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Numerical case studies of the ice loads to an Azimuthing thruster during the ridge interaction

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An interaction between an azimuthing thruster and an ice ridge was simulated by the finite element method (FEM). An explicit solution algorithm was utilized, which enabled an efficient way to simulate ice failure in a dynamic analysis. The model described the whole ridge: the sail and keel consisting of ice rubble and the consolidated layer close to the waterline. The geometry of ridge was discretized by the finite elements. The azimuthing thruster including a part of ship body was modelled as a 3-dimensional rigid structure.

The failure of rubble was modelled with a shear-cap material model. Spatially distributed material parameters together with the Concrete Damaged Plasticity –model (CDP) were applied to simulate the failure of the consolidated layer

In the selected case, the ship moves backwards with an initial velocity against the ridge. It was assumed that the propeller does not rotate. The numerical study introduced basic understanding about how the ridge fails during the interaction with the ship hull and thruster body, how the ice loads are distributed and how large the overall ice loads for the thruster are.

Three different ridge geometries were studied representing mild, typical and extreme conditions in Baltic Sea. Also, the parametric study included a variation of the initial velocity of the ship and the steering angle of the thruster. The simulations show a good correlation with the full-scale ice load measurements. The simulation results will be further utilized as background information for the upcoming proposal of the Finnish Swedish Ice Class Rules for Propulsion Machinery regarding Azimuthing thrusters.

1. Introduction

Ice ridges are common ice features in Northern seas. As they introduce significant loads on marine structures in navigation, ridge loads must be taken into account in the structural design. The structural design of propulsion systems designed for ice-covered sea areas is regulated by ice class rules.

The ice class rule development is aimed to be harmonized with international ice class rule work. The approach is first of all to determine the relevant ice load scenarios and load cases to be included in the ice class rules. Secondly, the ice loads will be calculated with sophisticated models including experimental verification. Thirdly, simplified load formulae will be developed based on ice load models and measurement data. To meet the above mentioned steps, this paper introduces background information based on numerical simulations of ridge-interaction with Azimuthing thrusters to be used in the upcoming proposal of the Finnish Swedish Ice Class Rules for Propulsion Machinery. This paper focuses only on ridge interaction studies. Other relevant load scenaria like the ice impact on the thruster body is introduced by Kinnunen *etal.* (2014) and ice-induced cavitation loads by Lämsä *etal.* (2014).

The aim was to make a parametric study for thruster-ridge interaction to find out the influence of the ship size, ship velocity, thruster size, thruster steering angle and ice conditions (ridge geometry). Icebreaker Fennica was selected as a ship model representing the basis for model validation, as earlier full-scale measurement data is available (Koskinen *etal.*, 1996). This paper highlights some of the main interesting observations from the parametric study.

A first-year ice ridge contains a large number of ice pieces of varying sizes and shapes that are piled arbitrarily. The 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. A continuum approach in Lagrangian framework was used to model the ridge behaviour. Numerical simulations were carried out by using the commercial software Abaqus/Explicit based on the finite element method (FEM). In-house user subroutines were applied to describe material behaviour of the ice rubble and the consolidated layer. A shear-cap model was used to introduce the shear and compaction failure in ice rubble (Heinonen, 2004). Spatially distributed material parameters together with the Concrete Damaged Plasticity –model (CDP) were applied to simulate the failure of the consolidated layer (Heinonen & Kolari, 2012).

2. Load scenario

Relevant ice load scenaria for podded propulsions have been studied by many research groups *e.g.* Koskinen etal. (1996), Hänninen *etal.* (2007) and Evenko *etal.* (2009). Guidelines for the design are given by various classifications authorities *e.g.* DNV (2010). Regarding the ridge interaction, the worst scenario to introduce the highest loads on the thruster body was assumed, when the ship reverses towards an ice ridge (see Fig. 1). It is noteworthy that the thruster body interacts both with the consolidated layer and unconsolidated part (ice rubble). It was further assumed that the propeller does not rotate.

This load scenario was studied by FEM -simulations. Even though the FEM simulation with an advanced ice failure model requires very intensive computation and is fairly complicated to use, it gives basic understanding about how the structural design and loading conditions influence on the failure mechanisms of the ice. Also, the simulations expand our knowledge of the main variables regarding the ice load and how it develops during the ice-thruster interaction. For instance, to justify the worst case, the influence of steering angle can be straightforwardly studied by the FEM-analysis. The FEM approach can then further be utilized to develop a simplified equation-type ice pressure model.

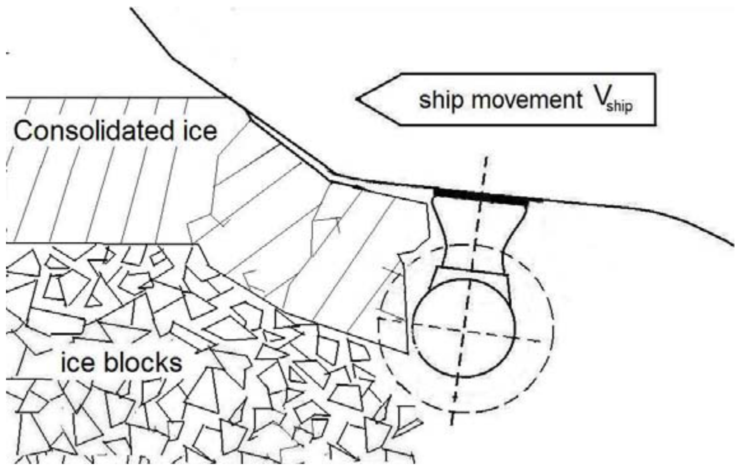

Figure 1. A sketch of the ridge penetration load scenario: a ship with the thruster(s) in selected steering angle is reversing towards an ice ridge.

3. Numerical model

3.1 Ridge geometry

The severity of the ice conditions were studied by defining the three ridge types: mild, typical and extreme. Total ridge height was 3.6 m (mild), 5.0 m (typical) and 10.0 m (extreme) as shown in Fig. 5 shows.

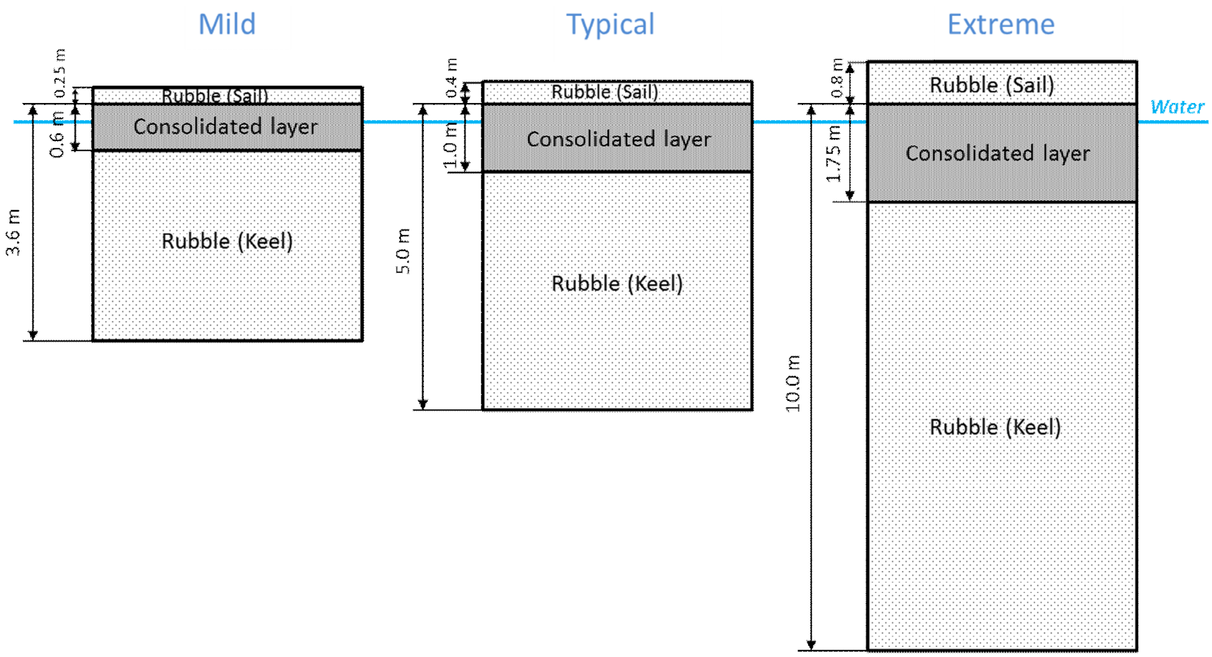

Figure 2. Three ice ridges geometries selected for the thruster-ridge interaction simulations.

3.2. Mechanical properties of the consolidated layer and ice rubble

The consolidated layer is 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 are varied randomly such that each layer consists of ten different material properties with the same mean and standard deviation as obtained in the material tests. More detailed description is given by Heinonen & Kolari (2012). Concrete Damaged Plasticity –model (CDP) is applied to simulate the failure of the consolidated layer. Mechanical properties of consolidated layer are listed in Tables 1-3. Ice density is ρ = 900 kg/m3. Tensile strength is about 8 % from compression strength.

Table 1. Ice properties of the consolidated layer, mild ridge.

Depth [m]	E_{ave} [GPa]	E_{stdev} [GPa]	$\sigma_{c,ave}$ [MPa]	$\sigma_{c,stdev}$ [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 2. Ice properties of the consolidated layer, typical ridge.

Depth [m]	E_{ave} [GPa]	E_{stdev} [GPa]	$\sigma_{c,ave}$ [MPa]	$\sigma_{c,stdev}$ [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 3. Ice properties of the consolidated layer, extreme ridge.

Depth [m]	E_{ave} [GPa]	E_{stdev} [GPa]	$\sigma_{c,ave}$ [MPa]	$\sigma_{c,stdev}$ [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

The values of the cohesion d and friction angle β of the ice rubble are chosen following: d = 6.0 kPa and β = 35°. Furthermore, the density of ice rubble is ρ = 642 Kg/m3, elastic modulus E = 1.1e+08 Pa, Poisson's value ν = 0.3 and friction coefficient in the ice-structure contact μ = 0.15. (Heinonen, 2004).

3.3. Geometrical model of the thruster and hull

The icebreaker Fennica, with two propulsors, was utilised as basis for the case studies. The size of the thrusters was the same as in Fennica, but their shape was different, without any nozzle. This report concludes the results with one specific thruster size having following main dimensions: thruster's diameter was 2.40 m and length 5.60 m, propeller diameter was 4.20 m and number of blades was 4. Ship hull length was 116.0 m, width 26.0 m and draught 12.5 m. The ship mass was 9 760 000 kg. The model of ship hull geometry and one thruster is shown in Fig. 3.

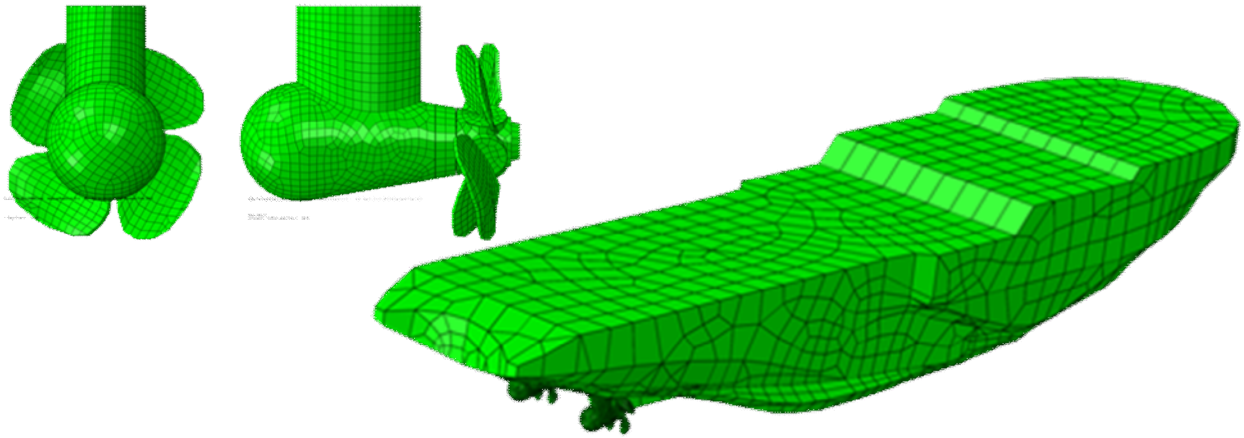

Figure 3. Two projections of the azimuthing thruster shape used with the model of the icebreaker Fennica.

3.4. FEM-model of ship-ridge interaction simulation

The geometry of ridge was discretized by the finite elements. Ridge thickness was modelled to be constant. The ship hull with two azimuthing thrusters was modelled as a 3-dimensional rigid structure. The FEM -model of ship-ridge interaction is shown in Fig. 4. To minimize the computational time, the number of degrees of freedom were minimized by varying spatially the density of element mesh. To avoid bouncing stress waves, infinity elements were applied to describe far-end boundary condition. Numerical simulations were carried out by Abaqus/Explicit version 6.12.

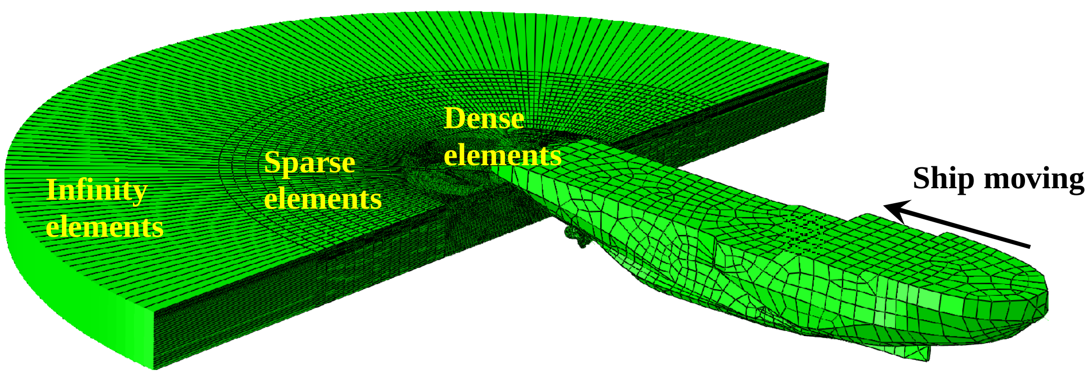

Figure 4. FEM -model of ship-ridge interaction.

In the simulation, the ship had initially a constant speed when reversing towards the ridge. During the penetration the ship decelerated due to the ridge resistance finally stopping after a certain amount of penetration. One individual run simulated the penetration of 10-15 s, corresponding 18-56 m movement of the ship. The simulation of ridge-interaction process resulted in among others contact pressures of the thruster and corresponding loads.

The parametric matrix for simulations consisted of following cases:

- Ridge type: mild, typical and extreme
- Ship initial speed: 5, 8 and 12 knot
- Thruster steering angle:
  -180° (longitudinal load scenario with the propeller ahead) and
  -90° (transversal load scenario).

4. Results

Fig. 5 shows the maximum horizontal thruster penetration loads in the ship moving direction examined during the simulated ridge interaction. One observes that the higher the ship velocity, the higher the load is. The increase from 5 to 12 knots doubled the ice loads, approximately. Also, for the typical and extreme ridges, turning the thruster to the transversal position increases the load between 40 and 70% compared to the longitudinal position. That is a natural consequence because the contact area of the thruster interacting with the ice in the transversal position is much larger than in the longitudinal position. However, similar conclusion cannot be made for the mild ridge. In that case more deviation was observed in the force signals with the high velocities (8 and especially 12 knots), which made it more difficult to make the comparison between selected steering angles. However, more studies are needed to make a conclusion regarding the mild ridges.

Various ridges describing different ice conditions had also a significant influence on the maximum ice loads. As the consolidated layer was harder than the ice rubble, the major part of the ice load was introduced by the consolidated layer, partly interacting with the strut of the thruster and with the pod. All the cases in Fig. 5 indicate that the thicker the ridge, the larger the loads are.

Based on the full-scale tests with Fennica ice breaker, the simulations show a good correlation with the measurements (Koskinen *etal.*, 1996).

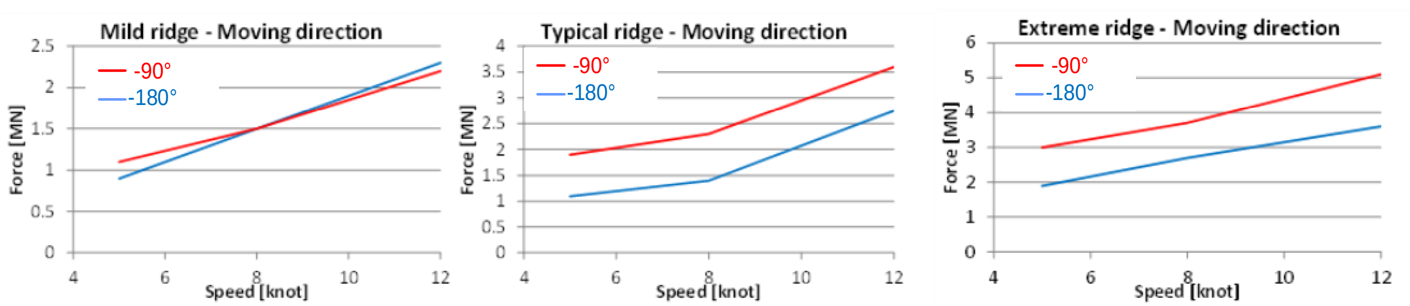

Figure 5. Maximum horizontal thruster penetration loads shown as a function of the initial ship velocity. The loads are considered in the ship moving direction in various ice conditions. Steering angle of -90° (transversal load scenario) is shown with a red line and respectively -180° (longitudinal load scenario) with a blue.

Discussion and conclusions

An interaction between an azimuthing thruster and an ice ridge was simulated by FEM. The ship had initially a constant speed when reversing towards the ridge. The numerical study introduced basic understanding about the ice loads during ridge interaction with the ship hull and thruster. Three different ridge geometries were studied representing mild, typical and extreme conditions. Also, the initial velocity of the ship and the steering angle of the thruster were varied.

Main observations from the simulations are following: the higher the ship velocity, the higher the ice load on the thruster is. Also, for the typical and extreme ridges, turning the thruster to the transversal position increases the load significantly compared to the longitudinal position. However, this was not observed in the case of the mild ridge. The ice load dependency on the thruster size and comprehensive experimental validation is left as future study.

The simulation results will be further utilized as background information for the upcoming proposal of the Finnish Swedish Ice Class Rules for Propulsion Machinery regarding Azimuthing thrusters. The proposed formulation will introduce the contact pressure on the thruster body with a simplified dependency of thruster loads and ice conditions, ship velocity and thruster size.

Acknowledgments

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