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ICE-STRUCTURE IMPACT CONTACT LOAD CALCULATION WITH DYNAMIC MODEL AND SIMPLIFIED LOAD FORMULA

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ABSTRACT

Shipping in arctic and in ice conditions is increasing. Modern propulsion systems often utilize azimuthing thrusters in their various forms. When operating azimuthing thruster equipped ships in ice conditions, the thruster will interact with ice. One such interaction type is an impact-type contact of an ice block and the thruster. The contact causes certain loading to the thruster. The contact load problem can be considered as an ice impact to a steel structure. In a study related to developing the Finnish-Swedish ice class rules, the impact forces due to an ice contact to a steel structure are dealt with a simple theoretical model and an experimental approach is used for the model validation. In this paper, the principle of the dynamic load model, its validation and suggestion for a simplified load estimation formula is presented.

For an azimuthing thruster operated in ice conditions, an ice block impact contact load can be solved effectively with a simple three-mass dynamic-system model. The contact region is assumed to be a hemisphere indenting into ice, representing the azimuthing thruster hull or the propeller hub. Model considers ship speed, ship mass, thruster mass, ice mass and connections between these. The dynamic model was verified with available full scale data and with two sets of experiments with ice from the Baltic Sea to give good estimate of the contact loads in impacts. The impact speed considered in these cases was below 5 m/s.

The suggested simplified formulation is based on the dynamic contact load model results. The dynamic contact load model was run with different initial values. This gives indication how different parameters effect the contact load. The most significant variables were identified and only they are included in the suggested simplified approach.

ICE LOAD SCENARIOS FOR AZIMUTHING THRUSTER

Ice contact load scenarios of an azimuthing thruster include at least ice block impacts to the thruster body and the propeller and propeller hub, see Figure *1*. Another considerable load scenario is ice ridge interaction with an propulsion unit. A FEM model example of the ridge-propeller interaction is shown in Figure 2 (Tikanmäki et al., 2010). Some ship classification instances have defined methods to calculate the ice contact related loads for the azimuthing propulsion units. The methods offered, for example by Bureau Veritas and DNV-GL, are relating the ice load to the estimated ice contact area. Here, an alternative method for estimating the loads is presented.

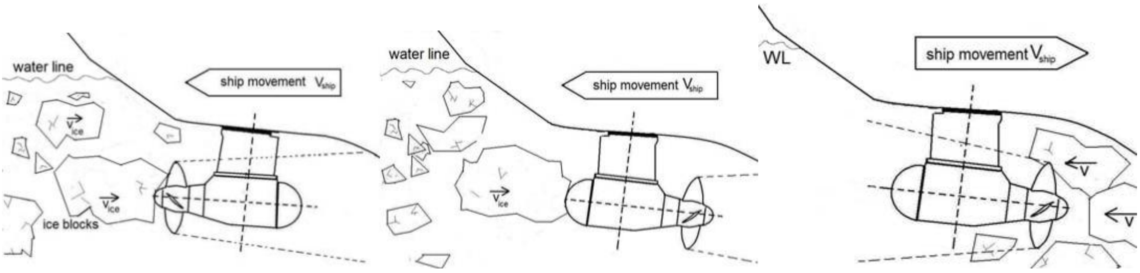

Figure 1. Ice block impact to azimuthing thruster.

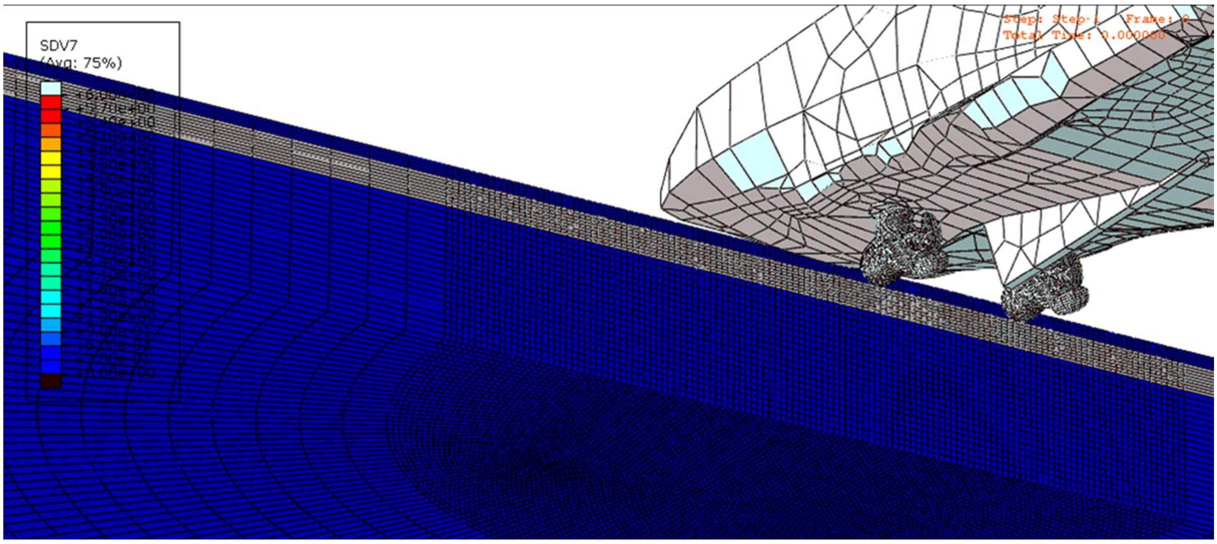

Figure 2. Azimuthing thruster interaction with ice ridge. Figure by Juha Kurkela VTT, from FEM simulation of ridge contact.

DYNAMIC IMPACT LOAD MODEL

Model principle

The general principles of the impact load model are presented here. For more details, see references (Kinnunen et al 2014, Kinnunen et al 2013, Kinnunen et al 2012, Tikanmäki et al. 2010).

The principle of the model is shown in Figure 3. The model utilizes a three-mass system, where a ship with a mass m_s is moving at an initial velocity v_0. The thruster is considered to have a mass m_t connected to the ship with a stiffness k. The thruster part that impacts with ice is assumed to be a hemisphere with radius r. A response force between the ship and the thruster is F_r. The ice block is assumed to have a mass m_i and the contact between ice and the thruster is described with a contact load function F_c. Furthermore, the ship is assumed to move, and ice is assumed to be stationary floating object in water prior to the impact. In the model, the thruster structure is assumed to have damping. The system is solved with difference method in the time domain (Tikanmäki et al, 2010). The model is implemented as a MATLAB function.

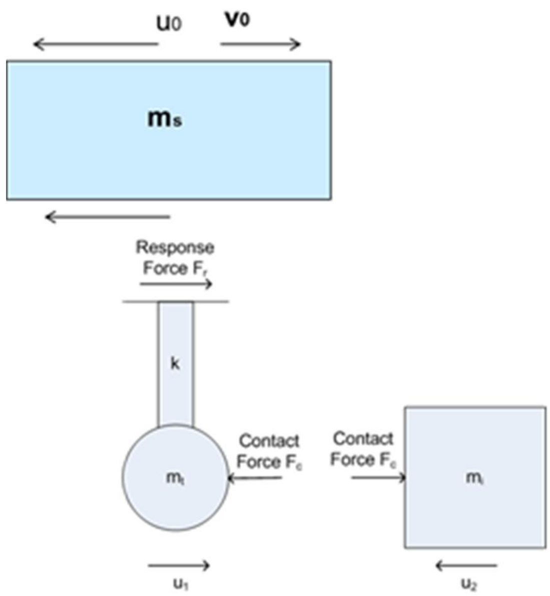

Figure 3. Impact model principle.

The contact load F_c is calculated as a function of the contact area A, the reference area A_{ref} and the reference ice crushing pressure p_{ref}. Here, the ice uniaxial compression strength is used as the reference pressure. Value of 3 MPa is used for the Baltic Sea. A maximum contact pressure limit of 10 MPa is used in the model. This is needed especially for small contact areas to prevent unrealistic high contact pressures.

A water film is assumed to squeeze out of the contact region during the penetration and the water film is assumed to recover if the contact starts to open again. This condition can be called as a hydrodynamic contact. The load component depending on the water film thickness, the squeezing velocity and the water viscosity is adopted from the lubrication theory.

The contact is assumed to be a hemisphere of radius r intending into ice and thus the contact area is assumed to be the spherical contact projection, and corresponding pressure-area relationships are

$$A = \pi(r^2 - (r - u_2 - u_1)^2) \quad (1)$$

$$F_c = p_{ref}\sqrt{A_{ref}A} \quad (2)$$

Ice is considered to have some linear elastic deformation prior to failure, and the floating ice block is assumed to have velocity dependent drag force acting on it. In the model, the maximum energy available for the structure indentation to ice is assumed to be the kinetic energy of the floating ice block accelerated to the impact velocity.

For solving the contact load problem, the model needs as inputs the three masses and their velocities, ice strength and the thruster connection stiffness to the ship. Water properties are taken as constant and the drag force for the ice cube is calculated with a drag coefficient 1.05. The contact load is solved in the time domain as a part of the indentation process. With current computers calculation is very fast for the duration of the impact.

Model validation experiments

The model needed validation so a downscaled experimental rig was constructed and experiments were made on sea ice. The setup consisted of a pendulum mass where a changeable impact head was attached, and a large mass to present the ship. In the setup, it was possible to measure impact load. Principle of the test is presented in Figure 4.

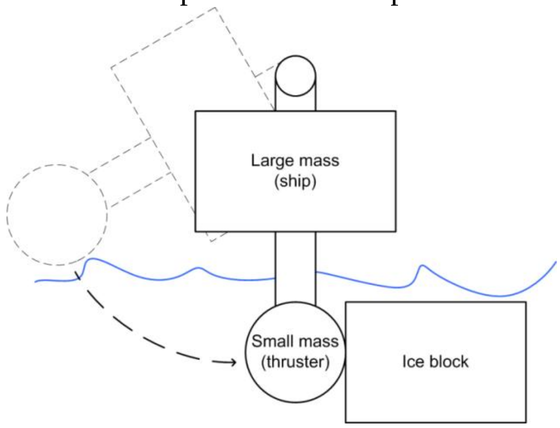

Figure 4. Principle of impact test setup.

Validation experiments were done during two winters, in 2013 andin 2014. The experiments were done by lifting the pendulum to a start height, and releasing the mass. This gave the pendulum a velocity for the impact. In the tests, the impact load measurement was based on steel bending and strain gauges. The constructed load measurement was calibrated with a reference load cell type HBM C4 / 100. The pendulum mass acceleration and the ice block acceleration were recorded with triaxial acceleration sensors, type PCB629A10.

In March 2013, first set of tests was done in Espoo, Finland, on ice of the Gulf of Finland in the Baltic Sea. Test summary is in Table 1. Impacts were done to solid ice and to a floating ice block. Two contact head hemisphere sizes were used, 100 mm and 150 mm diameter (denoted as small head and big head in the test case table below). Also, two contact speeds were used, 2 and 5 m/s (denoted as low and high speed). Ice conditions during the tests were rather constant, ice thickness being approx. 0.5 m and air temperature approx. – 10ºC. Ice temperature was measured from the bottom of the hole drilled to the surface of ice. The diameter of the hole was 5 mm and the depth approx. 30 mm.

Table 1. Impact tests in March 2013, Espoo, Finland.

Test Nr	Date	Time	Test description	Ice temperature C^o	Impact Mass kg
1	20.3.2013	10:59	Small head, low speed, solid ice	-3.5	220.0
2		13:09	Small head, low speed, solid ice	-3.5	220.0
3		13:30	Small head, low speed, solid ice	-3.5	220.0
4	21.3.2013	10:05	Small head, low speed, ice block	-1.25	220.0
5		10:17	Small head, low speed, ice block	-1.25	220.0
6		10:28	Small head, low speed, ice block	-1.25	220.0
7		13:14	Big head, high speed, ice block	-1.25	224.9
8		13:31	Big head, high speed, ice block	-1.25	224.9
9		13:58	Big head, low speed, ice block	-1.25	224.9
10	22.3.2013	9:44	Big head, low speed, ice block	-1.1	224.9

11		10:15	Big head, low speed, ice block	-1.1	224.9

Another set of tests were done in March 2014, in Oulu, Finland on ice of the Bay of Bothnia in the Baltic Sea. The test table is listed in Table 2. The air temperature during the test was 0°C ± 1 °C. The ice thickness was from 0.47 to 0.5 meters and the salinity of melted ice samples was 0 ‰. This was due to the fact that the test area was close to the delta of the Oulu river.

Table 2. Impact tests in March 2014, Oulu, Finland.

Test Nr	Date	Time	Test description	Ice temperature C^{o}	Impact mass kg
1	11.3.2014	16:38	Small head, low speed, solid ice	-0.05	201
2		16:50	Small head, low speed, solid ice	-0.05	201
3		17:02	Small head, low speed, solid ice	-0.05	201
4	12.3.2014	9:27	Small head, low speed, solid ice	-0.05	201
5	12.3.2014	10:14	Small head, low speed, ice block	-0.05	112.8
6		10:26	Small head, low speed, ice block	-0.05	112.8
7		10:40	Small head, low speed, ice block	-0.05	112.8
8	12.3.2014	11:33	Big head, low speed, ice block	-0.05	112.8
9		11:37	Big head, low speed, ice block	-0.05	112.8
10		11:48	Big head, low speed, ice block	-0.05	112.8

The test setup is shown in Figure 5. The pendulum frame was constructed from a rectangular tubing, and the pendulum base plate was cut from 60 mm thick S355 steel plate. The base plate serves as an impact load transducer. The test was done by building the pendulum on solid ice and cutting a hole into ice for the pendulum to swing into water to achieve a submerged contact. The pendulum frame was wide enough to give room to make a big enough hole in ice for hitting into a floating ice block.

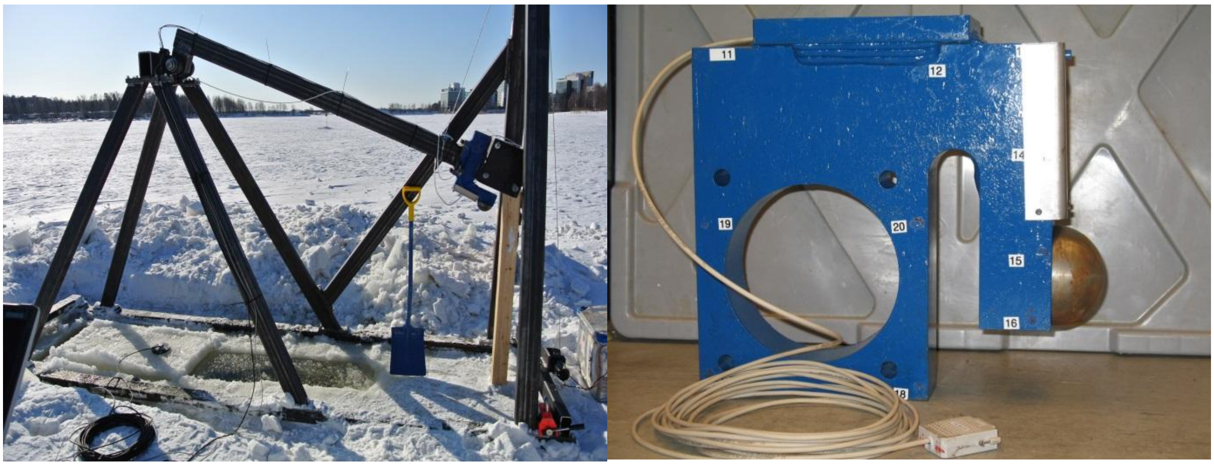

Figure 5. Test rig in 2013 experiments in Espoo, Finland. On the left, the pendulum setup, ready to impact into ice. On the right, the pendulum baseplate with hemisphere impact head. Baseplate is used for the impact load measurement.

Model validation results

The impact tests were started with impacts to solid ice, as a baseline test. Then, tests were done with impacts to a floating block. The measurements and corresponding results from the dynamic impact load model are shown in Figure 6 for 2013 tests and in Figure 7 for 2014 tests. The tests and the calculations give similar results.

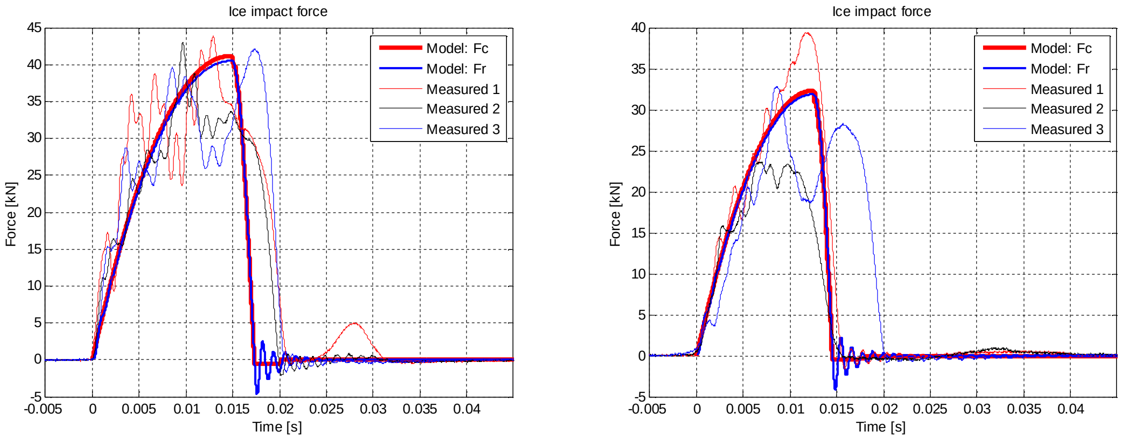

Figure 6. Impact load measurement in 2013 tests and calculated impact loads. On the left, test cases 1-3, an impact to solid ice with an 100 mm impact head. On the right: test cases 4-6 and respective load calculation with an 100 mm impact head, impact to a floating 400 kg ice block.

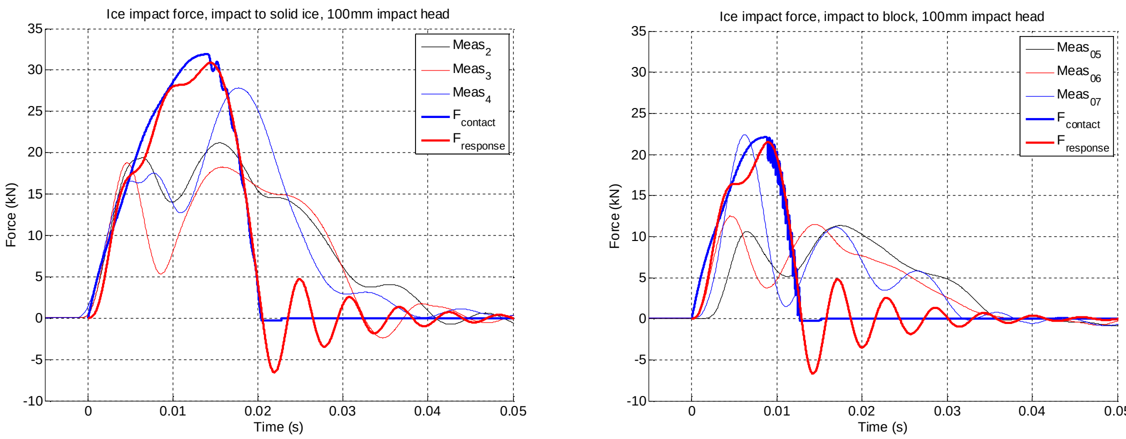

Figure 7. Impact measurements in 2014 experiment and respective load calculation. All results are achieved with an 100 mm impact head. On the left, tests 2 -4, impact to solid ice. On the right, test cases 5-7, impact to a floating ice block of 240 .. 300 kg.

The full-scale validation of the impact model

Full-scale load measurements of loadings from ship thruster units were also considered in the validation of the impact load model. Here, the obvious challenges are naturally the lack of knowledge of the ice block size and the actual contact velocity. However, with reasonable assumptions, the model indicates ice loads of correct magnitude for the vessels from which the measurement data were available for the validation.

THE SIMPLIFIED LOAD FORMULATION FOR THE IMPACT

As described above, the dynamic impact load model was considered as a valid way of estimating the impact contact load for a steel hemisphere impacting into a floating ice block. Thus, it was considered feasible to use the dynamic model as a tool to evaluate effects of different impact parameters to the contact load. Based on these effects, a proposal for a simplified contact load model was attained. Here, the procedure for defining the simplified load formulation is presented together with the final formulation.

Parameter effects to the impact contact load

The effect of the input parameters to the impact contact load estimate was studied. This was achieved by varying the ship mass, the thruster mass, the stiffness of the thruster mount, the radius of the impacting part of the thruster, the impact speed, and the mass of the ice block. As the model lives in MATLAB®, the parametric study was straightforward to do. The results are presented below.

The simplified model formulation

The forging of the simplified contact load model was an iterative process of trial and error; different formulations were tested along the way.

The method for creating the simplified model was to use the input and output datasets of the dynamic contact load model as a nonlinear regression model database. Then, different forms of regression models were tested. The aim was to create simplest possible model with a reasonable relation to the input values and the output load accuracy.

The underlying assumptions for the model were that the impact load is governed by a) the kinetic energy available for the impact b) the contact size (impacting steel part radius *r* in this case), and c) the ice strength, the dynamic mass and stiffness of the thruster were considered to be able to cover with a constant.

This lead to test a simplified load model of form

$$F_{contact} \sim b_2 R^{1/b_1} \left(m_{ice} v_{ship}^2\right)^{1/b_3} \tag{3}$$

where R is the radius of the impacting steel part in meters, m_{ice} is the mass of the ice block in kilograms, and v_{ship} is the ship speed at time of the impact in meters/second. The parameter variation was following: R varied from 0.1 to 2.5 m, m_{ice} from 1 to 50 tons and v_{ship} from 1 to 15 knots.

With the dataset used, and MATLAB nonlinear regression model fit tool, the results shown in Table 3 were achieved.

Table 3. Results for simplified load model regression fit.

Estimated coefficient	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				

The coefficient values presented in Table 3 have a lot of decimals, and for the sake of simplicity, the model was tested also with the rounded coefficients. The simplified form of the simplified model is proposed to be included in the Finnish-Swedish ice class rules. The formulation for the rule proposal is

$$F_{contact} = 34500\, R^{\frac{1}{2}}\left(m_{ice} v_{ship}^{2}\right)^{1/3} \qquad (4)$$

Here, R is the radius of the impacting steel part in meters, i.e. scaling for the contact size, m_{ice} times v_{ship} squared is showing the relation to the impact energy.

The evaluation of the simplified model against the dynamic impact contact load model was done by calculation of loads from the same initial values. The results are shown in Figure 8, where dynamic contact load model result is on x-axis and corresponding simplified load model result is on y-axis. Two versions of the simplified model are shown, the one with decimals and the simplified version used in the rule proposal.

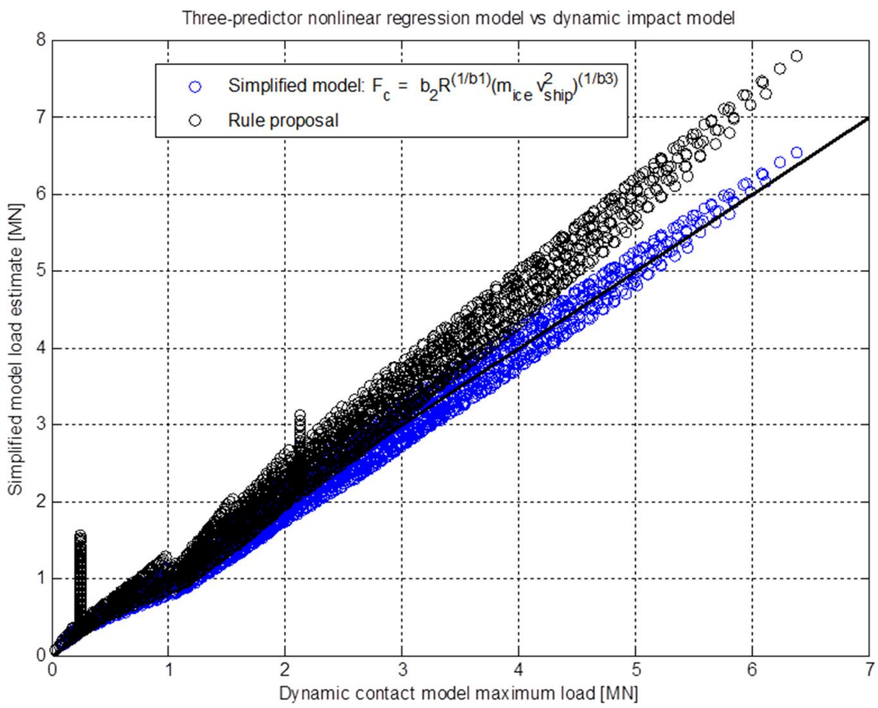

Figure 8. Simplified impact load results as a function of corresponding dynamic impact load model results.

Comparison to other models

There are also other energy-based methods available for defining the ice collision contact load. This particular case can be compared with works of Daley (1999) and Daley and Yu (2009). Daley (1999) wrote a force formulation for a spherical indenter penetrating into ice

$$F_n = p_0 f_a \left(\frac{K E_e f_x}{p_0 f_a}\right)^{\frac{f_x - 1}{f_x}} \qquad (5)$$

where the term p_0 was a reference pressure over 1 m^2 area and the other terms were defined to be

$$f_x = 2 + ex \qquad (6)$$

$$f_a = (2\pi R)^{1+ex} \quad (7)$$

where *R* is the radius of the indenter and *ex* is a constant.

Daley and Yu (2009) presented a load calculation example for the ice block impact to the azimuthing thruster. In this model, the effective kinetic energy limits the load. The kinetic energy definition was based on the effective mass for the impact. In the example cases in Daley and Yu (2009), the effective mass was 228 kg for 233 tonnes of ice impacting into azimuthing thruster. In the presented work, it is assumed that the kinetic energy limit comes directly from the ship speed and the ice mass, i.e. energy change maximum is when the ice block is accelerated from standstill to the ship speed during the impact. This kind of definition increases the kinetic energy limit significantly compared to that by Daley (1999) and Daley and Yu (2009).

Applying the kinetic energy limit principle described in this paper and using the load calculation formulas above, we get to compare the simplified formulation proposed here and presented by Daley (1999). Setting p_0 as constant 3 MPa, and choosing two exponent values *ex* = -0.1 and -0.5 to be used together with the impact velocities, radiuses, and masses in tables 4 and 5. Results in Figure 9, 10 and 11 show similar results for the Daley's model and the simplified model by VTT.

Table 4. Load calculation parameters for method comparison – changing ice mass.

Ice class	H_{ice}	***v***	m_{ice}	***R***	p_0
[ ]	*[m]*	*[knots]*	*[kg]*	*[m]*	*[Pa]*
IC	1	10	5400	1	3.00E+006
IB	1.2	10	9331	1	3.00E+006
IA	1.5	10	18225	1	3.00E+006
IA Super	1.75	10	28941	1	3.00E+006
PC5	2	10	43200	1	3.00E+006
PC4	2.5	10	84375	1	3.00E+006

Table 5. Load calculation parameters – changing the speed values and changing the R values listed, values that were kept constant, are greyed

Ice class	H_{ice}	***v***	m_{ice}	***R***	p_0
[ ]	*[m]*	[knots]	*[kg]*	[m]	*[Pa]*
na	*1.75*	12	*28941*	2	*3.00E+006*
na	*1.75*	10	*28941*	1.75	*3.00E+006*
na	*1.75*	8	*28941*	1.5	*3.00E+006*
na	*1.75*	6	*28941*	1.25	*3.00E+006*
na	*1.75*	4	*28941*	1	*3.00E+006*
na	*1.75*	2	*28941*	0.8	*3.00E+006*
na	*1.75*	1	*28941*	0.6	*3.00E+006*
na	*1.75*	0	*28941*	0.2	*3.00E+006*

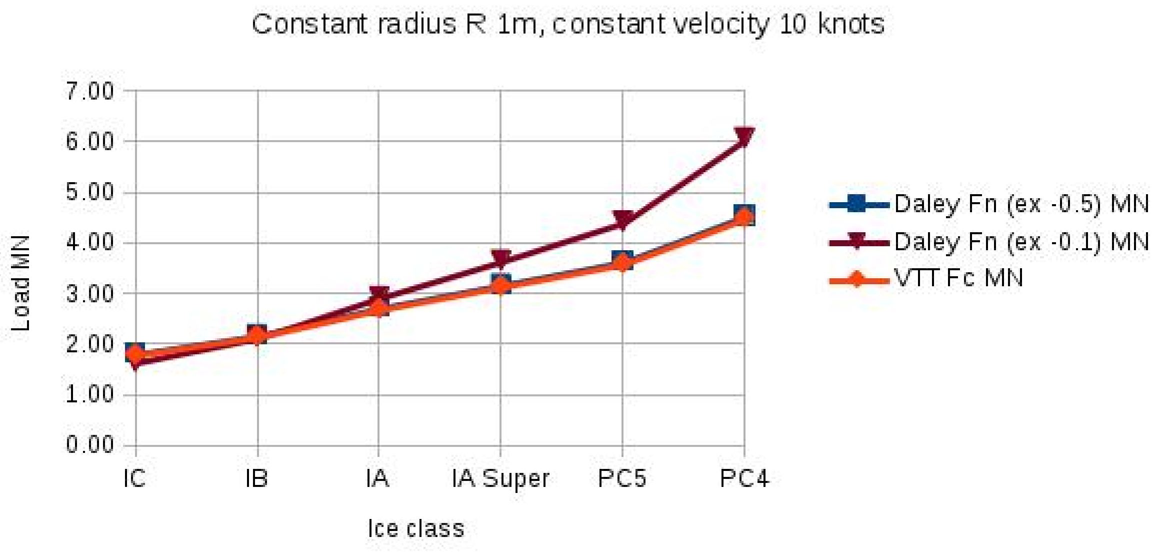

Figure 9. Impact load comparison, effect of the ice block mass to the impact load. The formulation by Daley with exponents -0.5 and -0.1 compared to the proposed model.

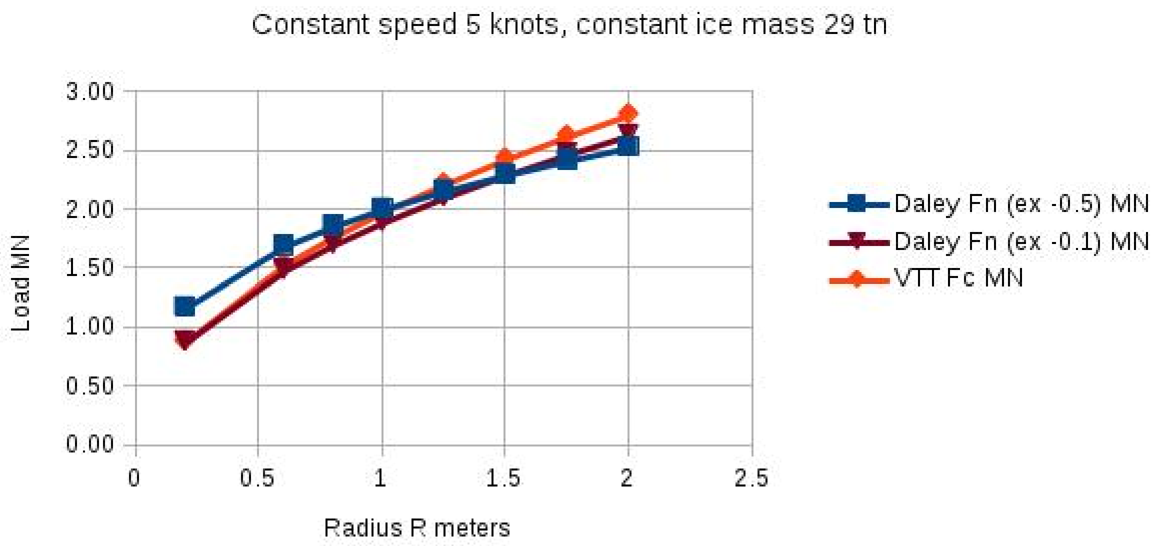

Figure 10. Impact load comparison, changing of the radius R effect to the load. The formulation by Daley with exponents -0.5 and -0.1 compared to the proposed model.

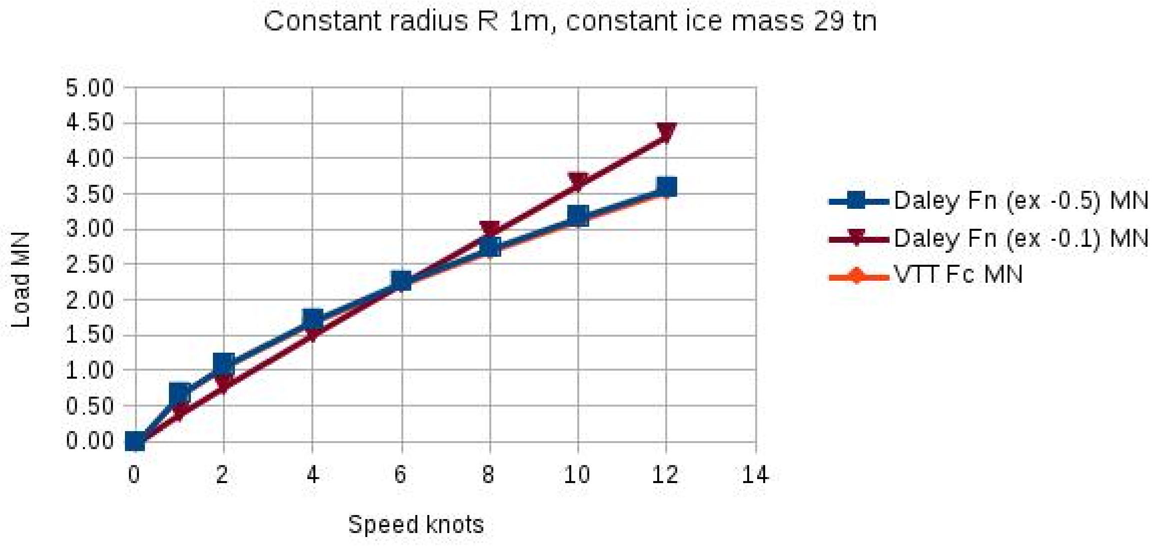

Figure 11. Impact load comparison, effect of changing the impact speed to the load. The formulation by Daley with exponents -0.5 and -0.1 compared to the proposed model.

CONCLUSIONS

The developed dynamic impact model described well the loading events observed in the experiments. This gave a good ground to make a simplification based on a parameter study of the dynamic model. . The proposed simplified model seems to have the same load levels as the dynamic impact model. Also, the proposed model agrees very well with previous theories with reasonable assumptions. The simplified formulation is proposed to be included in the Finnish-Swedish ice class rules in the future.

For further development of the impact model, energy dissipation in the impact due to crushing ice could be included in the model. The ice crushing energy has been studied by Kim and Høyland (2014) and their findings can be implemented in the impact model. Also, more experimental validation both in the laboratory and full scale is always welcome.

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