RESEARCH REPORT

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Comparison of ice load models for azimuthing thruster ice load calculation

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Summary

The ice class rule development is aimed 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.

In this document, the work done during 2010 is documented. The relevant load scenarios and applicable ice load calculation methods are presented, example cases are selected and ice loads calculated for these example cases with different methods.

The included load scenarios are ice block impact to azimuthing thruster. For this scenario, impact load model including structure dynamics is developed

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Contents

1 Introduction

The Finnish Transport Safety Agency (Trafi) initiated ice class rule development project for azimuthig thrusters. 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 Reasearch Centre of Finlad 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 meeting held in Espoo, October 2010.

In this document the 2010 activities and key results are presented.

Simplified load formula for ice class rules are to be developed further in the following years project(s).

2 Goal

The ice class rule development is aimed 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 2010, goal was to

Review the available ice load models for the following aspects:
- Review of the technical background of the load models.
- Ice load scenarios that are basis for the load models
- Comparison of the load obtained with the load models.

Planning of future work (See Appendix A)

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

Ice block impacts to the structure. The affecting ice mass m kg, ice structure contact initial velocity v knots. 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.

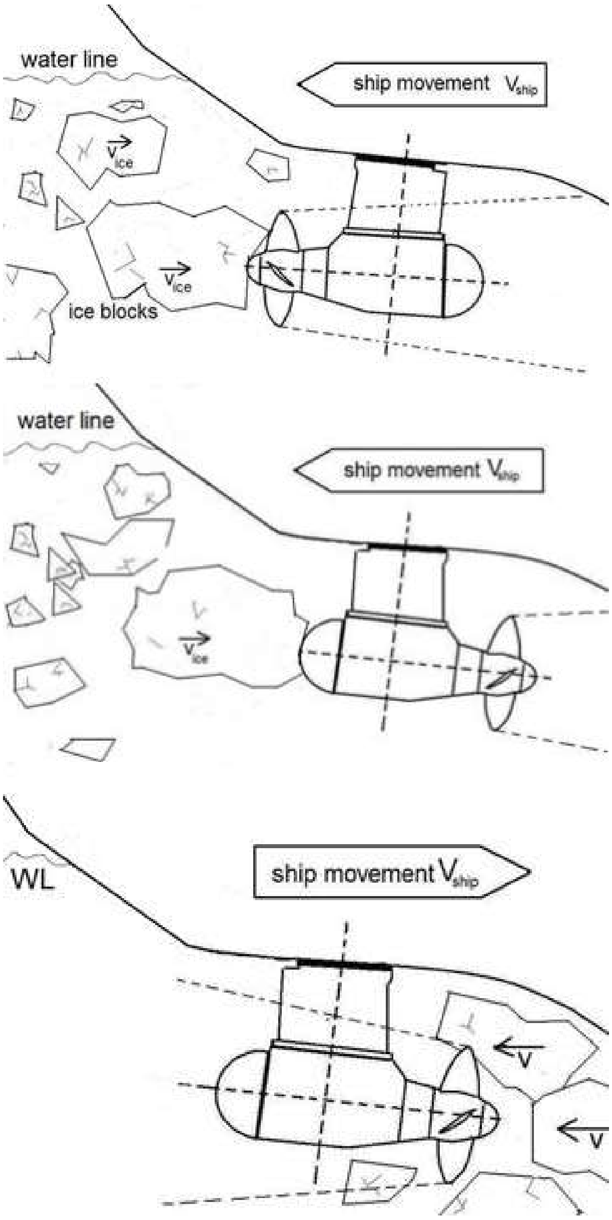

Figure 1. Ice impact load scenario.

3.2 Ridge penetration

Ice ridges are common ice features in Northern seas. 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.

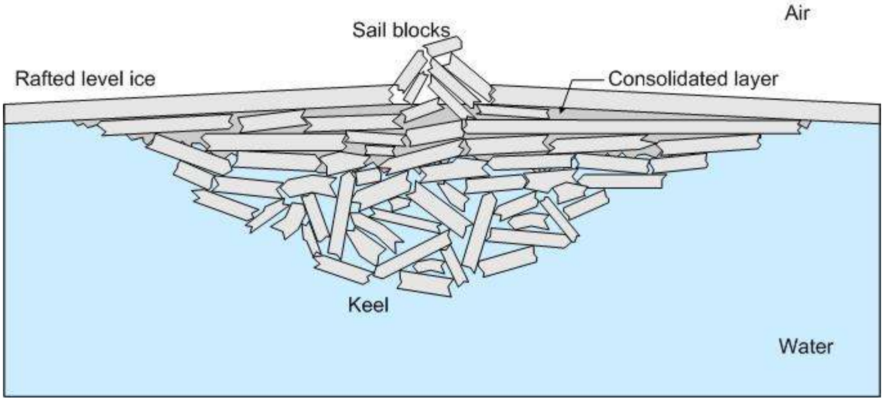

Figure 2. Principal sketch of ice ridge.

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.

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

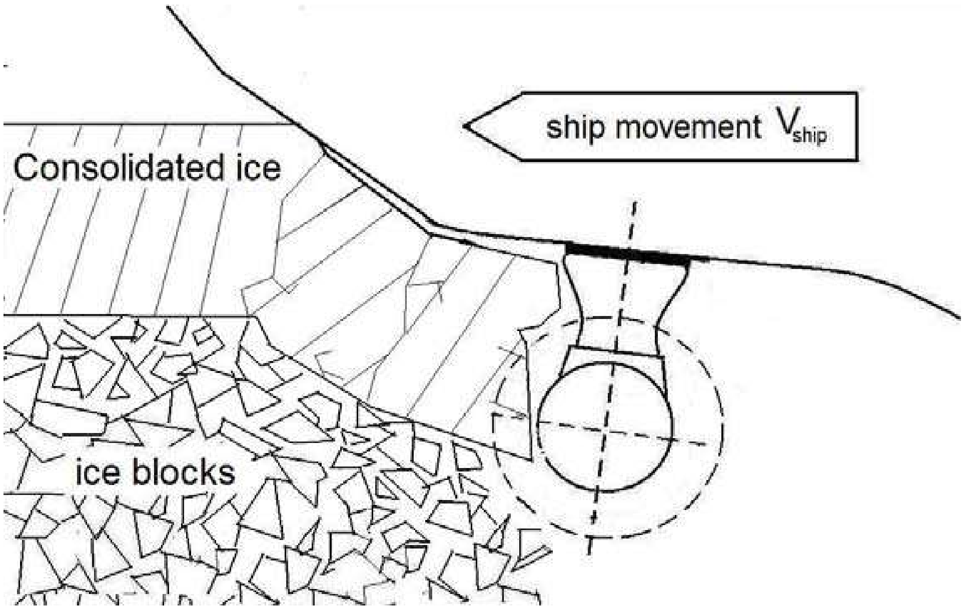

Figure 3. Ridge penetration load scenario.

4 Limitations

4.1 Load scenarios not included

Propeller milling ice, propeller contacting to ice directly or radially and propeller blade bending considerations are not yet included in this study.

5 Included ice load models

Description of included ice load models theoretical background follows.

5.1 Impact model with structure dynamics, VTT impact model

5.1.1 General

In VTT impact model forces between ice block and the propeller hub are calculated as a function of time during the impact. The propeller penetrates to the ice block during the impact. The reaction force affecting in the connection of the ship and the thruster is calculated from the contact force. Maximum values of the contact force and the reaction force are used to estimate the realistic loads for the ships service life. Figure 4 illustrates the impact between the thruster and the ice block.

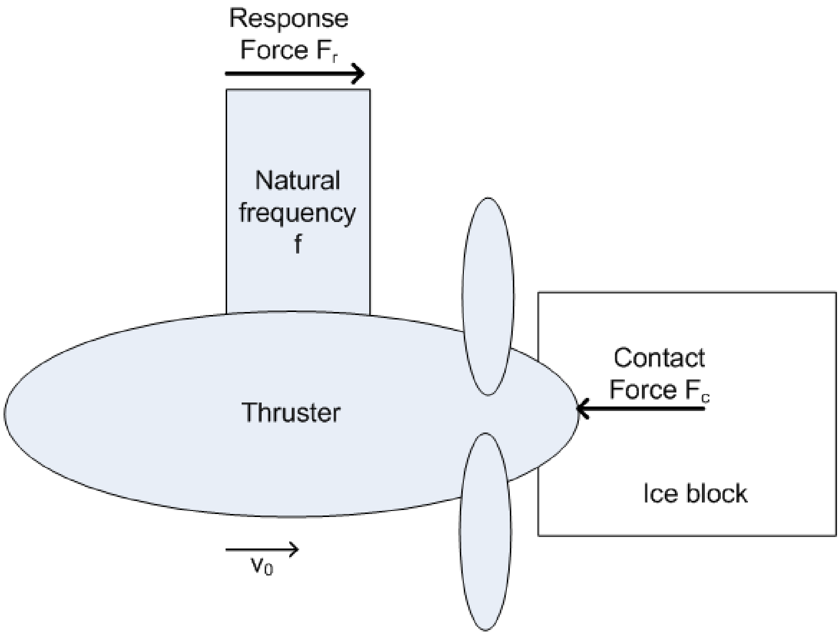

Figure 4. Sketch of the impact between the thruster and the ice block as estimated in VTT impact model.

5.1.2 Indentation pressure

The contact area grows when penetration goes further. This means that the contact force grows because indentation pressure p is a function of contact area A and it is defined by

$$p = p_0 \sqrt{\frac{A_0}{A}},$$

where A_0 is a reference area and p_0 is a reference pressure which are in this case 1 m^2 and 3 MPa respectively. 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 Aatos (Huovinen, 1990) and rest of the data is collected from different sources by Bjerkås (2007)

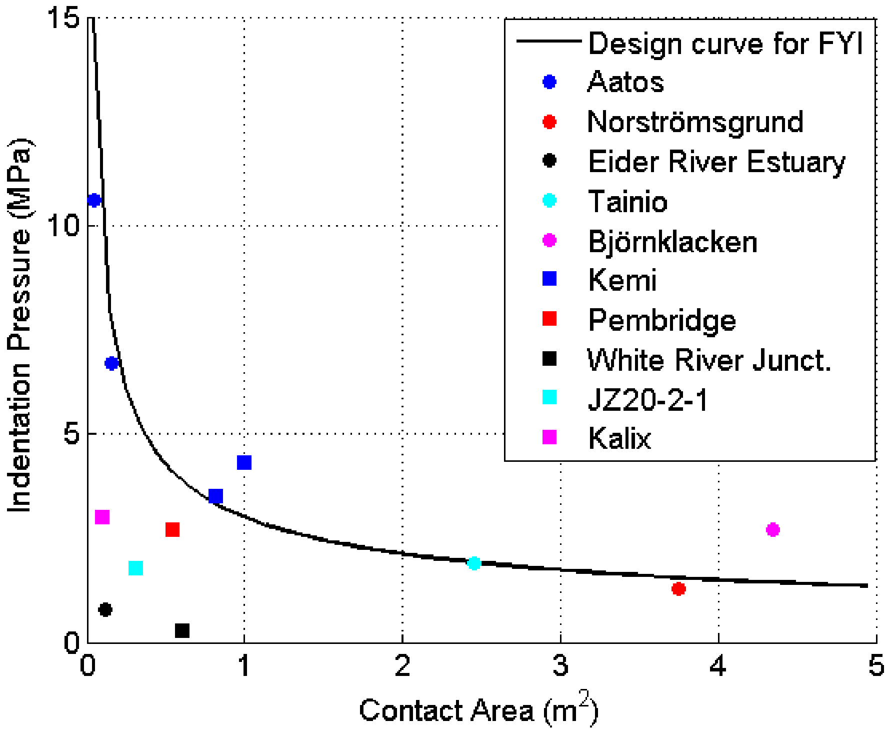

Figure 5. Indentation pressure as a function of contact area.

5.1.3 Description of the model

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

$$F_c - F_r = m_t \ddot{u}_1$$
$$-F_c = m_i \ddot{u}_2$$

where m_t is mass of the thruster, m_i is mass of the impacting ice block and u_1 and u_2 are displacements as shown in Figure 6. Contact force F_c is based on indentation pressure and is determined by equation

$$F_c = p_0 \sqrt{A_0 A},$$

where A is the current contact area defined by

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

where r is radius of curvature of the thruster hub. Response force F_r is determined by equation

$$F_r = k u_1,$$

where k is the stiffness of the thruster which is calculated from the thruster's natural frequency f by

$$k = 4\pi^2 f^2 m_t.$$

Finally these equations are solved by difference methods with initial values

$$u_1(0) = 0$$
$$u_2(0) = -t_0 v_0$$
$$u_1(t_0) = 0$$
$$u_2(t_0) = 0$$

where t_0 is the increment of time and v_0 is the speed of the vessel. Penetration ends when all the kinetic energy is used for ice crushing. Time history of the contact and response forces calculated from these equations by difference methods is shown in Figure 7. Places of the contact and the response force are shown in Figure 8. Figure 9 presents the effect of the mass of the ice block to the contact and response forces.

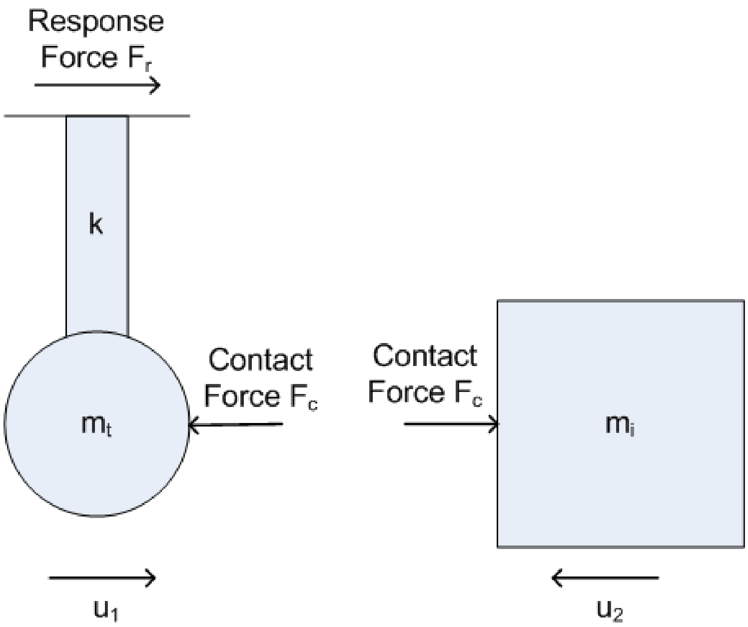

Figure 6. Symbols as they are used in VTT impact model.

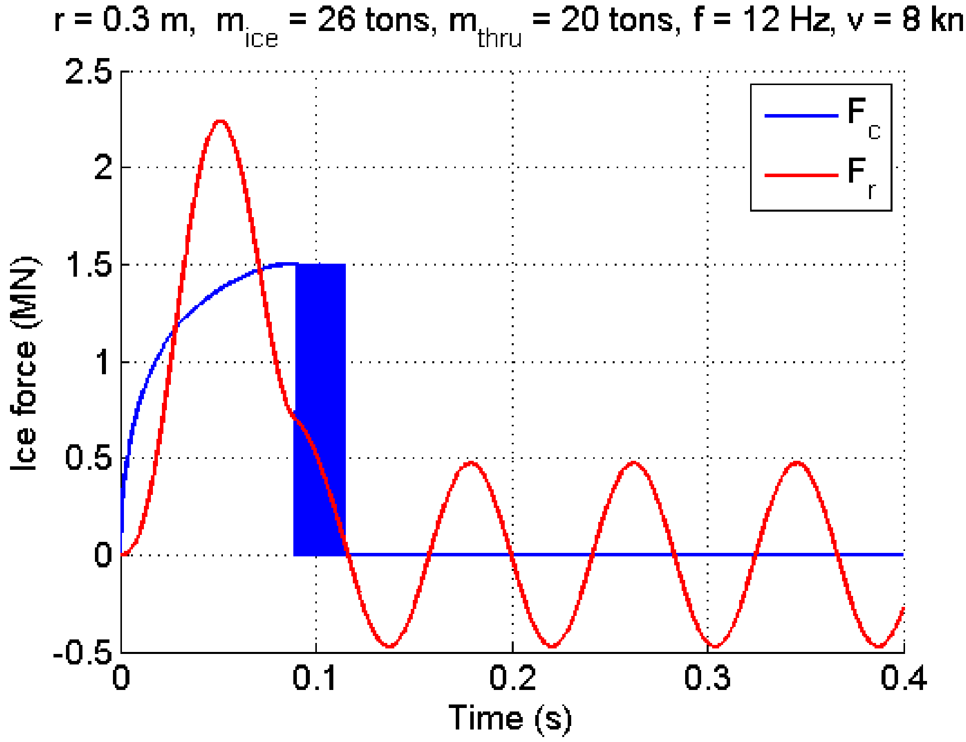

Figure 7. Time history of the contact and response forces when ice block is impacting to the thruster, where radius of the curvature of the thruster is 0.3 m, mass of the ice block is 26 tons, mass of the thruster is 20 tons, natural frequency of the thruster is 12 Hz and the vessel speed is 8 knots. The blue line corresponds to the contact force and the red line to the response force.

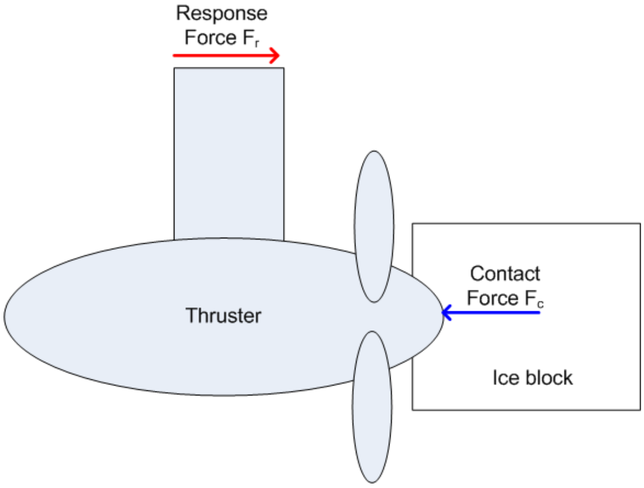

Figure 8. Places of the contact and the response force.

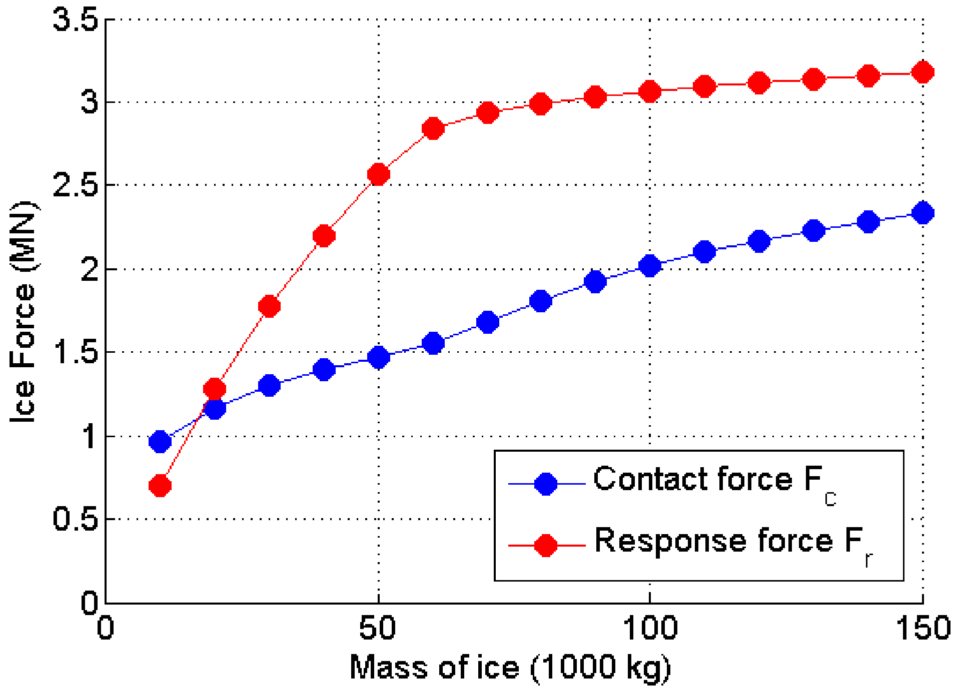

Figure 9. The effect of the mass of the ice block to the contact and response forces.

5.1.4 Limitations of the model

At the moment impact model does not take influence of the water into account. Only hemispherical indentator has been implemented so far. Influence of water and other indentator shapes are implemented to the model in the future.

5.2 Impact model with rigid appendage, ABS method

ABS's method is based on the conservation of energy in impact (Daley, 1999, Daley and Yu, 2009). All the kinetic energy is used to the ice crushing (as in VTT's model). ABS's method is not so clear and easy to use.

Ice load is calculated by

$$F = p_0 f_A^{1+ex} \left(\frac{KE_e}{p_0 f_A^{1+ex}} \right)^{\frac{d(1+ex)}{d(1+ex)+1}},$$

where p_0 is pressure at 1 m^2, f_A and d load function parameters based on the contact geometry, ex is a constant exponent from the pressure – area curve and KE_e is the effective kinetic energy. The effective kinetic energy is defined by

$$KE_e = \frac{1}{2} M_e v_n^2,$$

where v_n is the normal component of the velocity and M_e is the effective mass, which is calculated by

$$M_e = \frac{M_{ship}}{Co},$$

where M_{ship} is the mass of the ship and Co is the Popov's factor.

5.3 DnV load model

In DnV's Classification Notes No. 51.1 (2010) ice load F on a defined area A is calculated by

$$F = {p_0}^{0.8}(AC^{0.3})^{exp} C_1 C_2 C_3 C_4,$$

where

- p_0 and H_{ice} depend on the ice class as shown in table 1
- A is considered projected area exposed to ice pressure in m^2 if less than $2{H_{ice}}^2$, $2{H_{ice}}^2$ otherwise
- exp is an exponent 0.3 when area is 1 m^2 or more and 0.85 otherwise
- $C = A/2{H_{ice}}^2$ or 1 at minimum (it is not clear whether the actual or the modified projected area should be used)
- C_1 location and propeller type factor for hub and strut loads
  - 1 in general
  - 1.5 for pulling and pushing "front propeller" strut loads and pushing propeller axial pod loads
  - 2.2 for pulling propeller axial load ("hub load") calculated based on projected hub area
- C_2 reduces pod ice loads by 1/3 for under bottom mounted units
  - 1 in general
  - 2/3 for "deep submerged" under bottom located propellers
- C_3 ship type factor
  - 1 in general
  - 1.25 for icebreaker and ice management vessel
- C_4 statistical factor for expected maximum load during 20 years lifetime
  - 1.2 in general

Table 1. Values of H_{ice} and p_0 as a function of ice class in DnV's method.

Ice Class	H_{ice} (m)	p_0 (MPa)
1AS	1.75	1.4
1A	1.5	1.25
1B	1.2	1.1
1C	1.0	1.0

5.4 FEM simulation of ridge penetration

5.4.1 General

FEM simulation results in valuable information of thruster-ice interaction, which is difficult to gain by other methods. One can observe from simulations which failure mode of ice takes place during thruster interaction or what is the influence of ridge composition, ice thickness etc. Simulation results can be utilized to develop simplified equations for ice load predictions. However, the validation with full-scale data is required.

5.4.2 Material models to describe ice failure

The material models for ice ridge and FEM-model development for the ice-thruster interaction were carried out in a previous AHRAVUO-project (http://ahravuo.vtt.fi/, Heinonen, 2004). These include a material model for the ice rubble and a model for the consolidated layer which describe the failure of ice. These models have been implemented into Abaqus finite element software. Figure 9 illustrates a shear-cap failure criterion for ice rubble in stress space. The material parameters were evaluated according to full-scale measurements in Gulf of Bothnia. In these tests, the mechanical properties of ice ridge were measured by different type of loading tests during five winters (Heinonen, 2004).

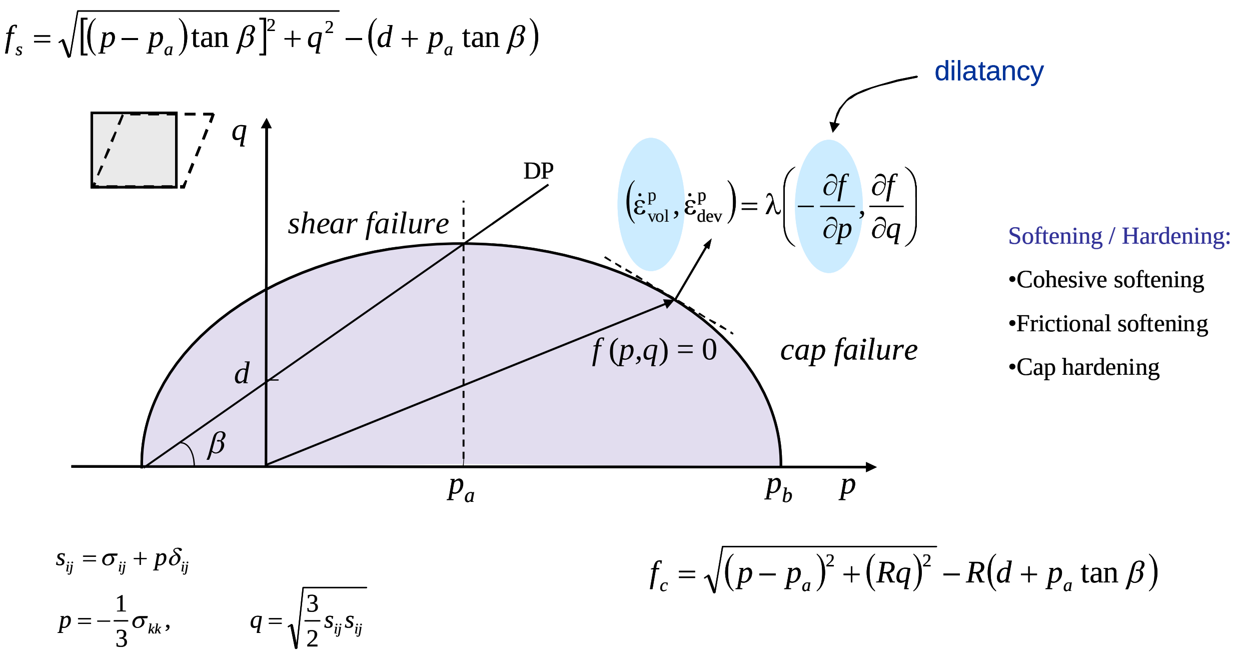

Figure 10. Shear-cap failure criterion in stress space for ice rubble introducing the shear failure and the compaction failure (Heinonen, 2004).

5.4.3 Finite element model

The FEM model for ice-thruster interaction is shown in Fig. 10. The ridge is modelled by deformable elements including the failure criterions as mentioned above. The ship body and the thruster are modelled by rigid elements, because the stiffness of these parts is high compared to ice. Therefore, the deformations of thruster or ship body do not influence on the ice loads significantly.

The ridge was modelled to float on the water by controlling the vertical position with the gravitation and buoyancy forces. The ridge was idealized to include three layers of constant thicknesses: the sail, the consolidated layer and the keel. The ridge field was assumed infinite in the horizontal direction by utilizing infinite elements at the circular edge (see Fig. 10). The ship body with the thruster was moved horizontally towards the free edge of the ridge. The steering angle was 90 degrees.

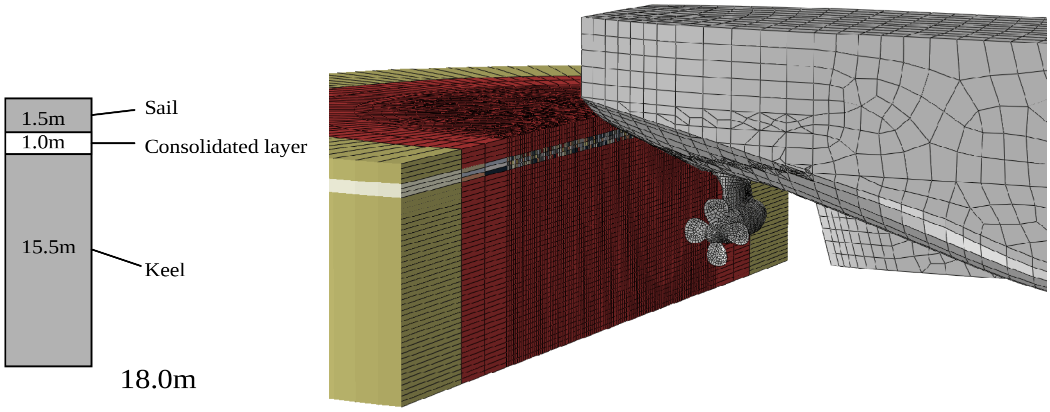

Figure 11. FEM model for ice-thruster interaction. At left: main dimensions of selected ridge. At right: the idealized ridge is floating on the water and the ship body with a thruster is moving horizontally towards the ridge. The steering angle is 90 degrees. The model represents a large scale thruster.

6 Results

Load calculation examples and result comparison for selected load scenarios and load models follow in this chapter.

6.1 Comparison of the load models

6.1.1 Ice impact

In comparison of the load models two example thruster are used. Small thruster has the hub diameter 0.6 m and mass 20 tons and large thruster has the hub diameter 1.8 m and mass 100 tons. Loads are compared in ice classes 1AS and 1C. For ice class 1AS the mass of the ice block is defined to be 26 tons and for ice class 1C 6 tons. Loads are calculated with two vessel speeds, 4 and 8 knots.

When using the ABS method kinetic energy is calculated from the ice block mass instead of effective mass of the ship. Value ex = -0.5 is used as in VTT's impact model instead of ex = -0.1 which is used in ABS's own calculations.

When using the DnV method the following values for factors are used

- C1 =2.2 for pulling propeller axial load (”hub load”) calculated based on projected hub area
- C2 =1 in general
- C3 =1 in general
- C4=1.2 in general

Ice loads calculated by different methods for small thruster are shown in Figure 12 and for large thruster in Figure 13. Ice loads are calculated with vessel speeds 4 and 8 knots and for ice classes 1AS and 1C.

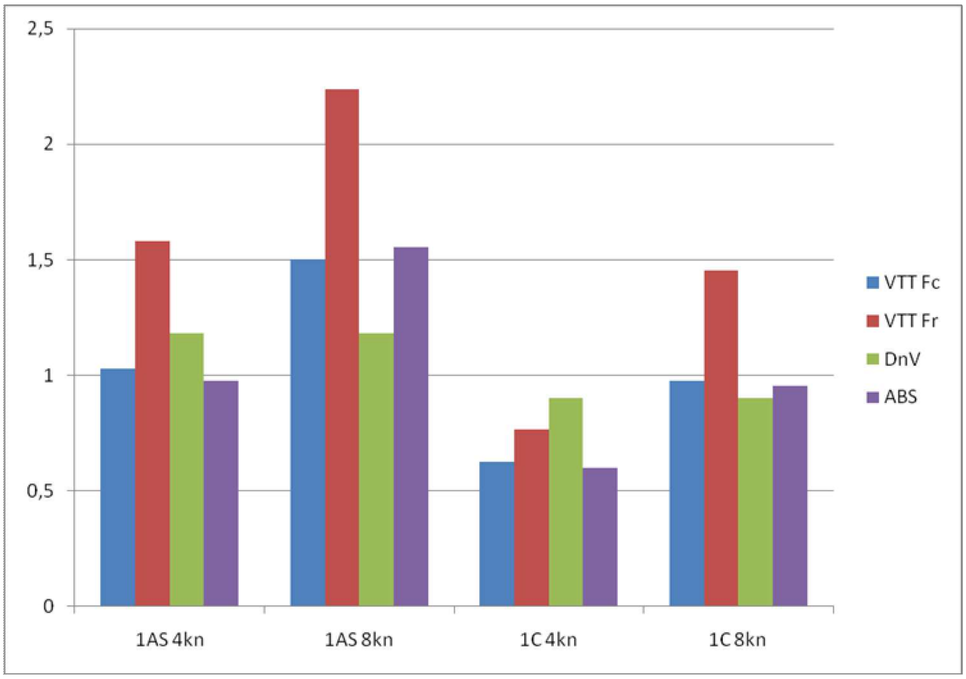

Figure 12. Ice loads for small thruster with hub diameter 0.6 m and thruster massa 20 tons. Loads are calculated with ice classes 1AS and 1C, speeds 4 kn and 8 kn and methods of VTT, DnV and ABS.

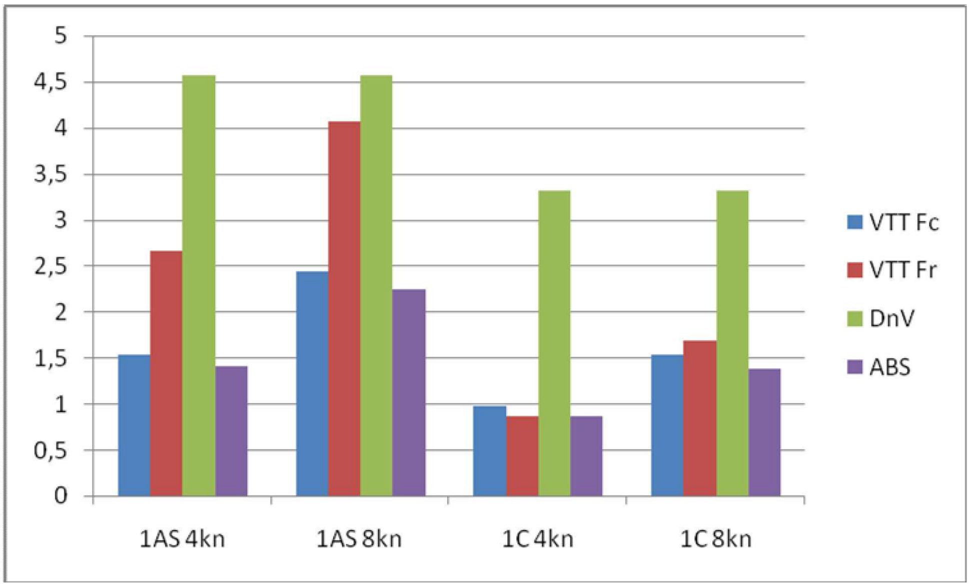

Figure 13. Ice loads for large thruster with hub diameter 1.8 m and thruster mass 100 tons. Loads are calculated with ice classes 1AS and 1C, speeds 4 kn and 8 kn and methods of VTT, DnV and ABS.

6.1.2 Ridge penetration

Simulations resulted in pressure distributions on the thruster body. Figure 13 introduces the cross section view along the symmetry axis of ridge. Therefore, only part of the thruster and ship body is shown. One observes that ship hull push the consolidated layer downwards causing increased pressure in the front of the body. Although the ship hull fails the consolidated layer by bending it downwards, increased pressure makes the underlying rubble stronger. That has a disadvantage to increase the loads on thruster body due to ice rubble.

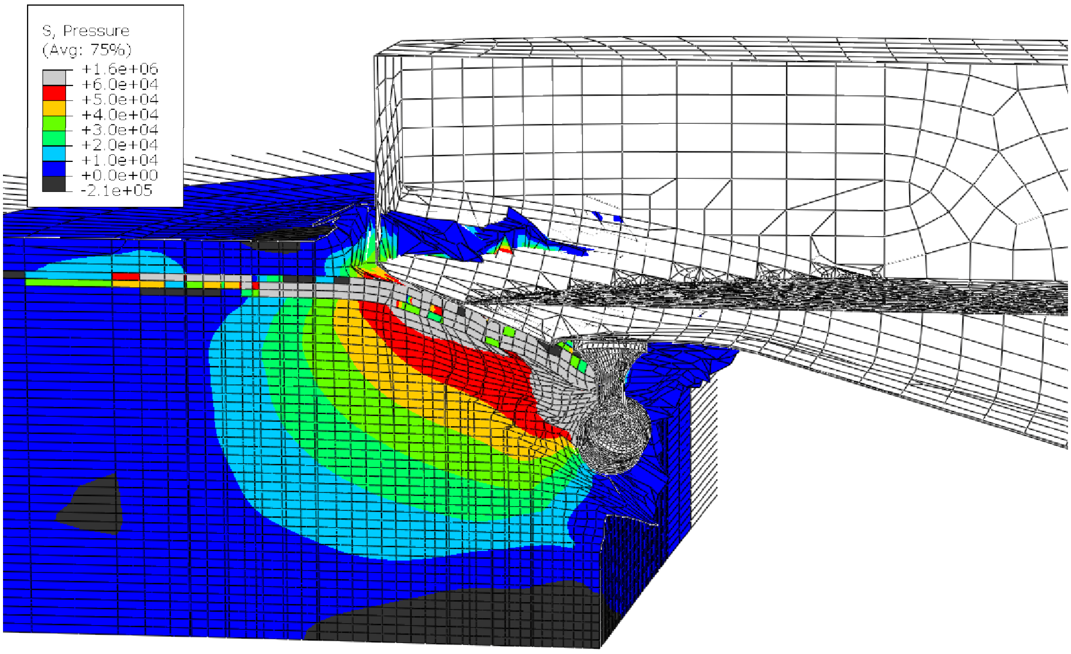

Figure 14. Pressure stress distribution in ridge during thruster penetration. Cross section view along the symmetry axis of ridge. Therefore, only part of the thruster and ship body is shown. The light grey area represents pressure over 60kPa and dark grey area below zero.

Figure 14 represents the ice pressure distribution on the thruster and ship hull at one selected time instant. Due to non-simultaneous ice failure, high pressures occur only in few spots. The locations of spots vary continuously. These spots represent the load mostly due to the consolidated layer of the ridge, which is observed from Fig. 13.

Ice pressure distribution depends much on the size of the thruster and the composition of ridge. The thicker the consolidated layer is, the larger the high pressure region is.

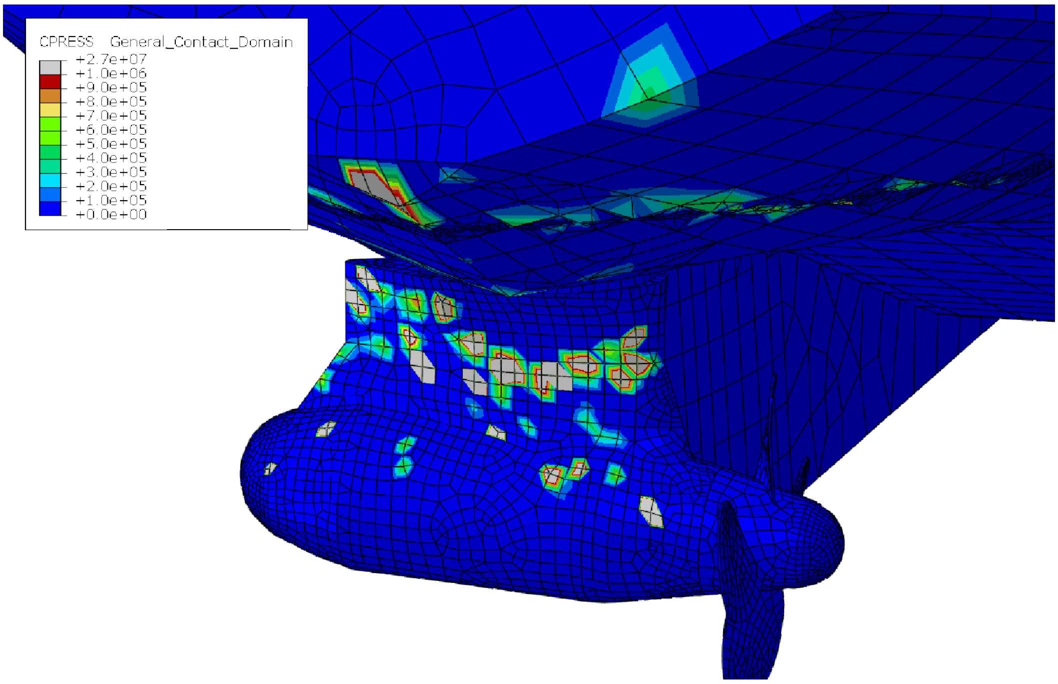

Figure 15. Ice pressure stress distribution on the thruster body during ridge penetration. Therefore, only part of the thruster is shown. The light grey area represents pressure over 1MPa.

FEM simulations were utilized to introduce an effective pressure distribution on the thruster body. A simplified model was developed by introducing a number of layers with equal thicknesses. Each layer was attached with a constant pressure varying from layer to layer as shown in Fig. 15. The pressure for each layer was selected as the highest value of the corresponding region during the time history analysis. Since the maximum values occurs at different times for each spot, this assumption results in a conservative ice load prediction. Therefore, further studies are needed to define more accurate estimate for the equivalent ice pressure distribution and corresponding resultant ice load.

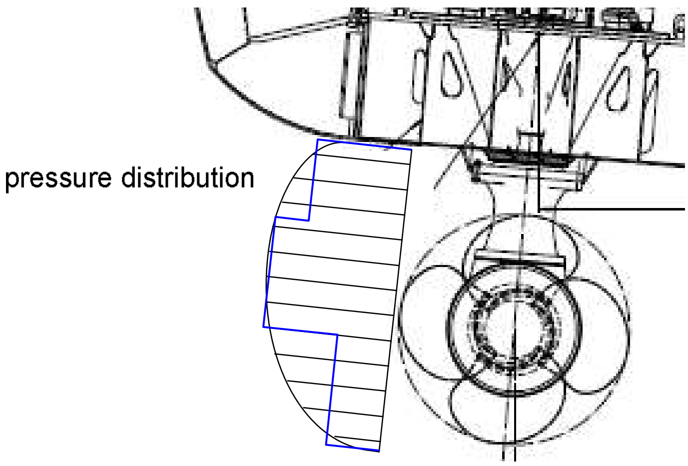

Figure 16. Theoretical load distribution from ridge interaction shown by black curvilinear line. Corresponding stepwise linear distribution is shown by blue line.

From the pressure distributions one can define the ice force (F_i) corresponding to each layer of thruster body and total force (F_{max}) as

$$F_i = p_i A_i$$

$$F_{max} = \sum_i F_i$$

in which p_i is the effective pressure for each layer and A_i is the corresponding projection area of the thruster.

Case study

Simulation based ice loads for a large size thruster are introduced in Table 2. Simulations with a small size thruster have not been done, but the corresponding DnV calculations were carried out for both thruster sizes. Simulation based load predictions were compared to DnV's prediction in Table 3.

Table 2. Simulation based ice loads in ridge penetration case for ice classes 1AS and 1C. Corresponding thicknesses, areas, effective pressures and forces are shown for each layer resulting in the maximum ice force.

1AS

h=1.75m

Layer	Ice feature	Thickness	Area	Eff. pressure	Force
		(m)	(m2)	(MPa)	(MN)
1	CL	0.58	3.50	0.70	2.45
2	CL	0.58	3.50	0.75	2.62
3	CL	0.58	3.50	0.40	1.40
4	Rubble	3.85	31.50	0.04	1.26
Sum		5.60	42.00		7.73

1C

h=1.00m

Layer	Ice feature	Thickness	Area	Eff. pressure	Force
		(m)	(m2)	(MPa)	(MN)
1	CL	0.33	2.00	0.70	1.40
2	CL	0.33	2.00	0.75	1.50
3	CL	0.33	2.00	0.40	0.80
4	Rubble	4.60	36.00	0.04	1.44
Sum		5.60	42.00		5.14

Table 3. Ice loads according to DnV and from simulations in ridge penetration case for ice classes 1AS and 1C. Only larger thruster was simulated. On contrary the ice impact load calculation, C_1=1.0 was used in DnV ice load prediction.

		Small thruster A=6m^2		Large thruster A=42m2	
		DnV	*Simulation*	*DnV*	*Simulation*
Ice class	Ice thickness (m)	Force (MN)	Force (MN)	Force (MN)	Force (MN)
1AS	1.75	2.7	x	3.2	7.7
1C	1.00	1.6	x	1.9	5.1

According to DnV guidelines, the influence of considered projected area exposed to ice pressure becomes minor, when the area exceeds the parameter $2h_{ice}^2$. In this study the projected area of large thruster interacting with the ridge is 7 times the area of small thruster. Respectively, the ice load according to DnV is however only 19 % higher.

The ice loads according to DnV are much less than from the FEM-simulations. The comparison is not unique, because the simulation takes into account the whole ridge including the consolidated part, sail and keel. DnV prediction was based on the thickness of consolidated layer. Even though DnV ice rule is straightforward to use, it does not describe accurately how the projected area exposed to ice pressure should be determined. The ice pressures according to DnV are 1.4 and 1.0 MPa respectively to ice classes 1AS and 1C. These are however much higher compared to simulations, see Table 2.

Conservative prediction of simulation concerning to the pressure distribution model was discussed above. One should also pay attention that experimental validation and comparison would be essential in future studies.

7 Conclusions

In this study VTT's dynamic impact model was developed. Ice force calculation methods from ABS and DnV were introduced. After this ice force levels predicted by all methods were compared for two example thrusters in ice classes 1AS and 1C.

VTT's dynamic impact model includes azimuthing thruster flexibility and defines the reaction force affecting to the connection of the ship and the thruster unlike other methods. Benefit of the VTT's model is that physical background is clear and hence the method can be developed further.

ABS load model is also based for impact and it estimates ice contact loads for rigid appendage. The background of the ABS model is also available but it is still not clear. The method is not so easy to use especially because of the concept of the effective mass. When used literally the method estimates several decades lower loads than other methods. Hence ABS model input parameters were re-evaluated and after that VTT and ABS estimated contact loads rather close together.

Background of the DnV's method is not clear and it is not based on impact. The method can be understood in two different ways. DnV estimated similar loads for small thruster than other methods but loads for large thruster were remarkably bigger.

Taking account of the problems with other methods and the facts that VTT's method has a well known physical background and that it takes account of structure dynamics it is recommended further to develop the VTT's impact model and to use it as a base of the Finnish-Swedish Ice Class Rules for azimuthing propulsion units. Actual load level estimation verification is recommended to be done with measured data in the follow-ups of this project.

In this study, the FEM analyses were utilized to the large size thruster penetrating into ice ridge. A method to transform the simulation results into a simplified load calculation routine was presented. It was based on equivalent pressure distribution to the thruster body. The assumed equivalent pressure for each layer was selected as the highest value of the corresponding region during the time history analysis. This results in a conservative ice load prediction, because high pressures occur at different times. Instead of the projected area, high pressures occur in small spots which locations vary continuously. These features should be included in future studies to introduce more realistic equivalent ice pressure distribution, which can be used for simplified ice rule for this loading scenario.

It is recommended to make additional FEM simulations in order to study the influence of different thruster sizes, ice thicknesses and ridge compositions. This would enable more extensive comparison to present ice rules and improve the applicability of results in various thruster sizes. DnV introduces a straightforward method, but applicability in the case of large thrusters in ridge penetration load scenario needs further development and comparison to simulations and full-scale tests.

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http://ahravuo.vtt.fi/
AHRAVUO - Ridge-structure interaction simulation, Project www-pages

Appendix A. Project plan for 2011 and further