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Ice crushing tests with variable structural flexibility

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ABSTRACT

To learn more on ice crushing phenomena against a compliant stiffened plate structure, near full-scale ice crushing tests were conducted in Aker Arctic test basin with a 1:3 scaled model. The dimensions of the to be crushed ice sheet and the stiffened plate were chosen to present a full size ship or offshore structure steel plating which are designed to withstand the crushing loads of 60 cm thick level ice. A major difference to the crushing tests published earlier in literature was that the compliance of one stiffener could be adjusted. The instrumentation in the plate included both strain gauges for load paths from the plate to the stiffeners and a large tactile sensor for detailed direct crushing pressure distribution measurement. In order to have repeatable and homogeneous model ice properties the ice blocks were manufactured by snow ice technique with low salinity water impregnation under vacuum in the mould. Altogether 22 ice blocks were crushed with different ice velocities and plate compliancy. The well-known line like contact prevailed in continuous crushing. The test data indicates that the crushing load distribution is independent from the underlying plate stiffness distribution and no higher crushing pressure at the location of stiffeners was found.

1. Introduction

While ice edge is crushing in brittle mode against a structure the contact load distribution is not even through the ice thickness but is concentrated to either a line like contact, first reported by Joensuu and Riska (1989), or to isolated contact spots (Jordaan et al., 2008). These measurement results have been obtained initially from relatively small area observation windows and later by tactile sensors. Ship or offshore steel structures under direct ice action typically consist of surface plating and reinforcing frames or stringers. A common assumption in the design of steel plate thickness is a higher ice crushing pressure close to reinforcements – the stiff areas – and lower pressure at the free plate span (Fig. 1, Riska et al., 2002; Varsta, 1983).

The introduction of pressure sensitive membranes, or commonly tactile sensors, allows direct contact pressure measurements. However, tactile sensor measurements in ice crushing experiments have been conducted most often against constant stiffness surfaces. Lindholm et al. (1990), used natural 250 mm thick ice, a compliant plating covered with a pressure sensitive film, and confirmed the reduced crushing pressure at mid span.

This far the most comprehensive set of medium scale crushing tests using tactile sensors have been carried though in Japanese JOIA project starting in 1994 (Frederking, 2004; Sodhi et al., 1998, 2001; Takeuchi et al., 1997). In the tests natural sea level ice plate thicknesses varied from 65 to 451 mm and widths from 0.6 m up to 6 m (Dempsey and Shen, 2002). Separate parallel tactile sensor patches measured crushing pressure distribution, and parallel load transducers the total load. The ice thickness range covered a wider range, and the ice sheet was wider, but its strength lower due to warmer ice temperature at −1.8 °C and higher salinity than in the tests described in this paper. In general the ice failure modes and dependence on loading rate were identical. The main difference is that in Japanese tests there was no provision to adjust the structure surface stiffness.

In order to find out more on the crushing load distribution against a reinforced plate, and the effect of stiffener compliance, a Finnish joint industry project was carried through scale model tests in the spring of 2010. To minimise scale effects the dimensions of the reinforced plate and ice sheet were modelled in 1 is to 3 ratio. In addition to the different stiffness at the location of stringers the test set-up included a possibility to reduce the stiffness of one stringer in relation to the others.

This paper describes the test structure, instrumentation, model ice manufacturing, test procedures and data analysis. The objectives are to find out the correlation of crushing pressure distribution to loading rate and instrumented plate stiffness distribution. The results of the conducted tests differ from some earlier tests (Lindholm et al., 1990; Riska et al., 1990).

2. Test structure

The test structure was a trade-off between accuracy and cost. Full scale tests would have given the best accuracy but at too high cost. The

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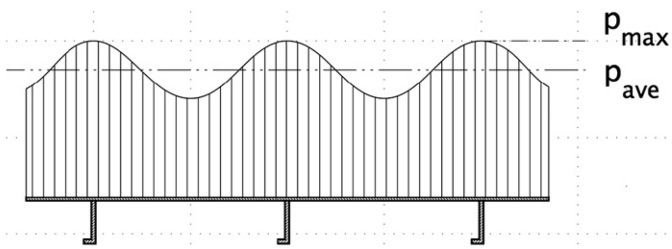

Fig. 1. Assumed ice pressure distribution.

scale-ratio for level ice crushing was chosen to be 1:3. Thus a 200 mm thick model ice would correspond to a 600 mm thick level ice. The stiffener spacing of 200 mm was chosen corresponding thus to 600 mm spacing in full scale. The ice crushing target plate was chosen to be 12 mm thick — 36 mm in full scale. It has four spans with five stiffeners. The total plate area of $1000 \times 220\ mm^2$ was wider than the intended 700 … 800 mm wide ice crushing area.

The test rig (Fig. 2), was designed for 300 kN crushing load. The rig structure was a closed frame manufactured from rectangular hollow steel profiles. The 1 MN hydraulic cylinder was attached to one end of the frame. It pushed at controlled velocity a moving sledge into which the test ice block was attached. The pusher end of the sledge had rubber surface to give an even driving pressure. The side edges of the ice block were restrained in the sledge from movement by rubber pads and to keep the ice block crushing straight and squarely on the instrumented target plate.

The compliance of the ship hull or offshore structure plating comes from two factors. The first is from the bending deformation of the surface plate itself, and secondly, from the stiffener compliance. The instrumented target plate to crush the model ice sheet is 12 mm thick. The five stiffener plates had 200 mm spacing and connected the surface plate to the test rig frame. To enhance the stiffener compliance effect the centre stiffener stiffness could be adjusted. Three settings were used during the tests:

Normal — equal stiffness in all of the five stiffeners ($\delta_{max} = 0.013$ mm)
Soft — reduced centre stiffness by rubber bearing ($\delta_{centre} = 0.476$ mm)
Free — no stiffener at the centre ($\delta_{centre} = 2.12$ mm)

The deflections in parenthesis correspond to calculated maximum displacement under an even 1 MPa crushing pressure. In the normal case the maximum deflection is at the mid span between supporting stiffeners, and in the last two at the location of the adjustable centre stiffener. These calculated maximum displacements in the plate give an indication on the effect of different compliance ratios. The centre stiffener compliance was increased by replacing the solid connection to the surface plate with a rubber bearing, or by disconnecting the centre support completely. Even the soft bearing case results to a more than an order of magnitude larger compliance.

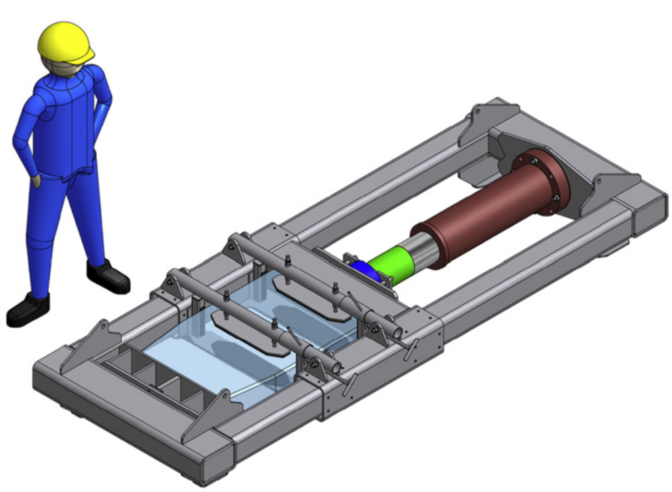

Fig. 2. The test rig.

3. Model ice

The objectives of the model ice are to repeatedly produce as close as possible the same ice failure processes as in the full scale. The model ice shall be homogeneous and its mechanical properties scalable at the same ratio as the model geometry. The target value for these crushing tests was 1:3 scale ratio to model a typical 0.6 m thick sea ice.

The model ice homogeneity was sought by choosing natural snow for ice crystal seeding and by promoting unidirectional freezing from below. The test ice blocks were manufactured in $1400 \times 800 \times 190\ mm^3$ moulds, whose bottom plate was made of steel while the sides and cover were made from plywood to enable smooth gradual freezing from bottom to the top. The mould was filled and packed with natural clean snow and the airtight cover plate was fixed on top. First the air was sucked out from the top of the mould and then 1.3 …1.4 ppt salinity water was let into the mould through two valves located at the bottom plate. During filling the mould by water, the mould was positioned to a slightly inclined position to ensure gradual smooth water filling of all the cavities between snow crystals from bottom to the top. Once the whole volume was totally water impregnated valves were closed and the mould was left into −20 °C temperature to freeze completely.

After complete freezing the ice blocks were cut to the final testing shape (Fig. 3). A 200 mm wide section was cut from one end of the block and re-stored in the freezer container to be used for index strength tests. The cut end of the block was tapered to 700 mm width to ensure the crushing to start at this end against the instrumented target plate. Hence, as the crushing continued, the initial contact width increased from 700 to 800 mm. This effect could be observed in the measurement data, c.f. Fig. 8.

The intended temperature for the ice blocks during the tests was from −3 to −5 °C. This was achieved by increasing the storage container temperature up to this level 2 days before the tests. The crushing tests were performed in the neighbouring area of AARC's ice tank, where the actual air temperature was in range from +10 to +15 °C. After an ice block was taken out from the storage container its internal temperature was measured at the depths of 20 mm and 90 mm at the centre part of the block. Typically within 15 min the ice block was immersed into the −1 °C ice tank water. Attaching the floating ice block to the test rig, adjusting rig level to that of natural ice buoyancy, and checking instrumentation took another 15 min. Thus the total time between taking the ice block out from the storage and the actual test was around 30 min.

To ensure a planar initial ice edge contact the rig sledge was driven forward to make a slight ice contact against the instrumented plate. The

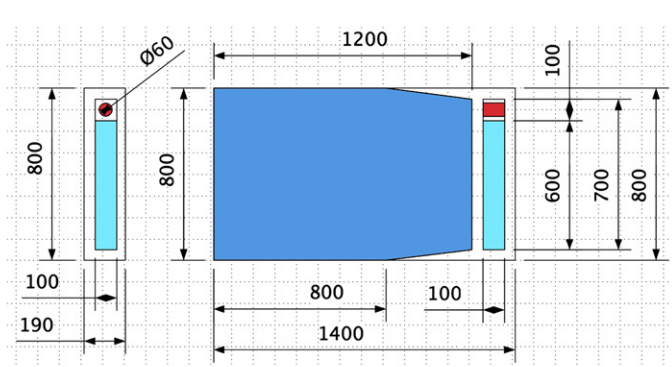

Fig. 3. The dimensions (mm) of the test block and index strength ice samples.