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Ice-structure impact contact load test setup and impact contact load calculation

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Shipping in arctic and other 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 ice block and thruster. The contact causes certain loading to thruster. The contact load problem can be considered as ice impact to steel structure. In a research project related to developing Finnish-Swedish ice class rules, the impact forces due to ice contact to steel structure are dealt with a simple theoretical model and experimental approach is used for model validation. In this paper, the experiment setup and result examples are presented.

The experimental setup presented was used for studying the contact force during an impact type contact. Impacts were hit to solid ice and floating ice block, contact point was submerged. The test device is representing a ship and thruster structure, and is laboratory scale equipment. The test device is a pendulum mass with changeable impact contact head. The device provides impact contact load measurement, pendulum motion measurement and the ice movement measurement. In addition, synchronized video recording was made. Tests were performed on sea ice during March 2013. The speed range capability for the test device is representative for ship speed in ice channel operation. In the tests, impact energy was varied by varying the pendulum start level. Two sizes of hemispherical contact geometries were used. Test results indicate distribution of energy in the impact event, i.e. ice kinetic energy, impacting mass kinetic energy and the rest is assumed to be drag and ice crushing energy. The test setup can very simply be tuned to different dynamic state to represent different stiffness of thruster installation to ship, and it can accommodate different contact geometries.

1. Introduction

When operating a ship in ice conditions, an ice load scenario for azimuthing propulsion can be considered when ice block impacts to thruster. Ice block can e.g. hit the thruster housing or propeller hub. Examples of such cases are shown in Figure 1.

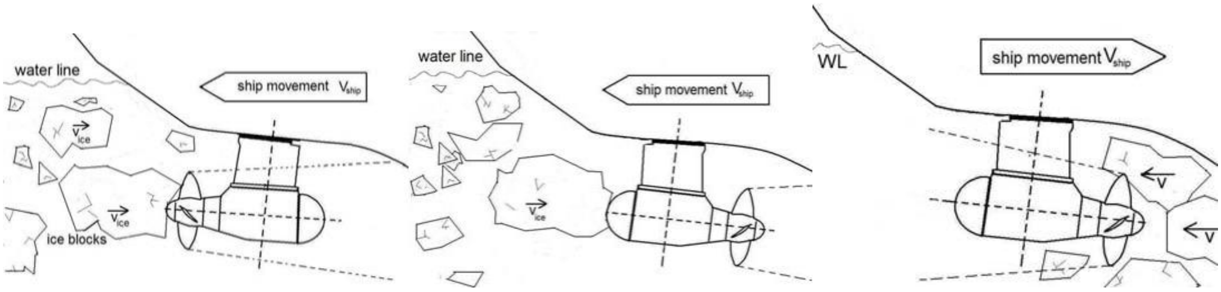

Figure 1. Ice block impact to azimuthing thruster

This kind of impact contact is assumed to give short duration loading for the thruster structure. At least ABS, DNV and VTT have published methods for estimating the loads originating from ice block impact. ABS's method is based on the conservation of energy in impact (Daley, 1999, Daley and Yu, 2009). In their method, all the kinetic energy is used to the ice crushing. VTT model (Tikanmäki et al, 2010) also uses the available kinetic energy to limit the ice crushing work in impact contact. DNV gives calculation formula (DNV, 2010) for estimating impact contact loads.

This type of impact loads have been observed in full scale measurements (Koskinen, 1993). For validating a impact load calculation model, full scale measurements are a good source of data but they lack the information of impacting ice block size and contact velocity. These parameters are assumed to be among the important ones when computationally determining the impact contact load. To study the impact contact of steel structure and ice, a simple experimental setup was built. The experimental setup is described in the following chapter, subsequently followed by review of results and impact load calculation example.

2. Experimental setup for ice impact testing

For making an experimental setup of ice-structure impact contact, the key definable parameters were considered to be a) impact initial velocity control, b) impact contact area shape control, c) capability to measure the impact contact load, d) impact contact under water with sea ice, and e) structure should somehow represent a ship thruster.

These rough targets in mind, a pendulum mass type realization was considered. The principle of the test setup together with the actual realization is presented in Figure 2.

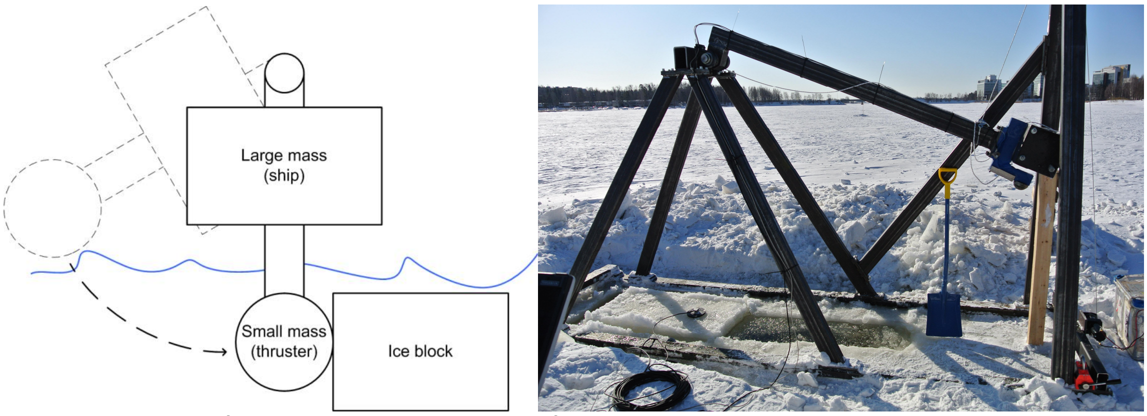

Figure 2. Principle for impact test setup on the left. The actual experiment device on the right. Pendulum setup where the impact contact point is under water.

The actual realization of the test setup was iterated to have the desired features, and in addition, the pendulum mass was chosen to be changeable. In the tests, pendulum moving mass was between 220 – 224 kg depending on the installed impact head.

The key element in the setup is the combined force transducer and impact mass. The actual contact head is screwed onto the baseplate with M12 stud. Baseplate serves also as the force transducer and attachment point for impact mass (see Figure 3).

The impact load measurement is based on measuring strain caused by bending in the force transducer plate. The strain is measured with strain gauges installed in ½ bridge configuration. Pendulum mass motion and ice block motion were measured with tri-axial acceleration sensors. The self-built force transducer was calibrated with mass loading against calibrated reference load cell (HBM C4/100 kN). Load calibration data is shown in Figure 3. Acceleration sensors are calibrated by VTT according to the calibration schedule against certified reference transducer.

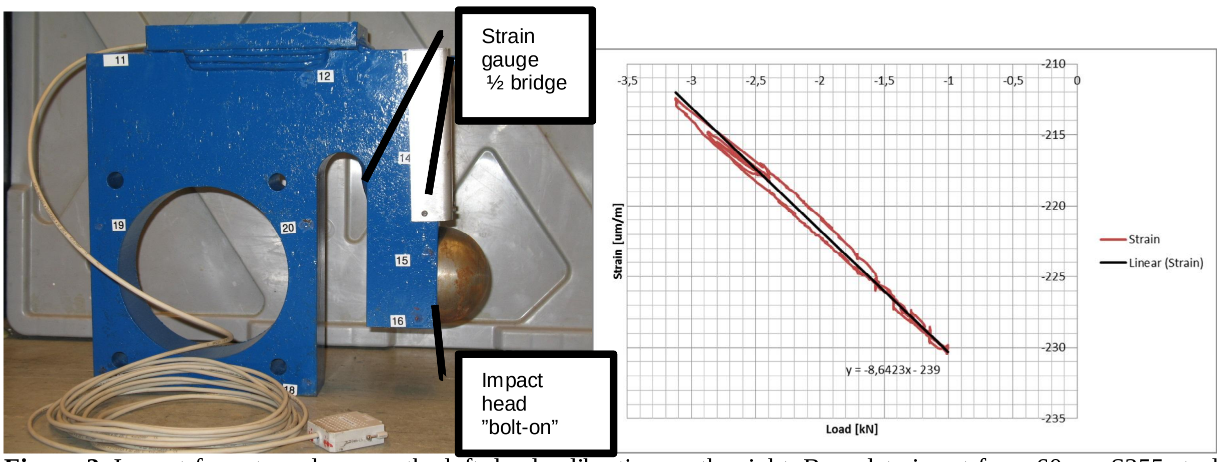

Figure 3. Impact force transducer on the left, load calibration on the right. Baseplate is cut from 60mm S355 steel plate. Acceleration sensor is attached with bolt. Impact head is hemisphere. The 100 mm diameter model is installed in figure, attached with M12 threaded stud.

3. Impact test results

In March 2013, set of tests was done on Baltic Sea ice in Finland, Espoo. Summary of tests is in Table 1. Impacts were done both to solid ice and floating ice block. In the tests, the impact velocity was controlled by setting the pendulum start height. The contact head was a hemisphere. Two impact head sizes were used, 100 mm and 150mm diameter hemispheres (denoted as small head and big head in test case table below). Ice conditions during tests were rather constant, ice thickness being approx. 0.5 m and air temperature approx. – 10C^0. Ice temperature was measured from bottom of 5mm diameter and approx. 30 mm deep hole drilled on ice top surface.

Table 1. Test series in March 2013.

Nr	Date	Time	Test description	Ice temperature C^o	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

For analysis, the measured strain was calculated to force, accelerations were integrated to velocity. Example of impact result from impacting to solid ice with 100 mm impact head is shown in Figure 4.

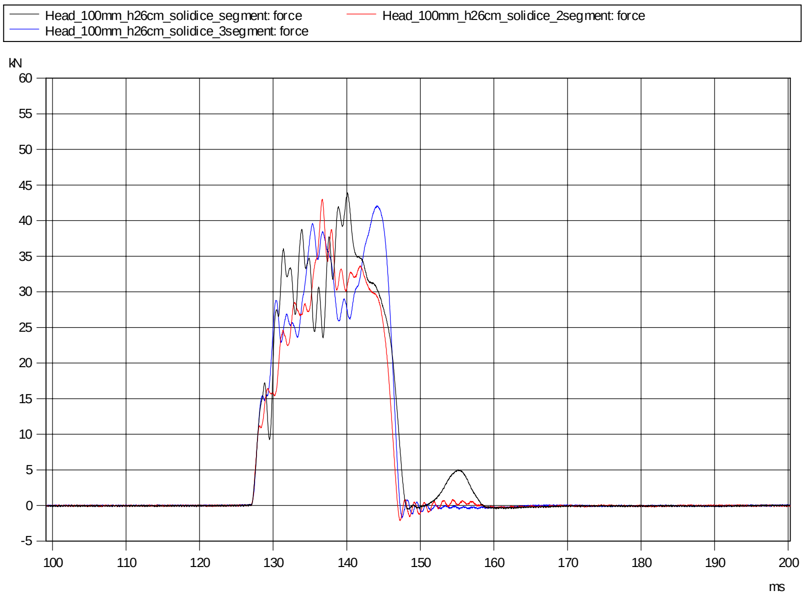

Figure 4. Load measurements from first three tests, March 2013.Three consecutive impacts to solid ice with 100 mm impact head.

In measurement analysis, the pendulum mass and ice block kinetic energies were calculated from mass and velocity. The analysis stage data example is presented in Figure 5.

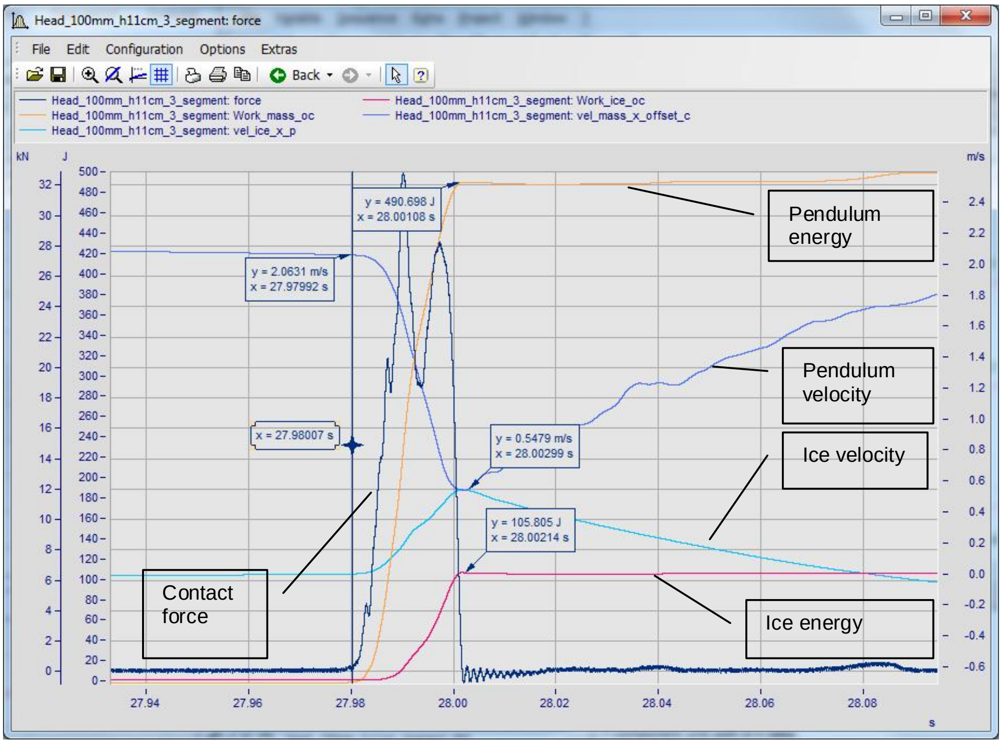

Figure 5. Example of the measurement data analysis. Test 6, impact to ice block with 100 mm impact head. The results shown are contact force, pendulum mass velocity and kinetic energy, ice block velocity and kinetic energy.

4. Impact load calculation method

The general principles of the impact load model are presented here, for more details see reference (Tikanmäki et al. 2010).

The principle of the model is shown in Figure 6. The model utilizes three-mass system, where ship mass m_s is moving at initial velocity v_0. The thruster is considered as mass m_t connected to ship with stiffness k. Response force between ship and thruster is F_r. The ice block is assumed to have mass m_i and the contact between the ice and thruster is described with contact load function F_c. The ship is assumed to move, and ice is assumed to be stationary floating object in water prior to impact. In the model, damping is assumed to be in the thruster structure. The system is solved with difference method in time domain (Tikanmäki et al, 2010). The model is implemented as MATLAB function.

The contact load is calculated as a function of contact area A, reference area A_{ref} and reference ice crushing pressure p_{ref}. Here, the ice uniaxial compression strength is used as the reference pressure. E.g. value of 3 MPa is good choice for Baltic Sea. A maximum contact pressure limit is set, this is needed especially for small contact areas to prevent unrealistic contact pressures. The contact is assumed to be a hemisphere of radius r indenting into ice. Between ice and steel there is assumed to be water film that is squeezed out of the contact region during penetration and the water film is assumed to restore if contact starts to open. This condition can be called as hydrodynamic contact. The load component depending on the water film thickness, squeezing velocity and water viscosity is taken from lubrication theory.

The area-pressure relationship and contact area are determined to be following

$$F_c = p_{ref}\sqrt{A_{ref}A},\qquad A = \pi(r^2 - (r^2 - u_2 - u_1)^2) \tag{1}$$

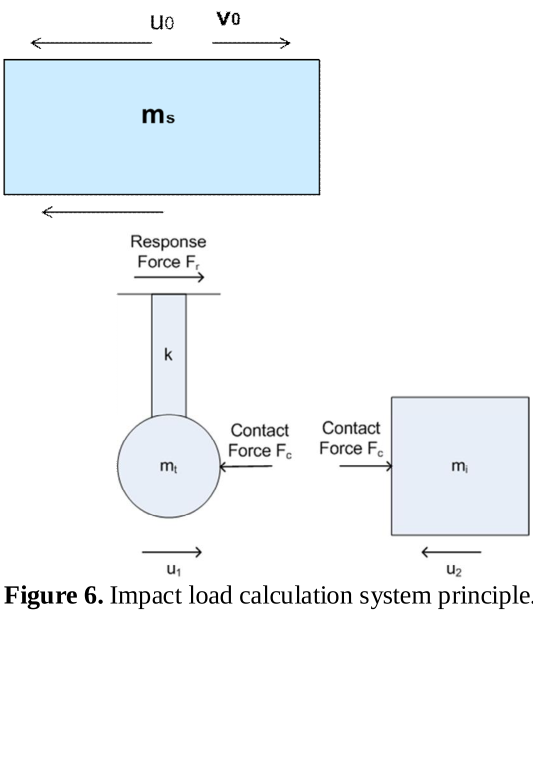

Figure 6. Impact load calculation system principle. (Kinnunen et al. 2012).

The system equations are simple, and they are solved with the known initial conditions. In addition ice is considered to have linear elastic properties prior to failure, and the water drag force to ice block is included. The limit for penetration is based on the kinetic energy. Ship and thruster is assumed to push the ice block to move at the same velocity as they are moving. This limits the crushing work.

Model input parameters are the three masses, connection stiffness of the thruster and the ship, damping values, impacting hemisphere radius, ice uniaxial compression strength and absolute contact pressure limit. In addition the values for water density, viscosity etc. are used but usually these remain unchanged for different calculation cases. Solution from the implemented model is in the time domain. Load calculation and measurements for impacts with 100 mm impact head to solid ice and 400kg ice block are shown in Figure 7.

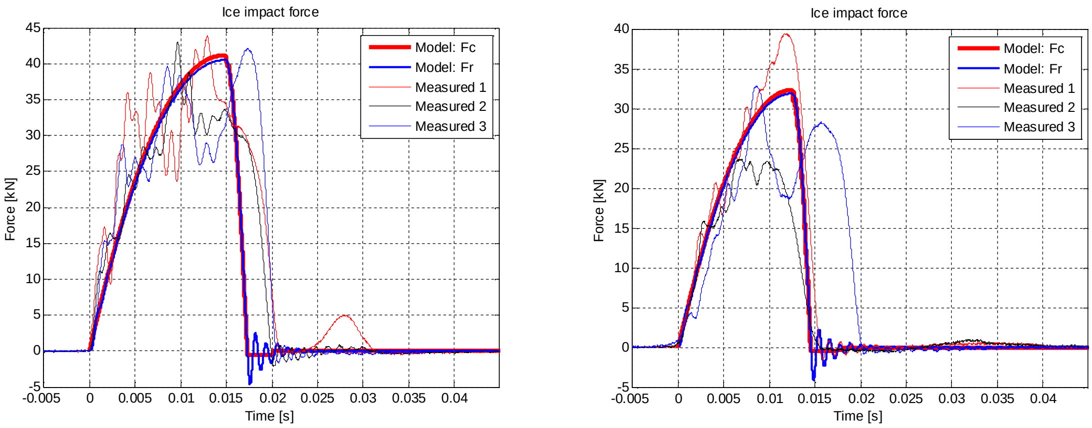

Figure 7. Impact load measurement and calculated impact loads. On the left, test cases 1-3, impact to solid ice with 100 mm impact head. On the right: test cases 4-6 and respective load calculation with 100 mm impact head, 400 kg ice block.

5. Conclusions

Experimental setup is simple, straightforward to use and provided means of getting controlled impact event measurements. The test area, Finnish coast of Baltic Sea in this case, has ice cover every winter so testing was very straightforward and easy and experiments can be repeated when needed. The impact tests provide good reference material for validating the applied impact load model. In the context of these tests, the applied impact model seems to give very good results for impact load calculation.

5. Discussion

The successful experiments and post analysis of data together with impact load modeling raised more questions. More studies are needed regarding the damping effect in impact and how to properly model it. This is crucial regarding actual azimuthing thruster load calculation, since damping is significant factor for response loads in real applications. Then, different contact geometries can be considered, for example cylindrical contact or propeller blade profile. For test parameter variation, a larger set of speed variation could be useful for developing the contact load calculation and validate the model in several points.

Acknowledgments
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