are bolted to both sides of centerplate. The center plate is cut from 50 mm steel plate. It is shaped to make it feasible to use as force transducer for impact. Impact head was mounted with a M12 stud to the center plate of pendulum.



Figure 8. Impact test rig on sea ice, March 2014, near Oulu, Finland.

4.4.2 Instrumentation and data acquisition

Data acquisition was done with imc Cronos PL8 measurement front-end, used together with imcDevices software for time data recording to laptop PC. Further analyses were done with imc FAMOS software (ver 6.1 rev 7).

Measured quantities were

- acceleration of impact mass (triaxial acceleration sensor)
- acceleration of ice block (triaxial acceleration sensor)
- force between impact mass and impact head (strain gauges)
- synchronization signal (led light voltage) to be used for video and measurement signal synchronization.

Acceleration was measured with PCB 629A10 type triaxial acceleration sensors. The sensor on impacting mass is seen in Figure 9. The sensor was directly bolted to the impact mass. On ice, a bolt was used for transducer attachment on ice surface.



Figure 9. Acceleration sensor mounted on impact mass. Triaxial sensor X-direction is in direction of impact.

4.5 Measurement results from 2014 tests

The measurements took place near Oulu, Finland, on March 10. – 14., 2014. The ice thickness in the test area was about 50 cm.

4.5.1 Impact force transducer dynamic properties

The force transducer dynamic properties (i.e. lowest natural frequency) were measured by means of experimental modal analysis. Natural frequency in impact direction is used in the impact load model as input to determine the connection stiffness. Measured natural frequencies for the different impact heads are shown in following table.

Table 1. Natural frequencies in measurement

Impact head size	Natural frequency	Damping
mm	Hz	%
100	166,5	0,08
150	151,8	0,11

4.5.2 Ice properties

Ice properties were measured during the field tests on Baltic Sea in Oulu. Level ice thickness varied between 47 cm and 50 cm. In Figure 10 is illustrated the typical structure and temperature of the ice ($T = -0,05 \text{ }^{\circ}\text{C}$). Air temperature during the test was $0 \text{ }^{\circ}\text{C} \pm 1 \text{ }^{\circ}\text{C}$. The salinity of the melted ice in all samples was 0 ‰.

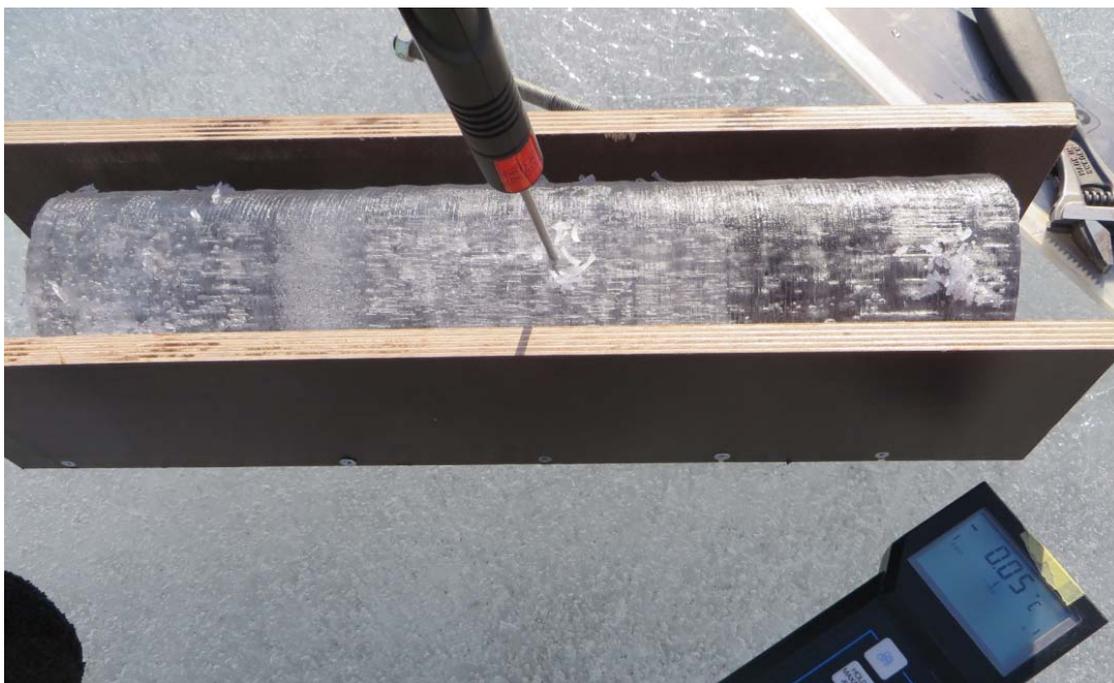


Figure 10. Typical structure and temperature of the ice ($T = -0,05 \text{ }^{\circ}\text{C}$).

4.5.3 Ice compression strength

In total ten (10) ice cores were drilled from the test location and compressed in vertical crystal direction. The compression velocity was 2,1 mm/s. Dimensions of the tested cores were 105 mm (diameter) and 250 mm (length). In Figure 11 one can see drilling and compressing of an ice core.



Figure 11. Drilling and compressing of an ice core.

Results of ice core compression tests and the average value of all ten tests can be seen in Table 2. In Figure 12 the ice core compression test results are illustrated as a graph. Compressive maximum pressure varies from 2,6 to 5,0 MPa. Average value of all ten tests is 3,7 MPa.

Table 2. Results of ice core compression tests.

Test #	Pressure [Mpa]
1	2,7
2	3,5
3	3,6
4	2,7
5	5,0
6	2,6
7	4,7
8	4,1
9	3,7
10	4,7
Average	3,7

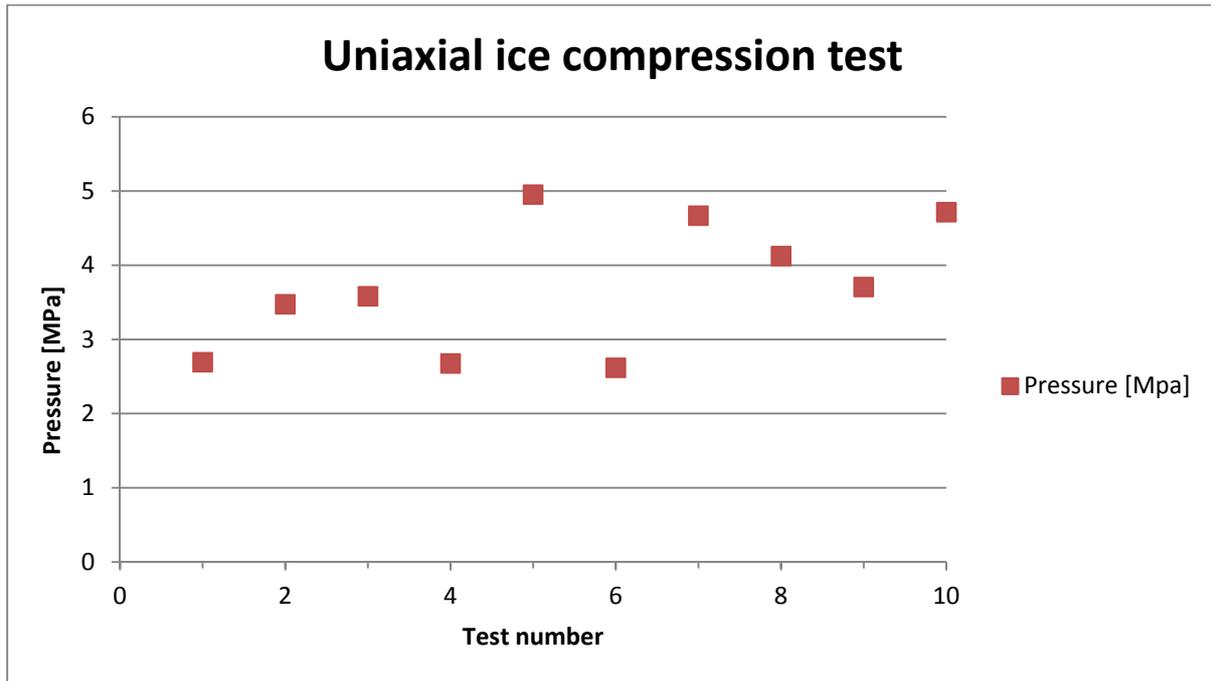


Figure 12. Uniaxial ice compression tests.

4.5.4 Performed impact tests

Tests included impacts to solid ice, and impacts to freely floating ice block of approximately 200 .. 300 kg. The pendulum start height (impact velocity) was kept constant and impact head size was varied.

The height of the pendulum was measured for each impact. The actual measurement was taken between pendulum mass plate mounting bolt and water surface. The pendulum height with respect to rest position (pendulum submerged) is calculated based on the submerging depth of the measurement point (0.310 m). Tests are listed in Table 3.

The pendulum mass was varied in the tests, and the masses are listed in Table 4.

Table 3. List of impact tests, March 2014.

Nr	Date	Time	Test description	Ice temperature C	Mass start height (1) m	Mass start height from water surface m	Ice block kg
1	11.3.2014	16:38	Small head, low speed, solid ice	-0,05	0,285	-0,025	na
2		16:50	Small head, low speed, solid ice	-0,05	0,285	-0,025	na
3		17:02	Small head, low speed, solid ice	-0,05	0,285	-0,025	na
4	12.3.2014	9:27	Small head, low speed, solid ice	-0,05	0,285	-0,025	na
5	12.3.2014	10:14	Small head, low speed, ice block	-0,05	0,285	-0,025	302
6		10:26	Small head, low speed, ice block	-0,05	0,285	-0,025	272
7		10:40	Small head, low speed, ice block	-0,05	0,285	-0,025	242
8	12.3.2014	11:33	Big head, low speed, ice block	-0,05	0,285	-0,025	242
9		11:37	Big head, low speed, ice block	-0,05	0,285	-0,025	242
10		11:48	Big head, low speed, ice block	-0,05	0,285	-0,025	212

(1 Mass start height is relative to pendulum mass lowest position)

Table 4. Pendulum masses in impact tests, March 2014.

Test ID	Baseplate + mass plates				Impact head					Pendulum total kg
	Base plate kg	Mass plate kg	Pcs	Total kg	Size mm	Mass kg	Mass plate kg	Pcs	Total kg	
1..4	42	14,7	10	147	100	2	2	5	12	201
5..7	42	14,7	4	58,8	100	2	2	5	12	112,8
8..10	42	14,7	4	58,8	150	6	2	3	12	112,8
Pendulum total = baseplate + mass plates + impact head + impact head mass plates										

4.6 Impact load calculation and comparison to measurement

4.6.1 Initial values for impact load calculation

The dynamic model needs input values of ice mass, contact pressure value, impact initial speed, impactor mass and stiffness properties (ship mass, thruster mass and stiffness between these) and the radius of assumed impacting steel hemisphere.

Based on the experiments, the initial impact velocity can be determined from acceleration measurement on pendulum and ice. Other values are static input values and can be determined directly.

Initial velocity for impact model load calculation is given as “ship speed”. The model limits the impact calculation by observing the kinetic energy of ice block. It is assumed that maximum energy available for ice crushing is the kinetic energy of ice block at the impact velocity.

4.6.2 Ice model parameters for impact model

Impact load calculation parameters that gave good correspondence to measurement with 2013 and 2014 tests are listed in table below.

In 2013 experiment, the ice was softer than in 2014 experiments, also by quantitative estimate on test site.

Table 5. Dynamic impact load model parameters for good fit to experiment

Parameter	Unit	Value 2013	Value 2014	Notes
σ_{ice}	MPa	3	3,7	Ice uniaxial compression strength
p_{lim}	MPa	8	10	Pressure-area relationship maximum pressure value for small area contacts
exponent	-	1/3	1/3	Pressure-area relationship exponent

4.6.3 Impact measurement and calculation results: 2014 test cases

The dynamic impact model was used to calculate loads for experiment cases. Following figures show the results with 2014 experiment.

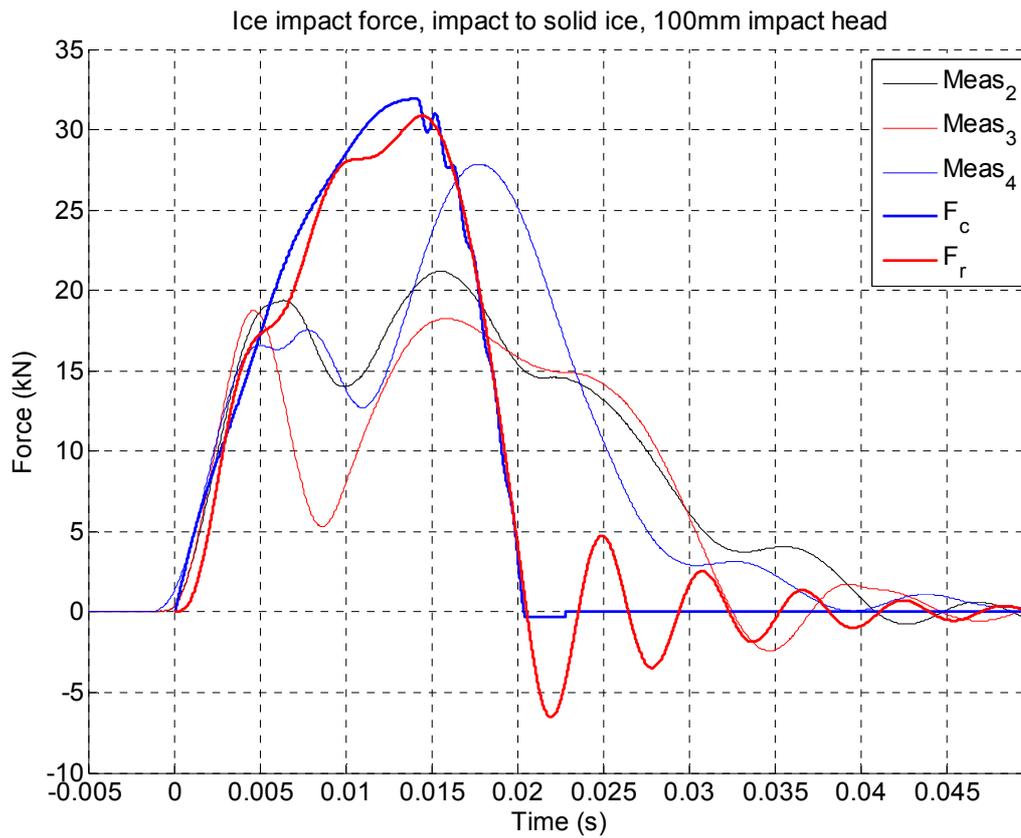


Figure 13. Impact load measurement and calculated impact loads for test cases 2-4, impact to solid ice with 100 mm impact head. Fr curve is calculated response load curve.

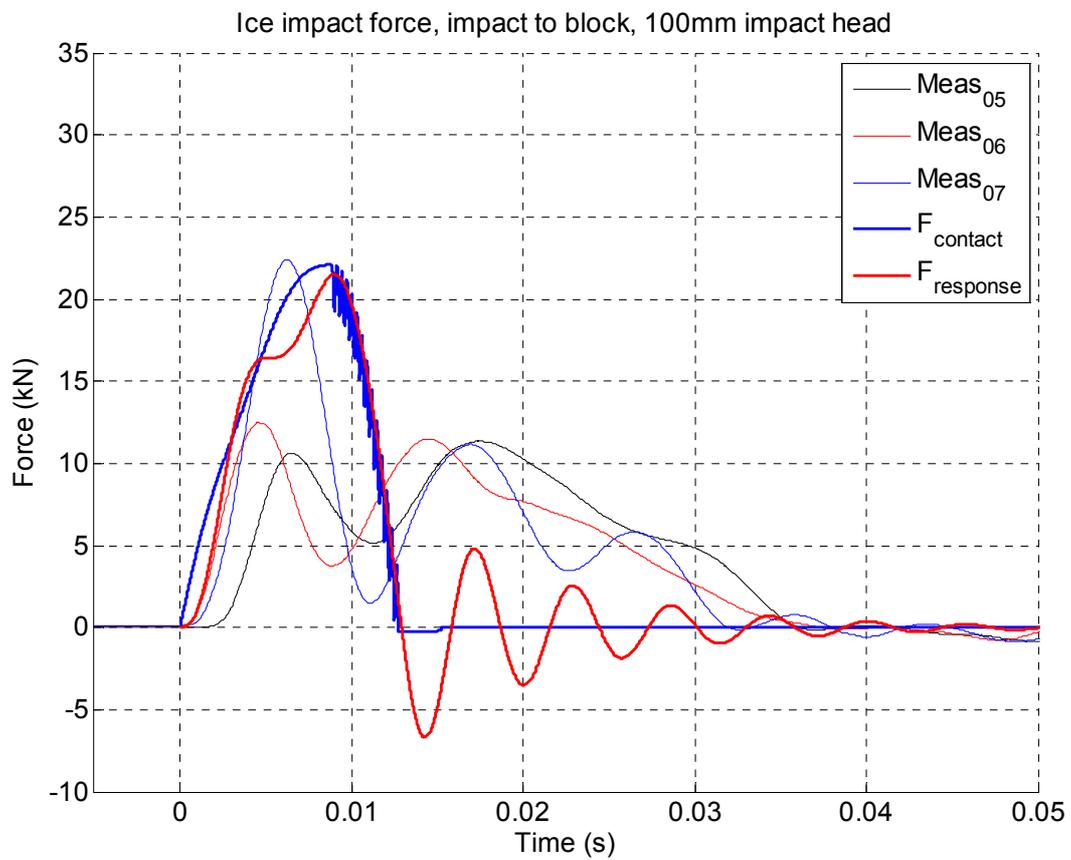


Figure 14. Impact load measurement for test cases 5-7 and respective load calculation. 100 mm impact head, F_r curve is calculated response load curve.

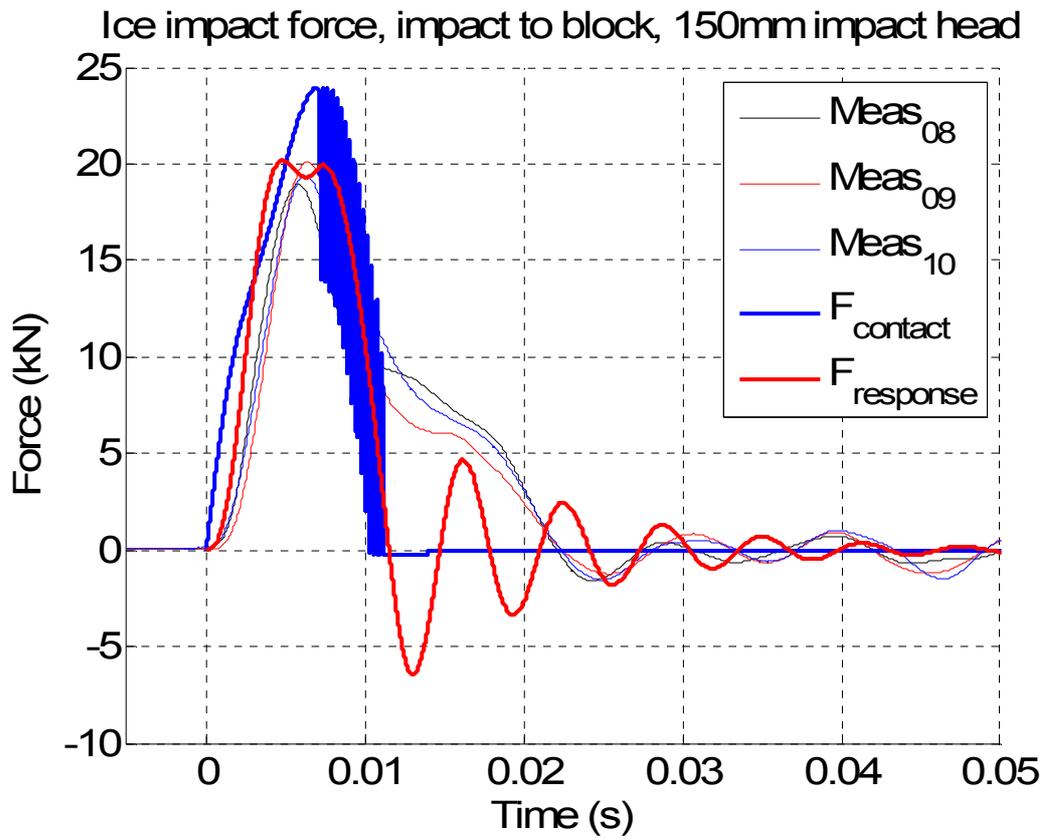


Figure 15. Impact load measurement for test cases 8-10 and respective load calculation. 150 mm impact head, .Fr curve is calculated response load curve.

4.6.1 Impact measurement and calculation results: 2013 test cases

The measured impact loads from 2013 tests and respective calculated loads with dynamic impact model are shown in following figures.

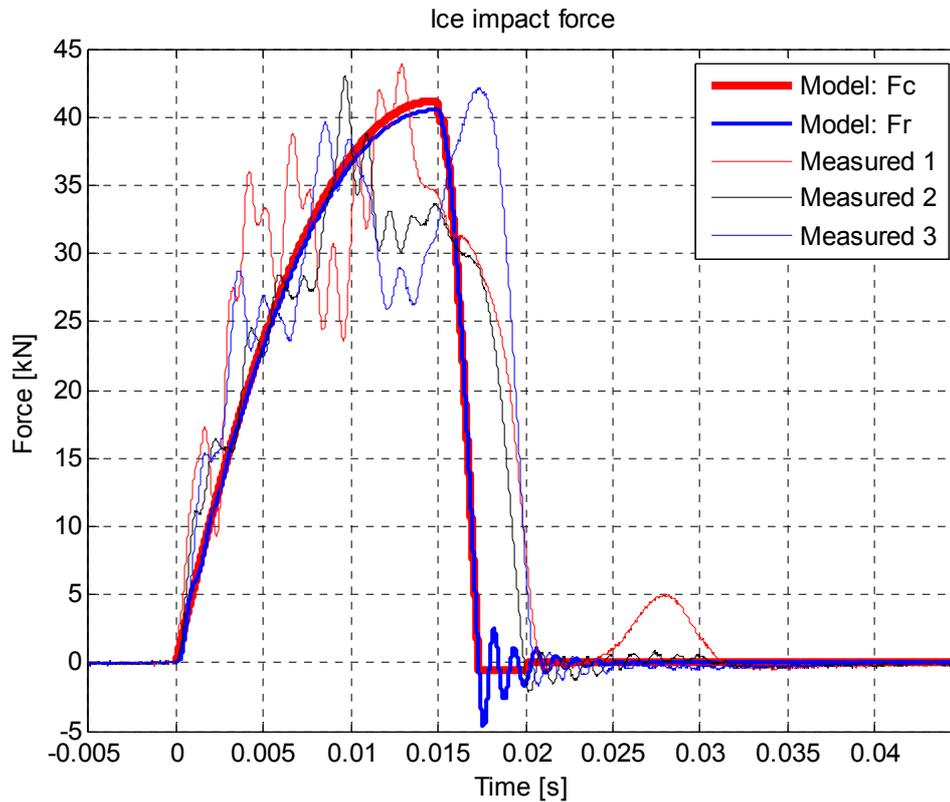


Figure 16. Impact load measurement and calculated impact loads for 2013 experiment test cases 1-3, impact to solid ice with 100 mm impact head. Model:Fc curve is calculated contact load and Model:Fr curve is calculated response load curve.

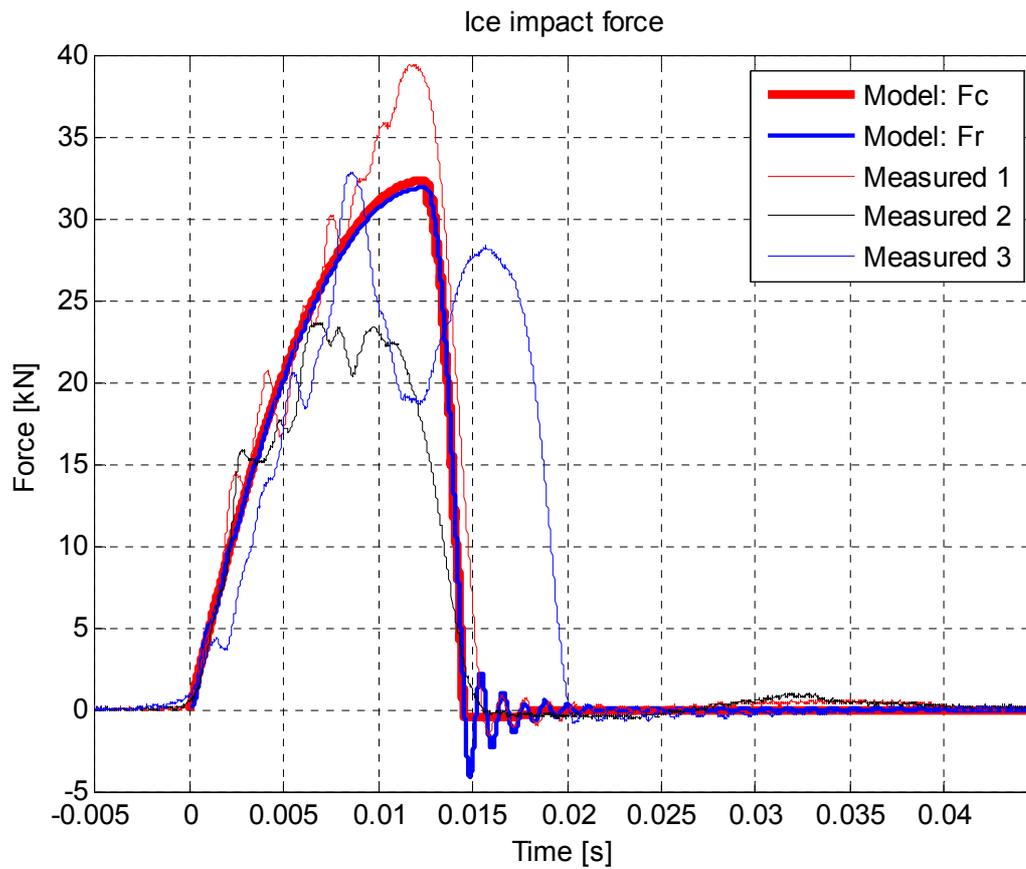


Figure 17. Impact load measurement for 2013 experiment test cases 4-6 and respective load calculation. 100 mm impact head, start height 0.11m above ice level, 400 kg ice block. Model:Fc curve is calculated contact load and Model:Fr curve is calculated response load curve

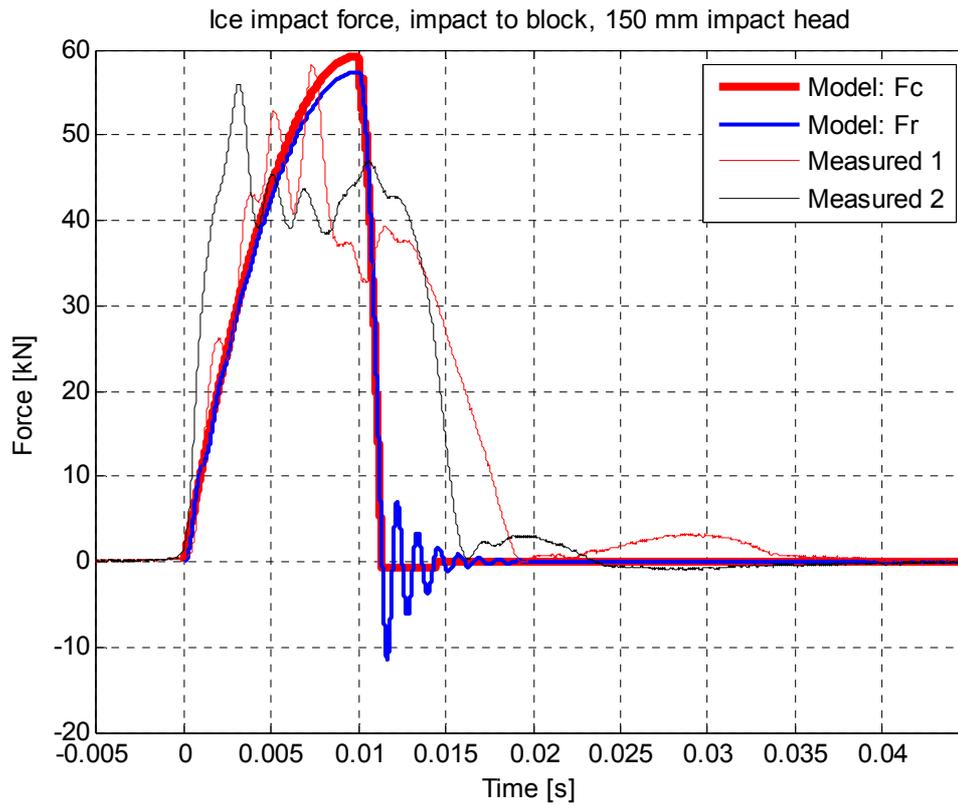


Figure 18. Impact load measurement for 2013 experiment test cases 7-8 and respective load calculation. 150 mm impact head, start height 1.28m above ice level, 400 kg ice block. Model:Fc curve is calculated contact load and Model:Fr curve is calculated response load curve

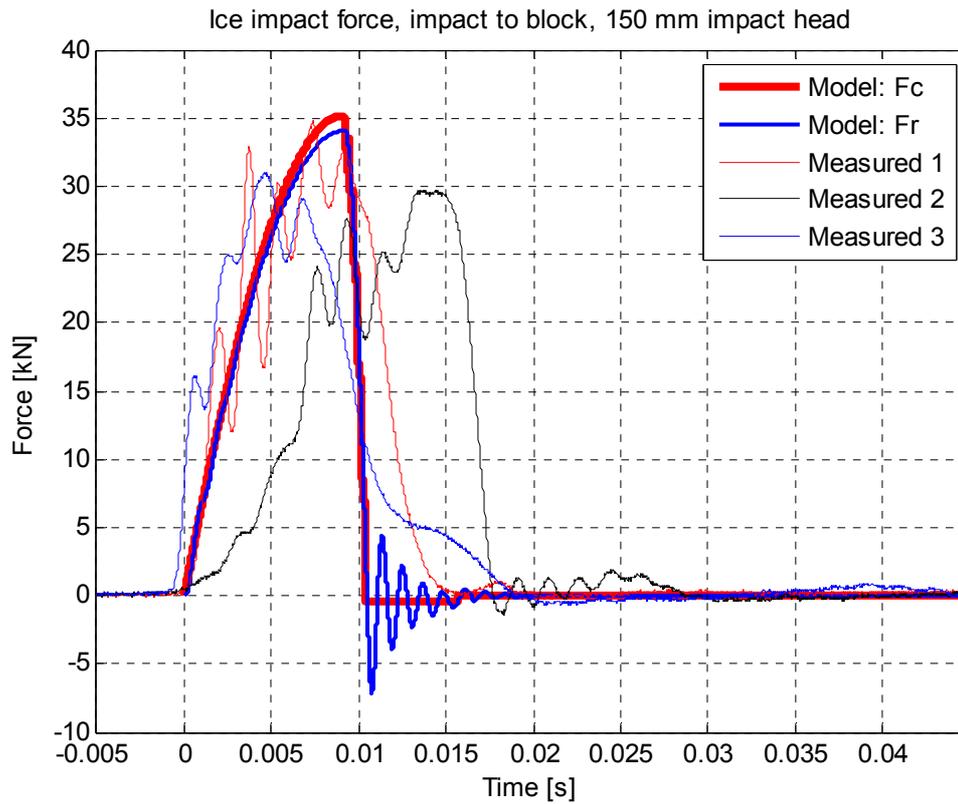


Figure 19. Impact load measurement for 2013 experiment test cases 9-11 and respective load calculation result. 150 mm impact head, start height 0.11 m above ice surface, 300 kg ice block estimated. Model:Fc curve is calculated contact load and Model:Fr curve is calculated response load curve.

4.7 Simplified impact load model

The simplified impact load model is assumed to be, in general, function of ice block mass, impact velocity, contact area, thruster flexibility and ice strength.

$$F_{impact} = f(m_{ice}, v_{impact}, A_{contact}, f_{thruster}, \sigma_{ice}) \quad (7)$$

The simplified model is achieved in following way

1. Developed the dynamic impact contact load model
2. Dynamic impact load model validation with experiments
3. Parametric study with the validated dynamic impact load model
4. Regression fit of simplified formulation to the parametric study results

The formation of the simplified formula was an iterative process, where different forms of formula were tested with least squares fit to the dynamic impact load model parametric study result set.

From testing several forms of simplified models, a good candidate for estimating the impact contact load is

$$F_{impact} = b_2 R^{1/b_1} (m_{ice} * v_{impact}^2)^{1/b_3} \quad (8)$$

The model variables are

- R : The impacting steel hemisphere radius, in meters
- m_{ice} : the impacting ice block mass, in kg
- v_{impact} : The impact initial speed, in m/s

The model in equation 11 was used in MATLAB regression analysis tool, and fitting the model to the parametric study data set achieved with dynamic impact model gives following results:

Nonlinear regression model:

$$F_c \sim (\text{Radius}^{(1/b_1)}) * b_2 * (\text{Mass}_{ice} * \text{Velocity}^2)^{(1/b_3)}$$

Estimated Coefficients:

	Estimate	SE	tStat	pValue
b1	2.1174	0.016651	127.17	0
b2	34653	867.65	39.938	3.2622e-265
b3	3.0962	0.017691	175.02	0

Number of observations: 2295, Error degrees of freedom: 2292

Root Mean Squared Error: 2.41e+05

R-Squared: 0.97, Adjusted R-Squared 0.97

F-statistic vs. zero model: 8.65e+04, p-value = 0

This means that the simplified model would be

$$F_{impact} = 34653R^{1/2.1174}(m_{ice} * v_{impact}^2)^{1/3.0962} \quad (9)$$

The decimals can be rounded off for the ice class rule proposal version of the simplified formula as follows

$$F_{impact} = 34500R^{1/2}(m_{ice} * v_{impact}^2)^{1/3} \quad (10)$$

Testing the simplified formulation results are compared to the dynamic contact load model results in Figure 20. On X-axis is the dynamic load model contact load estimate, and on Y-axis is the corresponding simplified load model result. Blue circles show the model with decimals and the black circles show the results with the proposed ice class rule formulation for impact contact load.

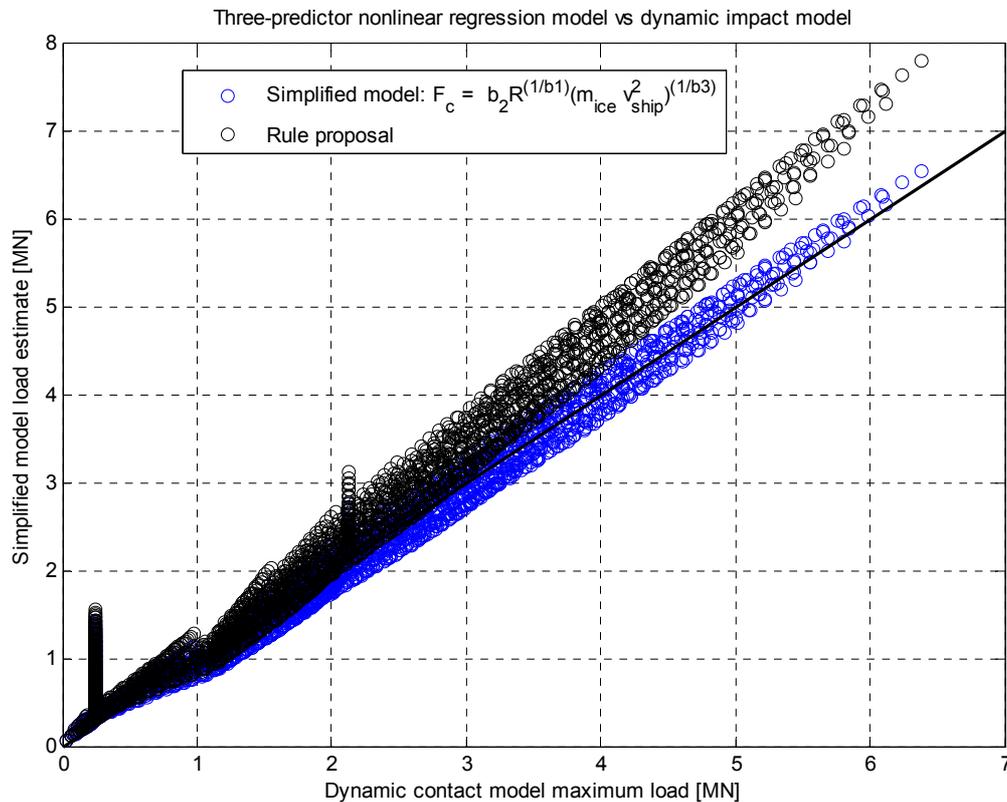


Figure 20. Simplified impact contact load model results (blue circles), the rule proposal formulation impact contact load model results (black circles) as a function of the dynamic impact contact load model results. Results are calculated with same input values.

4.8 Simplified impact load model application for full scale

The example application of the impact load model for full scale is presented in Table 6.

The impact contact load is estimated based on ice class dependent parameters and known thruster impacting part radius. The response load at the thruster connection to ship is estimated to be 1,5 times the contact load. The estimate is based on approximated dynamic magnification in impact.

Table 6. Example application of ice impact load estimate with the simplified load formula. Two vessels, assumed that thruster hits longitudinally into ice block.

Ice block impact contact load calculated with simplified impact load model					
		I A Super	I A	I B	I C
Ice block mass	kg	28940	18225	9330	5400
Impact speed for longitudinal loads	kn (m/s)	12 (6,17)	10 (5,14)	10 (5,14)	10 (5,14)
Fennica					
Impacting part radius (thruster end cap)	m	1,2	1,2	1,2	1,2
Longitudinal impact contact load	MN	3,90	2,96	2,37	1,97
Longitudinal response	MN	5,85	4,44	3,55	2,96
Botnica					
Impacting part radius (thruster end cap)	m	0,8	0,8	0,8	0,8
Longitudinal impact contact load	MN	3,19	2,42	1,93	1,61
Longitudinal response	MN	4,78	3,63	2,90	2,42

4.9 Impact load calculation summary

It can be concluded that the developed dynamic impact load calculation model, with three-mass system including ice-thruster contact model and flexible connection between thruster and ship, is capable of estimating the contact load rather well. The results presented in this document for the small scale experiment support this as well as previous work with full scale data verification [1,2].

The effect of damping during impact contact event is not yet properly modelled in the simplified impact model and is a point for further study. Tailored experiments are preferred way for establishing the proper understanding for damping in this case.

The developed dynamic load calculation model can be used as load calculation tool for estimating the effect of different parameters to impact load, when developing simplified formulation for ice class rule proposal.

With the dynamic impact load model, a parameter study was done. The input values and corresponding dynamic contact load result were used to formulate a simplified impact contact load formula.

The simplified formula includes term for impact kinetic energy, contact area size and constants. The constants were determined by nonlinear regression model fitting. The used regression fit tool was MATLAB nonlinear model fit.

The resulting simplified model was checked by comparing the simplified load formula results with dynamic model results and full scale applications. The simplified load model gives same level of load as the validated dynamic impact contact load model.

The simplified impact load model described here was distributed to the project steering group members for review purposes, and is therefore not final, subject to revision.

5. Ship interaction with ice ridge

5.1 Goal

The research goal was to clarify the contact pressure distribution of the thruster body and present a simplified calculation method for contact pressure and thruster total force. The results are compared to available full scale data for validation purposes.

5.2 Method

The ship interaction with ice ridge is simulated with a numerical finite element method. FEM-model is created from a ship and different ice ridges. The FEM simulations are validated with full scale measurements performed on ice breaker Fennica in 1994 [2].

5.3 Model introduction

5.3.1 Ice ridge

The three ridge types used in the simulations are called mild, typical and extreme. Total ridge height was 3.6 m (mild), 5.0 m (typical) and 10.0 m (extreme). Figure 21 shows the dimensions of ridge.

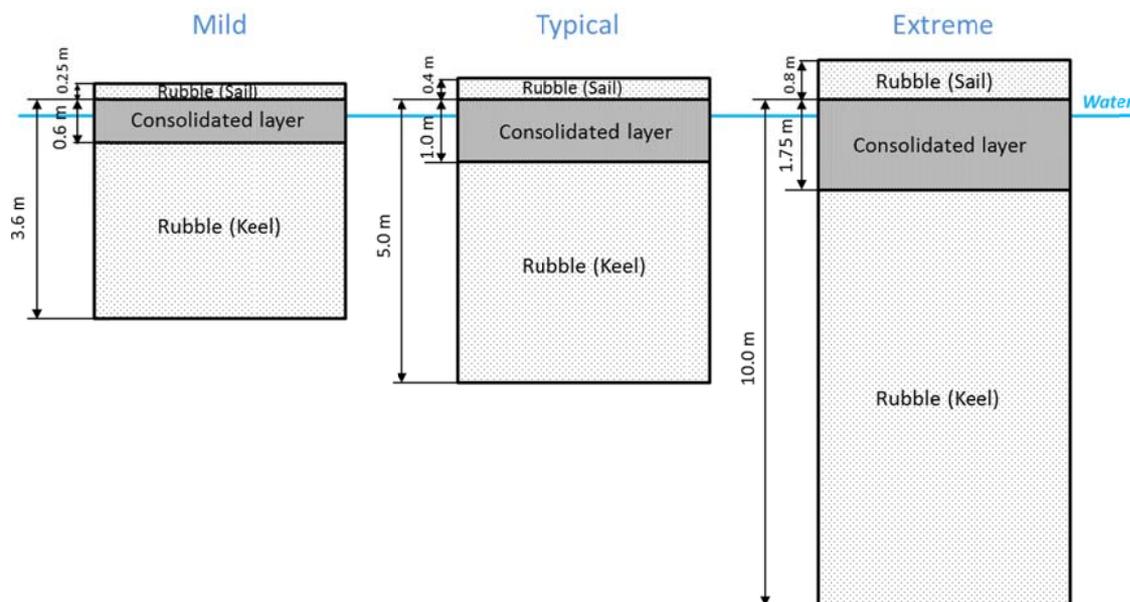


Figure 21. Ice ridges for ship interaction.

5.3.2 Ice properties

The consolidated layer was divided in FE model into three (mild ridge), five (typical) or nine (extreme) layers in the thickness direction. Mechanical properties: elastic modulus, compressive and tensile strength were varied randomly such that each layer consisted of ten different material properties with the same mean and standard deviation as obtained in the material tests.

Concrete Damaged Plasticity –model (CDP) was applied to simulate the failure of the consolidated layer. Mechanical properties of consolidated layer are listed in Table 7, Table 8 and Table 9. Ice density was $\rho = 900 \text{ kg/m}^3$. Tensile strength was about 8 % from compression strength.

Table 7. Consolidated layer ice properties, mild ridge.

Depth [m]	E_{ave} [GPa]	E_{stdev} [GPa]	$S_{c,ave}$ [MPa]	$S_{c,stdev}$ [MPa]
0.100	0.7655	0.2948	3.9092	1.2238
0.300	0.8441	0.2829	4.1934	0.7482
0.500	0.0916	0.0360	1.0498	0.2842

Table 8. Consolidated layer ice properties, typical ridge.

Depth [m]	E_{ave} [GPa]	E_{stdev} [GPa]	$S_{c,ave}$ [MPa]	$S_{c,stdev}$ [MPa]
0.100	0.7047	0.311	3.5218	1.3015
0.300	0.9418	0.33	4.9764	1.1171
0.500	0.8441	0.2829	4.1934	0.7482
0.700	0.5322	0.2036	2.7092	0.5307
0.900	0.0881	0.029	1.1032	0.3376

Table 9. Consolidated layer ice properties, extreme ridge.

Depth [m]	E_{ave} [GPa]	E_{stdev} [GPa]	$S_{c,ave}$ [MPa]	$S_{c,stdev}$ [MPa]
0.0972	0.6992	0.322	3.48	1.3224
0.2917	0.7655	0.2948	3.9092	1.2238
0.4861	0.9125	0.3242	4.7985	1.1349
0.6806	0.9074	0.3088	4.6729	0.9444
0.8750	0.8441	0.2829	4.1934	0.7482
1.0694	0.7383	0.2711	3.5709	0.6593
1.2639	0.4546	0.1742	2.4157	0.4862
1.4583	0.0916	0.036	1.0498	0.2842
1.6528	0.0857	0.0243	1.1387	0.3731

Cohesion value and friction angle of the ice rubble are $d = 6000 \text{ N/m}^2$ and $\beta = 35^\circ$. Density of ice rubble is $\rho = 642 \text{ Kg/m}^3$, elastic modulus is $E = 1.1\text{e}+08 \text{ N/m}^2$. Poisson's value $\nu = 0.3$ and friction coefficient in ice-structure contact $\mu = 0.15$.

5.3.3 Thrusters and hull

Ship hull shape is from Fennica ice breaker. Ship hull length was 116.0 m, width 26.0 m and draught 12.5 m. The mass of the ship varied according to the propeller size (see Table 10).

Also thruster's shape was same as Fennica, but it was without the nozzle in the simulations. Fennica thruster's diameter was 2.40 m and length 5.60 m. Propeller diameter was 4.20 m and number of blades was 4. In simulation, thruster size was scaled on the coefficient 0.5, 1.0, 1.5 or 2.0 (simulation cases 2 m, 4 m, 6 m and 8 m propeller size). Shape of the thruster and hull is shown in Figure 22 and thruster size in Figure 23.

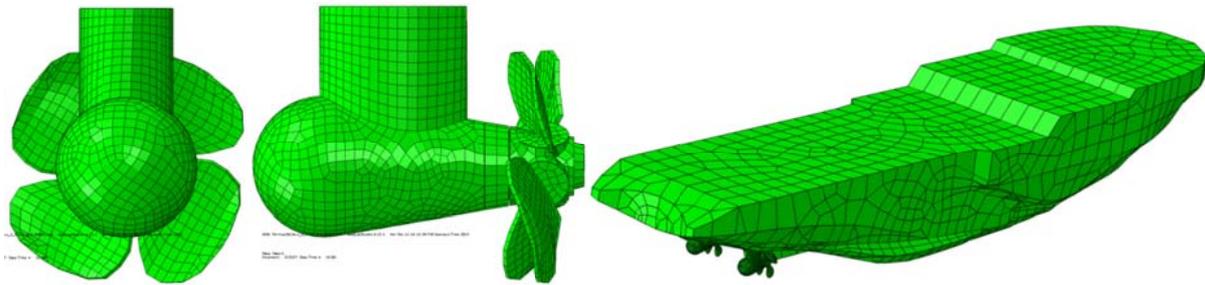


Figure 22. Thruster and hull shape.

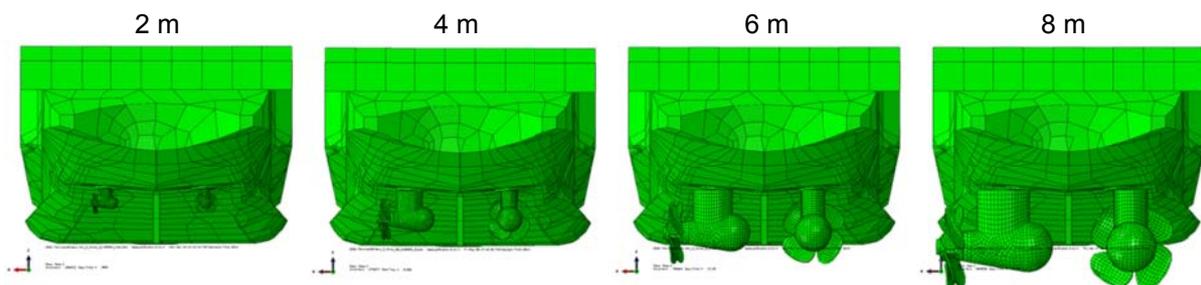


Figure 23. Different thruster size, simulation cases 2 m, 4 m, 6 m and 8 m.

Table 10. Total ship mass on the different propeller size.

Propeller size	Ship mass
2 m	1.22e+06 kg
4 m	9.76e+06 kg
6 m	3.29e+07 kg
8 m	7.81e+07 kg

Figure 24 introduces the used FEM-model. Middle part of the model was discretized with dense element mesh and the far-end boundary region with sparse mesh. A dense element mesh size was 400 – 500 mm and sparse mesh 1.0 - 2.5 m. Infinity element size in the edge was 20 - 40 m. In vertical direction the element size in the sail was 125 - 200 mm, in the consolidated layer 194 - 200 mm and in the rubble 375 – 400 mm. The model size was 100 x 200 m to 200 x 200 m, dense mesh area 25 - 100 m and sparse mesh area 10 - 35 m. The number of elements in the model was 240000 - 430000.

Numerical simulations were performed by Abaqus/explicit 6.12.1 program. Element types were C3D8R (ice), CIN3D8 (ice infinity), R3D3 and R3D4 (hull, thruster and propeller). The hull, thruster and propeller were assumed fully rigid. Simulation time was 5 - 30 s.

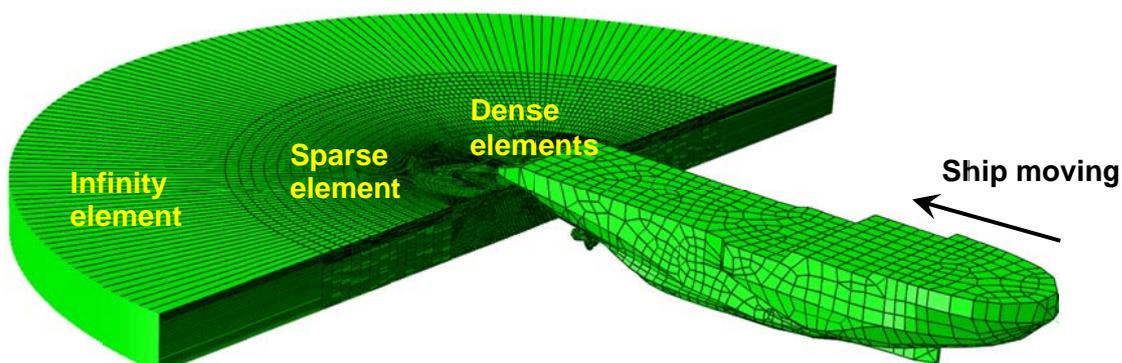


Figure 24. Fem-model.

5.4 Parameter variation

Simulation variables were:

- ridge type: mild, typical or extreme
- ship initial speed: 5, 8 or 12 knot
- propeller size: 2, 4, 6 or 8 m
- thruster angle: -180° or -90°.

In the model there were two thrusters. One straight ahead to ice, one sideways. In total, there were 24 simulation cases. In addition to the previous, some 180°/180° simulations were made. Part of the simulation (4 m propeller) was done 2013. The target simulation cases are listed in Table 11.

Table 11. Parameters for FEM model studies.

Ship speed [knot]	Ridge size	Thruster angle [°]	Propeller diameter [m]	Notes
5	Mild	180 / 90	2	<i>Done 2013</i>
	<i>Mild</i>	<i>180 / 90</i>	4	
	Mild	180 / 90	6	
	Mild	180 / 90	8	
	Typical	180 / 90	2	
	<i>Typical</i>	<i>180 / 90</i>	4	
	Typical	180 / 90	6	
	Typical	180 / 90	8	
	Extreme	180 / 90	2	
	<i>Extreme</i>	<i>180 / 90</i>	4	
	Extreme	180 / 90	6	
	Extreme	180 / 90	8	
8	Mild	180 / 90	2	<i>Done 2013</i>
	<i>Mild</i>	<i>180 / 90</i>	4	
	mild	180 / 90	6	
	Typical	180 / 90	2	
	<i>Typical</i>	<i>180 / 90</i>	4	
	Typical	180 / 90	6	
	Extreme	180 / 90	2	
	<i>Extreme</i>	<i>180 / 90</i>	4	
Extreme	180 / 90	6		
12	Mild	<i>180 / 90</i>	4	<i>Done 2013</i>
	Typical	<i>180 / 90</i>	4	<i>Done 2013</i>
	Extreme	<i>180 / 90</i>	4	<i>Done 2013</i>

The energy available for ship penetrating into ice ridge is the kinetic energy of the vessel before ice ridge – ship interaction event. This principle gives possibility to use same ship size for 2014 ridge penetration simulations that was used before. For example, the Fennica simulations (and full scale tests) were done at 5, 8 and 12 knots initial velocity. When ship mass is four times Fennica's mass, the equal kinetick energies are available at 2.5, 4 and 6 knots. Table 10 shows the ship mass on the different propellers.

For parameter variations, the initial speed is now taken to be as 5 knots, because this seems reasonable speed for merchant vessels, that are of similar size with IB Fennica. For smaller vessels, speed may be higher, for bigger vessels, speed may be lower.

5.5 Calculation

In simulation the ship was moving towards the ridge (Figure 24). The ship has an initial speed and ship speed slows down when it penetrates to ice ridge due to the resistance force during penetration. This simulation is considered to correspond to ramming into ice ridge. The contact pressures of thrusters are obtained as results of simulations. Result time histories were printed at 0.005 s intervals.

Only the port side (left) thruster is turned, the starboard side (right) thruster remains unchanged. Table 12 introduces used thruster angles and moving direction.

Table 12. Thruster angles and moving direction.

Angles	Port side thruster	Starboard side thruster
-90° / -180°		



In the calculation of the contact pressure the thrusters is divided into several slices. The upper part was divided into three and the lower part into five slices, see Figure 25 for slicing principle. The average contact pressure is calculated for the area of each slice.

The contact pressure is based on the node forces of the FEM-model. The nodes belong to some slice on the basis of the height coordinate.

Average contact pressure for thruster body p_i is

$$p_i = \frac{F_i}{A_i} \quad (1)$$

where F_i is sum of node forces in slice i
 A_i is surface area (perpendicular, projected area) in slice i .

The ice-structure contact forces acting on propeller area (see Figure 25) are not included in calculation of the average contact pressure for thruster body. The net contact force for propeller is summed separately according to the slice. Propeller loads are used for calculation of the thruster total force.

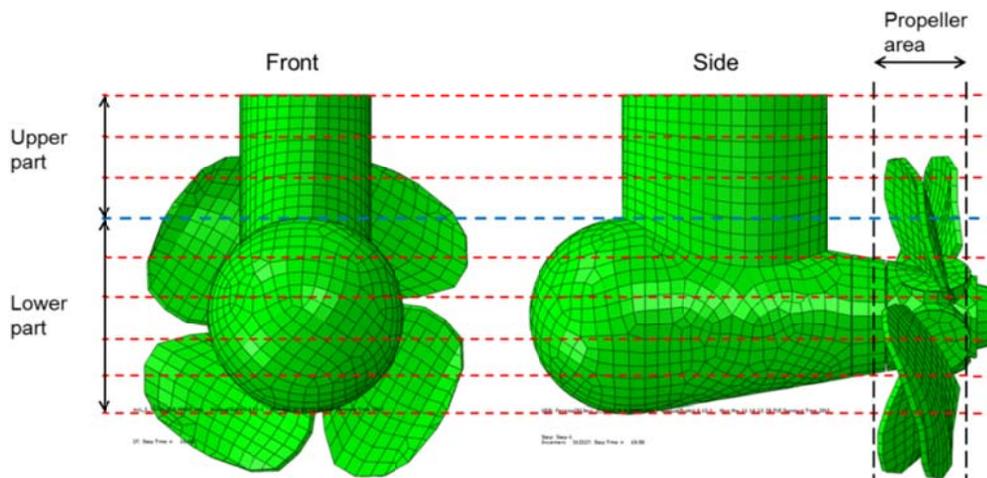


Figure 25. Division of the thruster into the slice. The slice numbering is below to up.

5.6 Results

5.6.1 Thruster forces

The total forces of the thrusters were calculated in all cases. Direction of the force is horizontal (moving direction). Simulated results contained some high frequency numerical disturbances which were filtered away with 15 Hz low-pass filter (Butterworth 8th order low pass filter with 15 Hz cut-off frequency).

Table 13 shows maximum simulated force of the thruster included or not propeller force. In cases where several simulations of same case have been done, linear average has been calculated from the results.

The total force increases approximately linearly as a function of the speed and ridge thickness (Figure 26). Also, turning the thruster to the transverse position (-90°) increases the force typically 20 – 30 % compared to the longitudinal position (-180°) if propeller force is included..

Table 13. Maximum simulated total forces of the thrusters. Force is ship moving direction. No include short-term peak values.

Ridge	Speed	Propeller	Thruster force [MN] No propeller force		Thruster force [MN] Include propeller force	
			Angle -180°	Angle -90°	Angle -180°	Angle -90°
Mild	5 knot	2 m	0.4	0.4	0.4	0.5
		4 m	0.8	0.7	0.8	1.0
		6 m	1.2	1.1	1.2	1.8
		8 m	2.1	2.3	2.1	2.7
	8 knot	2 m	0.6	0.5	0.6	0.7
		4 m	1.3	1.0	1.3	1.4
		6 m	2.2	1.7	2.2	2.8
12 knot	4 m	1.9	1.3	1.9	2.0	
Typical	5 knot	2 m	0.6	0.4	0.6	0.7
		4 m	1.1	1.3	1.2	1.7
		6 m	1.9	1.9	2.0	2.6
		8 m	3.8	3.8	4.0	4.6

	8 knot	2 m	0.7	0.6	0.7	1.0
		4 m	1.2	1.5	1.3	2.2
		6 m	2.9	2.8	3.0	4.0
	12 knot	4 m	2.2	1.8	2.5	3.3
Extreme	5 knot	2 m	0.6	0.6	0.6	1.1
		4 m	1.9	1.7	1.9	2.8
		6 m	2.8	3.4	3.7	4.8
		8 m	6.5	8.1	6.5	8.8
	8 knot	2 m	0.9	0.8	0.9	1.3
		4 m	2.5	2.3	2.5	3.6
		6 m	5.2	5.7	5.6	7.2
	12 knot	4 m	3.3	3.5	3.3	5.0

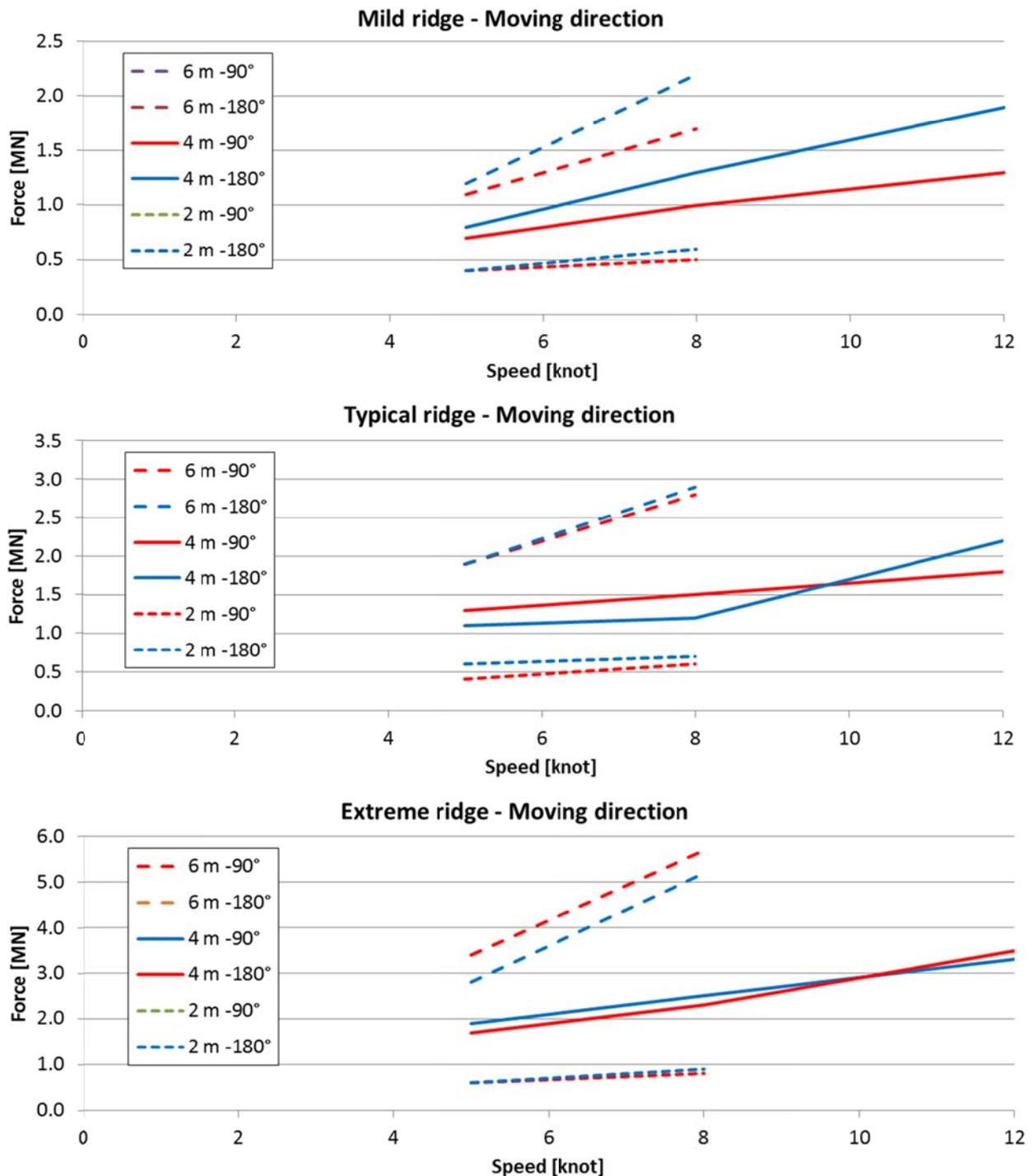


Figure 26. Effect of the ship initial speed on the thruster force on different ridge types. Values not include propeller force nor short-term peak values.

5.6.2 Thruster pressure distribution

From the simulation results the contact pressures were calculated according to chapter 5.5. Figure 27 is shown typical maximum thruster pressure distributions according to the slice, longitudinal or transverse position of the thruster.

For the longitudinal thruster position (thruster angle -180°), the maximum contact pressures are located usually in slice 3 to 7, according cases. Small thrusters (2 m and 4 m) maximum

pressure is located lower (slice 3 or 4). Large thruster (8 m), maximum pressure is located upper part of the thruster.

When thruster is sideways in ramming situation, (transverse position -90°), maximum contact pressure is located in the upper part, in slice 6 or 7. Generally, the contact pressure reduces linearly downwards. Level of the contact pressure is typically 50 % compared to pressure of the longitudinal position.

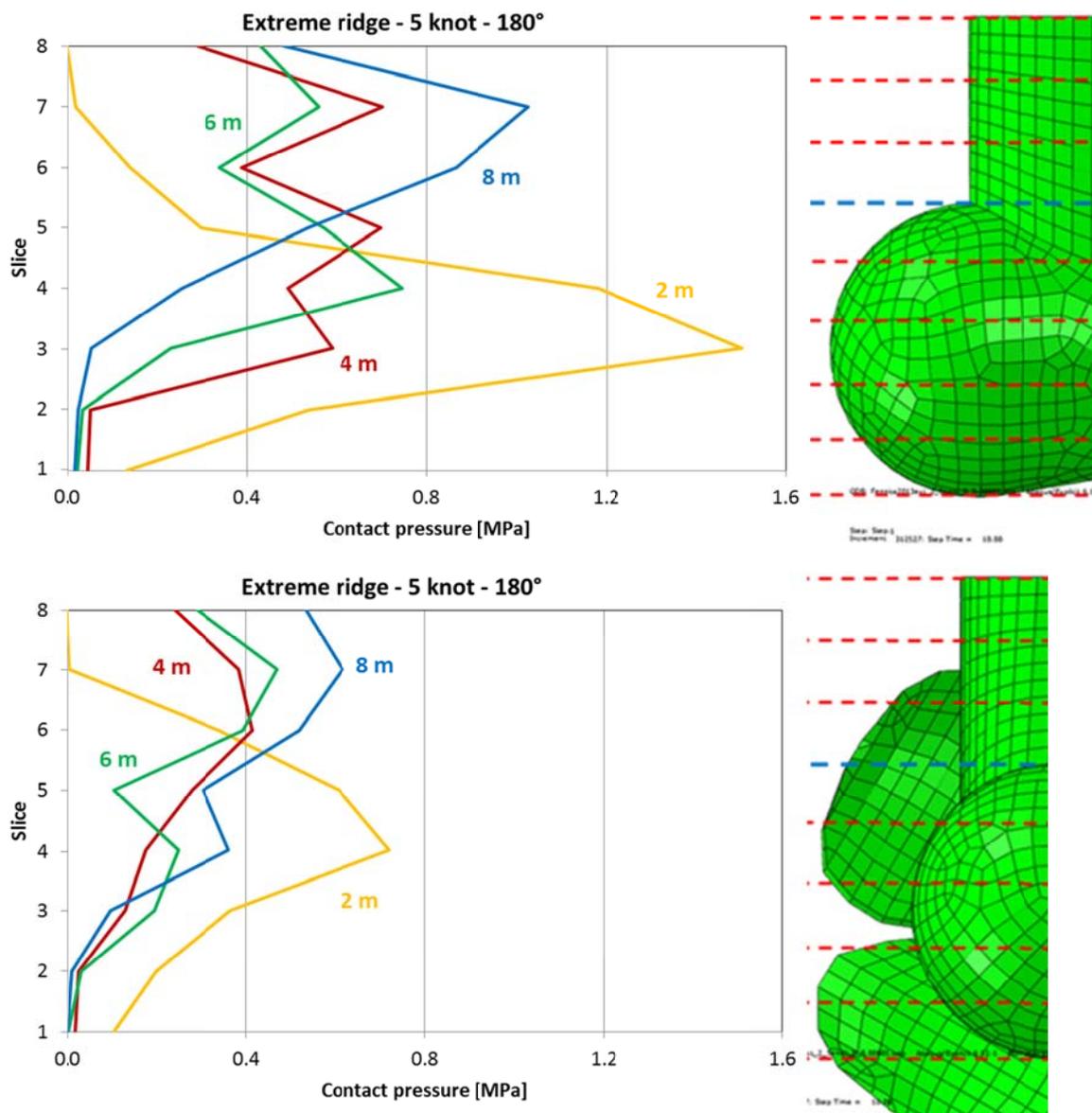


Figure 27. Maximum contact pressures of the thrusters by slice, effect of thruster size on the pressure distribution. The contact pressure maxima do not appear at the same time in all the slices.

Figure 28 is shown same as previous figure, but dependence on the height. From the figure it is seen, that the different size thrusters pressure distribution in the height direction is not similar. Relation of the thruster (propeller) size and ridge height have an effect a pressure distribution.

Small thruster (2 m) is always inside the ridge and therefore the pressure level is bigger. The lower part of the large thruster can be below the ridge bottom and therefore the pressure level in the lower part is smaller. The same effect can be seen on both longitudinal and

transverse thruster. The contact pressure maxima do not appear at the same time in all the slices.

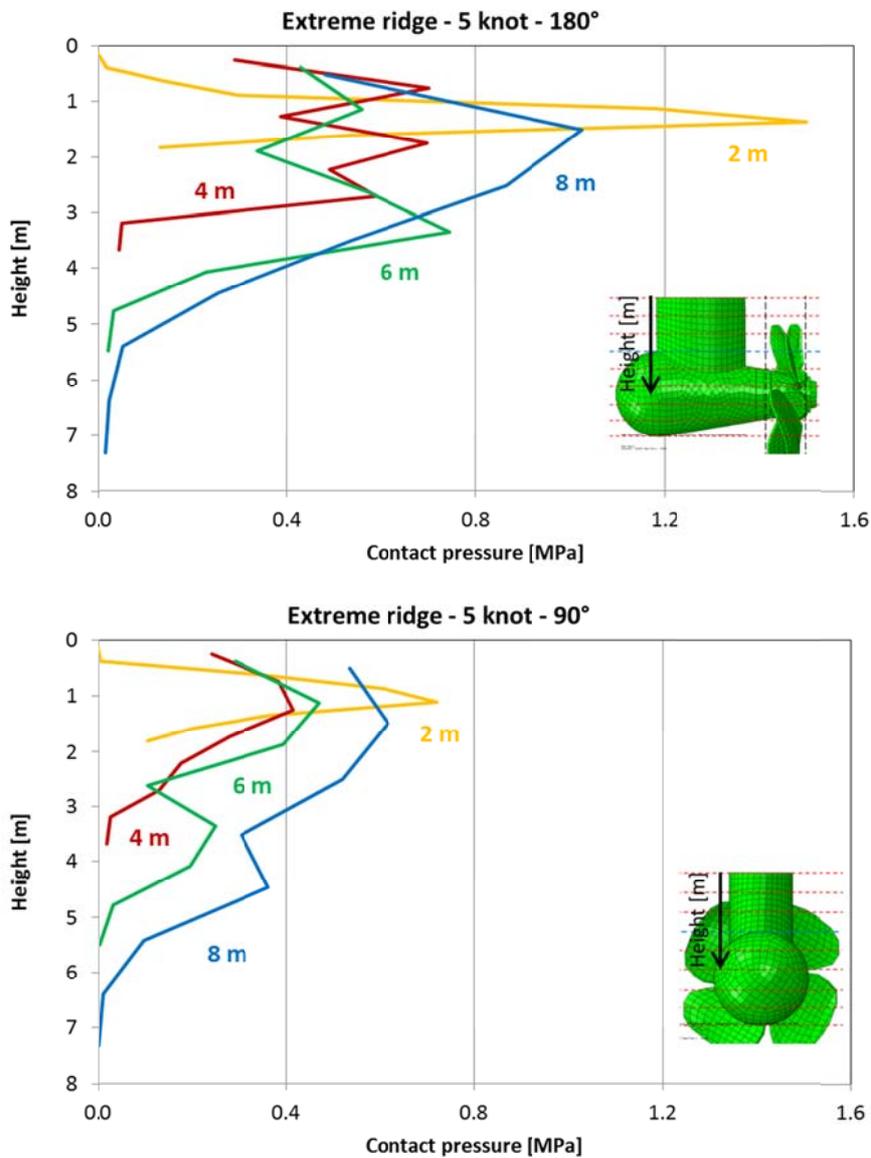


Figure 28. Maximum contact pressures of the thrusters by height, effect of thruster size on the pressure distribution. The contact pressure maxima do not appear at the same time in all the slices.

5.6.3 Proposed formulation for total force

A formulation for thruster total force is based on the FEM results. The force is assumed to depend on initial speed of the ship, height of the ridge and cross-sectional area of the thruster.

The form of the proposed formulation for total force F [kN] is:

$$F = a \cdot v^b \cdot H^c \cdot A^d \quad (11)$$

where v is ship speed [m/s]
 H is ridge thickness [m]
 A is cross-sectional area of the thruster [m²]
 a , b , c and d are constants.

The nonlinear regression model fit of the formulation to the FE model simulation result set is

$$F = 0.032 \cdot v^{0.66} \cdot H^{0.9} \cdot A^{0.74} \quad (12)$$

The correspondence of the FE simulation results and formula (12) is seen from Figure 29. Simplified formulation seems .

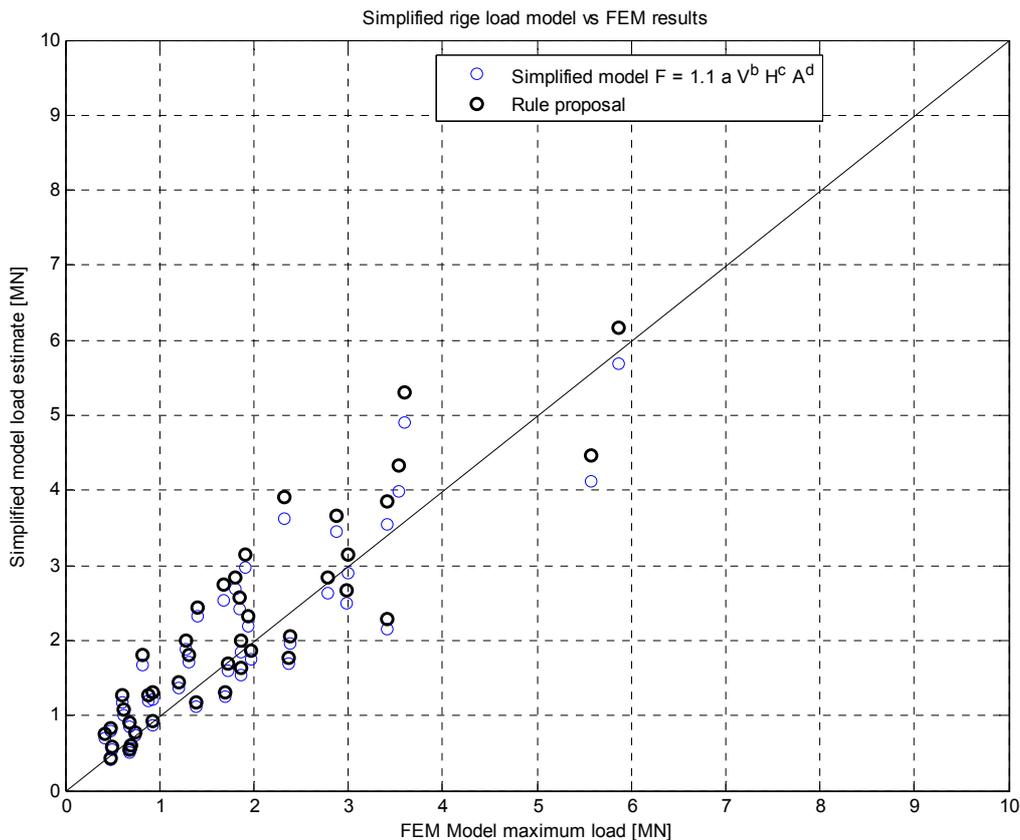


Figure 29. FE model simulation maximum global loads in ridge interaction and the load estimates with simplified formula (12). 8 m propeller size not included in the study.

5.6.4 Simplified pressure area model

A simplified pressure model was also developed from FEM results. According to results the contact pressure distribution is different for longitudinal or transverse thruster position. See Figure 30. The longitudinal position, the typical distribution varies in different cases, type a), b) or c). The transverse position, contact pressure distribution clearly reduces linearly downwards, type d).

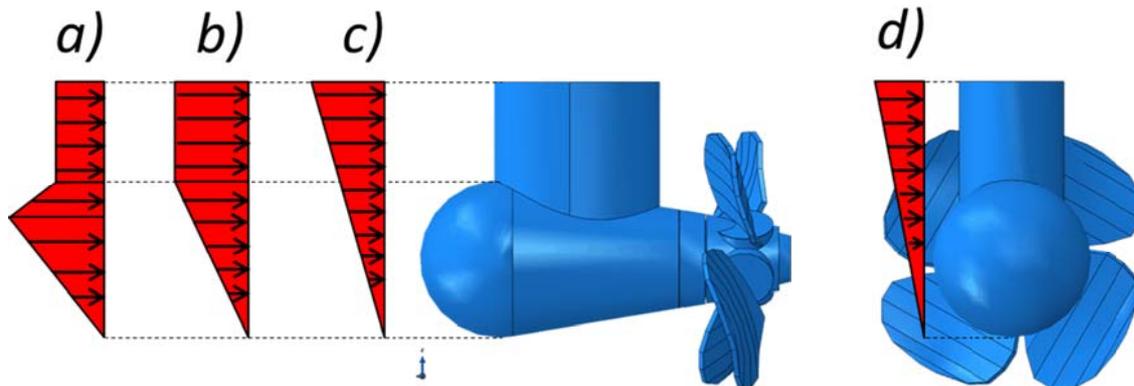


Figure 30. Typical contact pressure distributions. Left (a - c) longitudinal pressures and right (d) transverse pressure.

5.7 Simplified ridge load model

The suggested formulation for total force F [kN] is:

$$F = 0.032 \cdot v^{0.66} \cdot H^{0.9} \cdot A^{0.74} \quad (13)$$

where v is ship speed [m/s]
 H is ridge thickness [m]
 A is cross-sectional area of the thruster [m²].

The total force F is divided on the projection of the thruster area in the relation of the pressure distribution.

5.8 Simplified ridge load model application for full scale

As an example application, the simplified ridge load model is applied for two vessels. In Table 14 are shown an example values for ice class related input parameters for ridge thickness and ship speed. The azimuthing thruster projection areas are calculated from drawings.

The values for ice class based parameters are provisional in Table 14 and are subject to change when the ice class rules for azimuthing thrusters will be formulated.

Table 14. Ridge contact load calculation example with simplified ridge load model.

Loads when moving towards ridges or channel side walls, simplified ridge load model

		IA Super	IA	IB	IC
Thickness of the design ridge consolidated layer	m	1,4	1,2	1	0,8
Total thickness of the design ridge	m	10	8	6	5
Initial ridge penetration speed when backing	kn (m/s)	8 (4,11)	4 (2,06)	4 (2,06)	4 (2,06)

Fennica, thruster without nozzle

 Projection area
m²

Longitudinal ridge load, end cap first to ridge	7,1	MN	2,76	1,43	1,10	0,93
Longitudinal ridge load, nonrotating propeller first to ridge	13,9	MN	4,52	2,34	1,81	1,53
Thruster transversal to ridge	12,6	MN	4,21	2,18	1,68	1,43

Botnica

 Projection area
m²

Longitudinal ridge load, end cap first to ridge	3,8	MN	1,74	0,90	0,69	0,59
Longitudinal ridge load, nonrotating propeller first to ridge	11,3	MN	3,89	2,01	1,55	1,32
Thruster transversal to ridge	17,5	MN	5,37	2,78	2,15	1,82

6. Dynamic excitation of thruster based on propeller-ice interaction

Natural frequencies of azimuthing thrusters are typically close to the range of blade order excitation caused by propeller milling of ice. Risk for resonant vibration situation exists leading to a conclusion that the blade order (or twice blade order) resonance has to be covered in the ice class rules. Typical vibration modes are longitudinal and transverse vibration modes of the thruster. However, the vertical vibration mode can be of importance as well. The rotational mode around vertical axis is typically on much lower frequency and well damped.

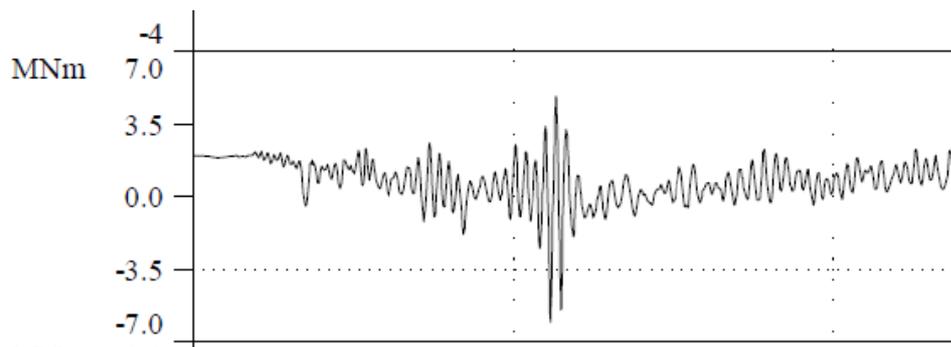


Figure 31. An example of vibratory behaviour of a thruster.

The dynamic excitation is caused by the propeller ice interaction. The formulae that have been developed for blade ice interaction and torsional ice loads on the propeller are used to estimate the excitation. Tangential force on propeller is calculated from the ice torque by dividing the ice torque by moment arm ($0.7 R$), i.e. it is assumed that the load acts on $0.7R$.

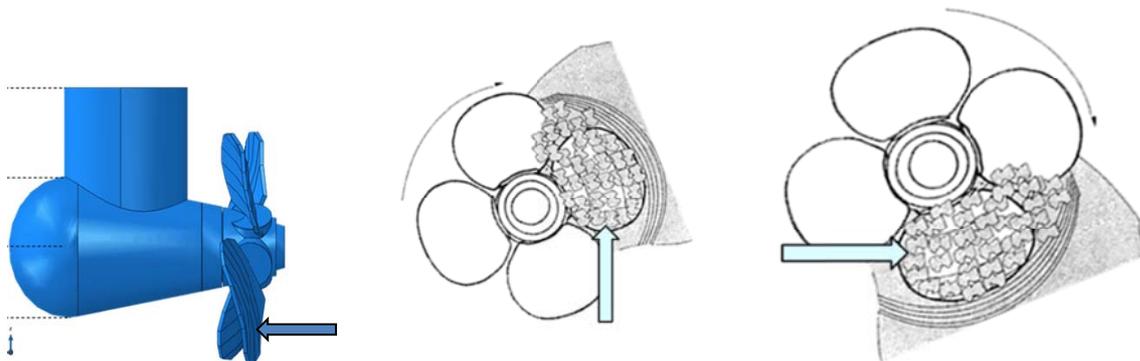


Figure 32. Principle for dynamic excitation coming from propeller-ice interaction.

The dynamic excitation loads are determined in following manner

Axial direction	$F_{bla} = F_b \text{ or } F_f \text{ which ever is greater}$
Vertical direction	$F_{blv} = 0.75 * Q_{max}^* / (0.7 * R)$
Lateral direction	$F_{blh} = 0.75 * Q_{max}^* / (0.7 * R)$

The Q_{max}^* is maximum ice torque calculated at the relevant rotational speed using the formulation in Finnish-Swedish ice class rules.

When assuming that the excitation from propeller ice interaction is a continuous series of half sine shape impacts (see Figure 33 below) we can estimate the sinusoidal excitation by taking fourier transform from it and showing the blade order component.

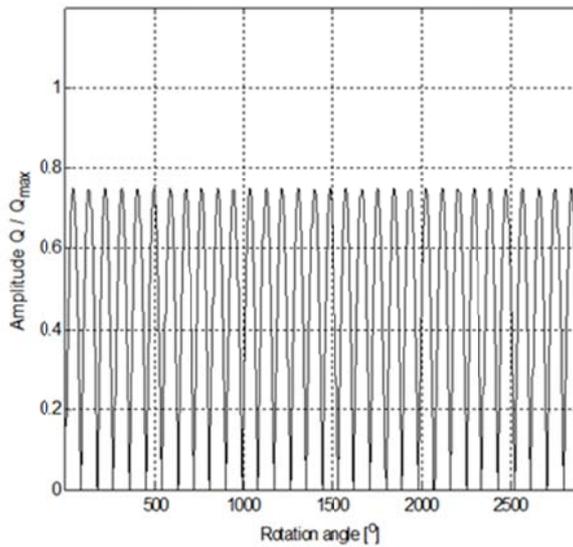


Figure 33. Dynamic excitation principle of continuous series of half-sine shape impacts.

The sinusoidal extreme excitation is then for any direction:

$$F_{bl}(\varphi) = F_{bl}C_{q1} \sin(Z\varphi + \alpha_1) \quad [kN] \quad (14)$$

The response force in a resonance taking into account dynamic magnification for transverse, longitudinal and vertical vibration is then defined

$$F_{blresp}(\varphi) = C_{DM}F_{bl}(\varphi) \quad [kN] \quad (15)$$

where :

- C_{q1} is first blade order fourier component coefficient
- φ is angle of rotation , in degrees
- $\alpha_1,$ is the phase angle of excitation component , in degrees
- Z is number of blades
- C_{DM} is the dynamic magnification factor for thruster body vibration

The blade order fourier component is defined in following table depending on propeller blade number Z .

Table 15. Blade order fourier coefficients for sinusoidal excitation on the propeller.

	C_{q1}	α_1
$Z=3$	0.375	-90
$Z>3$	0.36	-90

The dynamic magnification for a thruster global mode resonance is typically 10-20 in open water. This is considered as a reasonable estimate for ice operation.

For strength evaluation of the thruster, the response force has to be located at the location of the thruster vibratory mass. Typically at the propeller shaft level. See Figure 34.

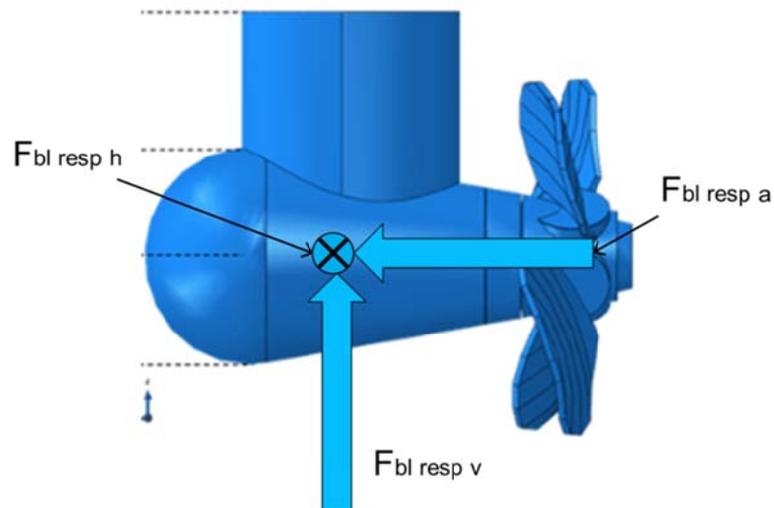


Figure 34. Schematic figure showing the location of the response force for longitudinal, transverse and vertical vibration.

7. Conclusions

Developed impact load model was capable to give realistic impact load values when compared with impact experiment. Also, full scale measurements indicate impact loads at the level the model estimates [1,2]

The effect of damping during impact contact event is not yet properly modelled in the simplified impact model and is a point for further study. For further studies, the energy dissipation in impact contact is very interesting area.

The developed dynamic load calculation model was used as load calculation tool for estimating the effect of different parameters to impact load, when developing simplified formulation for ice class rule proposal. With the dynamic impact load model, a parameter study was done. The input values and corresponding dynamic contact load results were used to formulate a simplified impact contact load formula.

The simplified formula includes relation of impact kinetic energy, contact area size and constants to the contact load. The constants were determined by nonlinear regression model fitting. The used regression fit tool was MATLAB nonlinear model fit.

The resulting simplified model was tested by comparing the simplified load formula results with dynamic model results and full scale applications. The simplified load model gives same level of load as the validated dynamic impact contact load model.

The simplified impact load model described here was distributed to the project steering group members for review purposes, and is therefore not final, subject to revision.

Ice loads for the case when thruster penetrates into ice ridge were done with FE model. The model was seen to give similar results to full scale measurements, the comparison was presented in VTT report from 2012 [2]. The parameters varied in this study were ship speed, ice ridge size, thruster orientation, propeller diameter (scaling propulsion unit size and ship mass), giving room for conclusion regarding the effect of these parameters.

Based on the FE-simulation parametric study results, a simplified formulation for azimuthing thruster total load is proposed for the load scenario where ship is going through ice ridge.

This simplification still needs further testing and verification, and is provided for industry and classification societies review.

8. Summary

For developing technical background for azimuthing thruster ice class rules, a research project was initiated in 2010. The need for rule development was stated by Finnish and Swedish maritime authorities. Funding for the work is covered by Winter navigation research board, a joint research funding instrument between Finnish Transport Safety Agency and Swedish Maritime Administration.

Research project was guided by steering group, where participants from classification societies (ABS, BV, ClassNK, DNV, GL, Lloyd's Register, RINA, RMRS) together with azimuthing thruster manufacturers were invited.

The project started with identifying azimuthing thruster ice load scenarios, and finding suitable load calculation methods for such ice-structure interactions. The identified load scenarios include azimuthing thruster interaction with ice ridge and ice block impact to thruster.

Ice load calculation for azimuthing thruster interaction with ice ridge, a finite element method (FEM) model was taken as a research tool. Modeling an ice ridge and ship hull with thrusters with FEM was used to study the interaction process. The simulations run in 2013 gave initial understanding of what the effect of different parameters are to global thruster ice loads. The variable parameters were ship initial speed for ramming into ridge, thruster steering angle, ice ridge size. From these simulations, the global loads for thruster unit are calculated, and were compared to ice breaker Fennica measurement data. Model shows same type of behaviour of loading and same magnitude of loading as in measurement. During 2014, the FEM simulations continued and provided results for different propulsion unit sizes and ship inertia as well.

Based on the parameter studies, a simplified total load formulation for ice ridge interaction with azimuthing thruster is suggested. The simplified model is provisional and subject to change, after it has been reviewed by manufacturers and classification societies.

For the ice block impact to azimuthing thruster type load scenario, a dynamic three mass model was considered the simplest possible approach. There a contact between azimuthing thruster housing or propeller hub is assumed, with a hemispherical metal structure indenting into ice block. The contact load for impact was assumed as a pressure-area relationship, and the contact load is increasing as the thruster structure indents deeper into ice.

The impact model validation relies on two sources, full scale data and small scale experiments. Full scale data from ice breaker Fennica and Botnica was used for validation. The rights to use measurement data from Botnica was granted by ABB Marine for this purpose and this is greatly acknowledged. The small scale tests made on Baltic sea ice. The test setup was a pendulum with hemispherical contact surface, with load measurement, impacting into ice. The impact contact point was submerged. The tests show that the model is capable of estimating the contact load quite well. However, the model is indicating less damping after the impact than is observed in the tests. This question in general is about energy dissipation in impact and ice crushin process and is area of further studies.

Based on the parametric runs of the dynamic impact load model, a simplified impact contact load model was formulated. The simplified model was achieved by nonlinear regression analysis, and is provided as suggestion for ice load calculation. The model was distributed to industry and classification societies for review and may be updated accordingly.

References

- [1] Tikanmäki, M., Heinonen, J., Kinnunen, A., Comparison of ice load models for azimuthing thruster ice load calculation, VTT-R-10310-10, VTT Technical Research Centre of Finland, 2010
- [2] Kinnunen, A., Tikanmäki, M., Heinonen, J., Kurkela, J., Koskinen, P., Jussila, M., Azimuthing thruster ice load calculation VTT-R-08842-12, VTT Technical Research Centre of Finland, 2012