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CONTROLLED PLASTIC DEFORMATION OF A GRILLAGE USING ARTIFICIAL FRESHWATER ICE AT A LARGE SCALE

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ABSTRACT

This paper discusses the elastic and plastic stress and strain experienced by steel grillage structures during large-scale ice indentation tests undertaken in a laboratory setting. The work is part of the STePS[2] (Sustainable Technology for Polar Ships and Structures) project, a 5-year engineering research project at Memorial University. The present work builds on previous experiments and is a part of a multi-stage project to investigate high-energy ice-structure collisions. The current experiments involve artificial glacial (freshwater) ice blocks loaded into a grillage representative of full-scale ship structure. The ice block is quasi-statically crushed against the grillage, and load and response data is recorded. Raw data is acquired through a network of strain gauges, and other instruments. The experiments are also recorded through several high-speed cameras. The work is unique in the scale of the tests, using realistic grillages and ice blocks at forces and pressure loads representative of a real-world ship-ice interaction. During loading, the structural grillage undergoes extensive plastic deformation but displays tremendous overload capacity, much more than the material's yield point, while demonstrating significant remaining reserve strength.

INTRODUCTION

Driven by oil discoveries as well as the potential for new shipping routes as sea ice retreats, interest in the Arctic is growing. With the accompanying increase in marine traffic, there is a need for new, improved designs of ice-strengthened vessels as well as structures for exploration and extraction of the hundreds of billions of barrels of oil in the Arctic region.

These interests by industry have resulted in the funding of research projects such as the STePS[2] (Sustainable Technology for Polar Ships and Structures) project, a 5-year engineering research project at Memorial University.

At a basic level, the shell of a ship is a stiffened plate structure, with an outer steel plate that is reinforced and strengthened by transverse and longitudinal stiffeners. This reinforced plating is designed to have the highest strength to weight ratio possible while meeting strength criteria, as required by classification societies.

Classification societies have recently been moving towards a plastic limit state design approach for structural rules for ships. This is based on the fact that complex structures have enormous reserve strength in the plastic region beyond initial yield. In particular, the International Association of Classification Societies (IACS) has developed universal rules for polar class ships that utilize plastic limit state design. The structural reserve strength is being taken into consideration in the class rules, so some plastic deformation is expected and considered acceptable (Daley, 2002). This approach allows for significantly lighter structures, which are in turn cheaper to manufacture as well as cheaper from an operational point of view when fuel consumption is taken into consideration.

The work discussed in this paper is a continuation of previous work done at Memorial University in ship structure research. Full-scale experiments have been completed to investigate the plastic response of single frames, as well as grillage structures using steel indenters (Daley et al., 2007), and small-scale plastic deformation experiments have been carried out in quasi-static as well as dynamic ice-steel plate collision interactions (Clarke, 2012).

The experiment discussed in this paper is the full-scale quasi-static loading of laboratory-grown ice samples into grillage structures causing significant plastic deformation at very high load levels.

EXPERIMENTAL SETUP

At a basic level, the apparatus for these experiments includes a rigid (or nearly rigid) test frame that holds the grillage, a hydraulic ram, a cone of ice inside the ice holder, and a data acquisition system.

The ice cone samples can be described as a cylinder with a diameter of 1m and a horizontal height of 300mm, and a conical tip on top of the cylinder. The mechanical properties of the artificially grown ice cylinders have previously been investigated via controlled ice crushing experiments using a high-resolution ice pressure panel at an earlier stage of the $STePS^2$ project (Reddy Gudimetla, 2012). The previous ice crushing experiments determined the optimal ice growth method and angle on the cone tip that results in the strongest ice under compression loads.

The rigid test frame is constructed from large steel I-beams and thick steel plates. It is designed to hold the grillage via bolted connections. The frame is designed to experience minimal elastic deflections during loading. Due to the forces and loads involved being on the scale of 10^6N, zero deflection of the holding frame is impractical to achieve, so the relatively small (but not insignificant) deflection of the holding frame is measured during experimentation.

The hydraulic ram used for loading of the ice cone into the grillage is capable of a maximum force of 3.1MN, with a maximum stroke length of 450mm.

The grillage is representative of a full-scale ship structure. It includes a shell plate, two transverse frame members and three longitudinal stiffeners with the webs and flanges of the stiffeners forming T-shapes. The stiffener flanges are made of 8mm plate steel, while the webs and the shell plating are made of 10mm plate steel. The Transverse frame webs and flanges are made of 20mm plate steel. The total size of the grillage is 6m long by 1.5m wide. A 3D model of the grillage structure is shown in Figure 1.

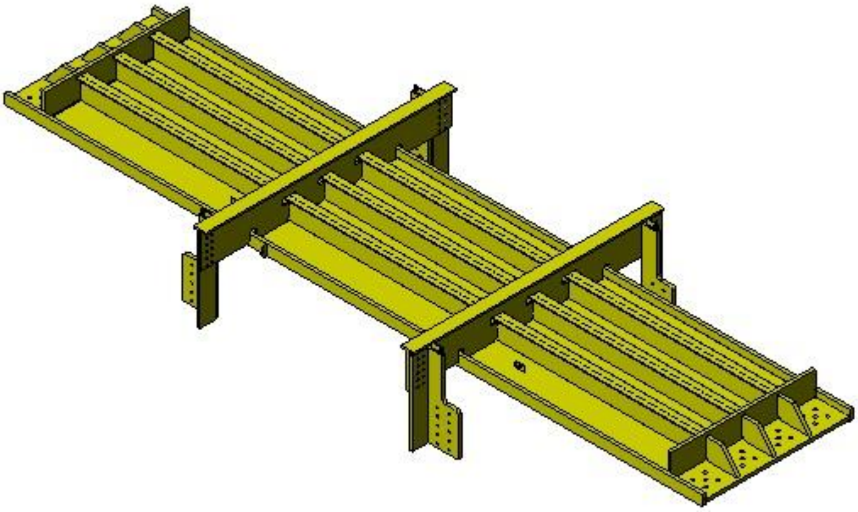

Figure 1: Computer model of grillage structure

Data Acquisition and Instrumentation

The data acquisition and instrumentation system for the experiments includes several forms of data. There is a network of 76 strain gauges placed in areas of interest on the grillage surface, including the shell plating, longitudinal stiffener webs and flanges, and transverse members. A Microscribe is used to map and create a 3D computer model of the physical grillage before and after the testing. The maximum deformation of the grillage at the point of contact with the ice sample is observed via a linear variable differential transformer (LVDT), which is used to produce a record of the deflection during experimentation, including plastic deformation and elastic rebound after loading. The deflection of the test frame is recorded using several string potentiometers at critical locations. A string potentiometer is used to measure the stroke of the hydraulic ram. Several fixed high-speed cameras are used to record the entire test procedure from different vantage points. There is also a fixed DSLR camera that records time-lapse images of the test frame during testing and the images are later used to measure deflection of the test frame. The total force that the hydraulic ram produces is also recorded.

All of the mentioned instrumentation produces redundant data that can be used to determine the deformation and displacement of the grillage, the stress and strain in critical areas of the grillage, the amount the ice sample has been crushed, the deformation of the test frame, and the loads involved, at any given point during testing.

EXPERIMENTAL PROCEDURE

Ice Growth and Preparation

The ice cone samples are grown using techniques developed by member of the STePS^2 project (Reddy Gudimetla, 2012). The ice growth procedure begins with mixing 0°C purified water with ice chips of a controlled size. Inside a room with an ambient temperature of -10°C, the water and ice chips are thoroughly mixed together at a carefully controlled ratio inside the ice holder. The ice sample is grown as a cylinder inside the ice cone holder. The rigid cylindrical ice cone holder is made of aluminium with a diameter of 1m, and a height of 300mm. During ice sample making, the holder is extended in height by 300mm, and the water-ice mixture is filled into the holder. When the ice is done growing, the extension is removed to leave ice that is 300mm above the ice holder edge. The ice sample is then placed into the ice shaping apparatus. The cylindrical ice sample is placed on a rotating base in the shaping apparatus while a shaving blade takes off a small amount of ice each rotation until the top of the ice sample is shaped into a perfect 30-degree cone. At this point, the ice sample is ready for testing. A test-ready ice cone sample is shown in Figure 2.

Figure 2: Ice cone sample ready for testing

Grillage Preparation

Before testing, the grillage needs to be prepared. First, an overhead gantry crane is used to position the grillage on the test frame. The grillage is then fixed in place using 80 grade-8 bolts. Next, the 76 strain gauges are mounted and wired to the grillage and then calibrated. This is a process that takes about 2 weeks. The grillage is then mapped using the Microscribe in order to get an accurate pre-test 3D model of the grillage form, including any deformations or fabrication defects. The LVDT is then attached overhead, and the string potentiometers are mounted and calibrated. Figure 3 shows the grillage surface during the strain gauge mounting procedure.

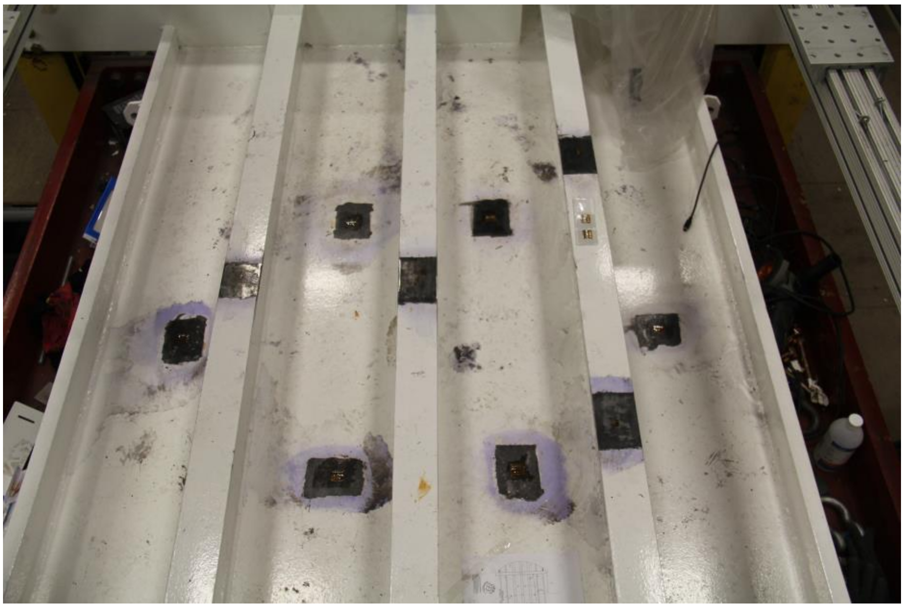

Figure 3: Grillage surface during strain gauge installation

Testing Procedure

The temperature in the laboratory during testing varies between 8°C and 12°C. With this ambient temperature, there is a window of 2 hours from the time the ice sample is removed from the cold room to complete the experiment.

The ice sample is removed from the cold room and, using a forklift, is placed into a transportation frame and put into position. An overhead gantry crane is then used to lift the sample while the forklift places the hydraulic ram in position under the grillage. The ice sample is then lowered onto and bolted to the hydraulic ram. The transportation frame is removed, and the hydraulics, and the string potentiometer used to measure the ram strike, are hooked up. A final calibration check is done on the instrumentation, as well as a final safety check, and testing may then proceed. Figure 4 shows the ice cone sample being loaded into place in preparation for testing.

Figure 4: Ice cone sample being moved into position for testing

The ice is loaded into the grillage at a constant rate of 0.3mm/sec. This is the slowest controlled rate possible with the hydraulic system. The ice cone experiences ductile rather than brittle failure at low strain rates, resulting in greater ice strength. At this low rate of loading, the results can be treated as being static during analysis. Once the ram reaches maximum stroke, or the maximum rated capacity of 3.1MN, the load is slowly released as the elastic rebound of the grillage is observed. The grillage at maximum deflection during testing can be seen in Figure 5. In the figure, the grillage has yielded without fracture.

Figure 5: The grillage at maximum deflection during experimentation

RESULTS

The results discussed here are largely on a qualitative scale, with some mention of the stresses and loads experienced during the experiment. During testing, the grillage structure underwent tremendous plastic deformation.

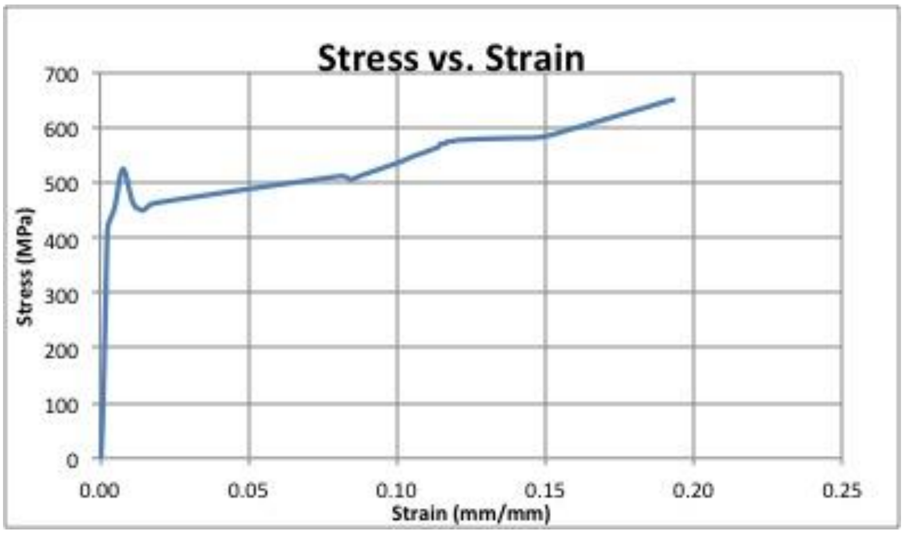

Figure 6: Stress vs. strain during loading of grillage

The yield strength of the steel used in the experiment is approximately 355MPa. During loading, the grillage experienced stresses much greater than the yield strength of the material, as shown in Figure 6. The plot displays a curve that resembles very much a typical stress-strain curve for a ductile material. However, the apparent point of yield on the plot is much greater than that of the yield strength for the steel itself. This shows that the complex grillage structure provides a tremendous amount of reserve strength beyond the yield strength of the material. This result largely supports the validity of plastic limit states design for ship structures, as used in the IACS polar class rules.

The grillage structure was not loaded to failure, and thus the ultimate strength of the grillage structure, and the point or pattern of failure is not known.
Figure 7 shows the shape of the load-deflection curve for the grillage structure during and after loading. The extent of total deformation while under load, as well as elastic rebound is observed. The values have been removed from the axes due to current confidentiality of the data.

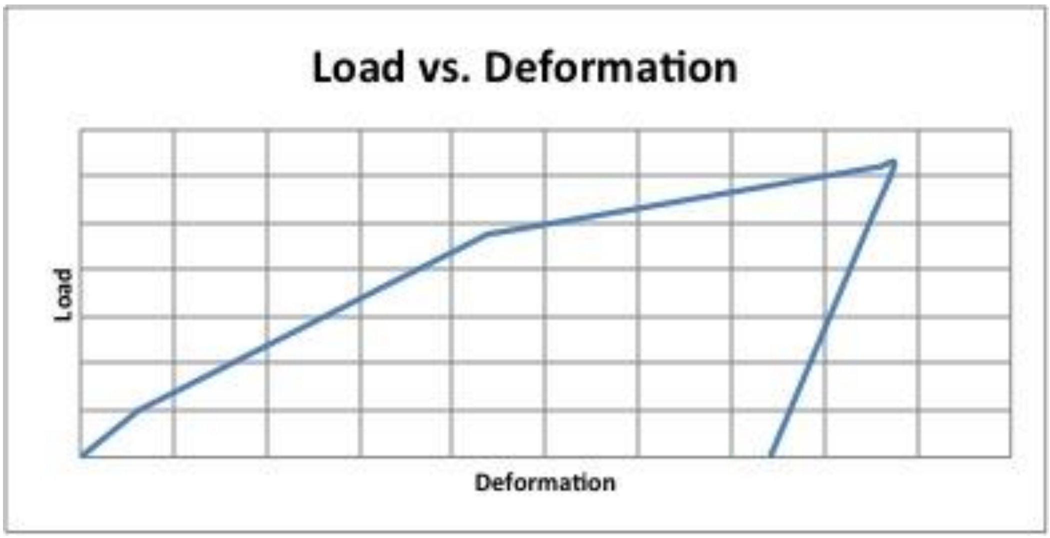

Figure 7: Load vs. deformation during and after loading of grillage

CONCLUSION

This experiment demonstrated a realistic, full-scale loading of freshwater ice into a stiffened grillage representative of full-scale ship structure. The results show that complex structures have a reserve strength that is much greater than what the yield strength of the material alone would suggest. As shown in, the grillage structure can withstand significant plastic deformation before failure, demonstrating the benefits of plastic limit states design of structures.
Future work on this project includes studying the effects of dynamic and impact loading on full-scale grillage structures in a double-acting pendulum apparatus. The effects of inertia, as well as the probable brittle failure of ice samples are to be studied, and can be compared to the results of static loads as similar levels of force for a further understanding of ice-structure interaction.

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