POAC'15
Trondheim, Norway

Proceedings of the 23rd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2015
Trondheim, Norway

SHIP STRUCTURE SUBJECTED TO EXTREME ICE LOADING: FULL SCALE LABORATORY EXPERIMENTS USED TO VALIDATE NUMERICAL ANALYSIS

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ABSTRACT

In the environmentally sensitive Arctic, the integrity of steel structures subject to ice loading is becoming more important as ships and marine structures are a major element of Northern activities. Although such structures are historically very conservatively designed, plastic limit states design is currently gaining currency for the design of ship structures for ice conditions.

This paper describes full-scale laboratory experiments involving ice-structure interaction in which the structure and the ice undergo significant deformation. Stiffened panels representative of full-scale ship structure are loaded with laboratory-grown ice blocks quasi-statically to extreme load levels, resulting in large scale plastic deformation. These experiments are unique in scale for a laboratory environment. The results demonstrate the enormous plastic reserve capacity that exists in a steel grillage structure.

Non-linear finite element (FE) analysis of the laboratory experiments is performed, and high fidelity is achieved between simulation and experiment. The close match between real-life results and finite element simulation validates the methods used and shows the value of nonlinear FE analysis in the application of ship structures.

INTRODUCTION

The International Association of Classification Societies' (IACS) Unified Requirements for Polar Class ships (IACS, 2012) outlines the specific structural and mechanical requirements for ships operating in polar waters. The scantling requirements for Polar Class ships were developed using energy methods to calculate the force on a ship's bow area in a collision with a level ice sheet. The Polar Classes range from PC 7 to PC1, with PC 1 having the most rigorous structural requirements. The Class Factors in the Polar Class structural requirements are based on a set of defined operational values for vessels in each Polar Class. These include: ship speed, ice thickness, ice strength, and ice contact pressure. Full-scale evaluation of the actual response of a representative Polar Class ship structure in a controlled environment is useful in validating and evaluating the response of structures designed to Polar Class to actual ice loading.

The purpose of this paper is to present the results of a large scale structural grillage ice loading experiment and to present the results of a non-linear FE simulation of the experiment. The experiment was conducted in a laboratory setting at Memorial University. Lab-grown seeded ice cones were loaded against steel grillages representative of polar class structure.

LARGE GRILLAGE LABORATORY EXPERIMENTS

The goal of the large grillage experiments was to observe quantitatively and qualitatively, the response of steel grillage structure to ice loading. A detailed account of the experimental procedure has been previously presented (Manuel et al., 2013). During these experiments, ice cones were loaded quasi-statically against a steel grillage structure representative of full-scale ship structure. The experiment took place in a laboratory setting. A total of four separate ice cones were loaded onto two steel grillage structures. Grillage A was centrally loaded with a single ice cone, in three loading steps. Grillage B was loaded with three separate ice cones in three separate locations. The results of grillage A are discussed in this paper. The results of grillage B are to be analysed and presented at a future time.

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

The two grillages were designed according to the International Association of Classification Societies' (IACS) Unified Requirements for Polar Class ships (IACS, 2012). The grillages, as designed, provide a single frame span for a longitudinally framed IACS PC 7 structure at the midbody ice belt of a 12,000 tonne vessel. The UR I2 design load for this structure is 572 kN. To provide lateral resistance along the sides of the length of the grillage, plate stiffeners were added to the structure. The dimensions of the grillage can be seen in Figure 1. All dimensions are in millimetres.

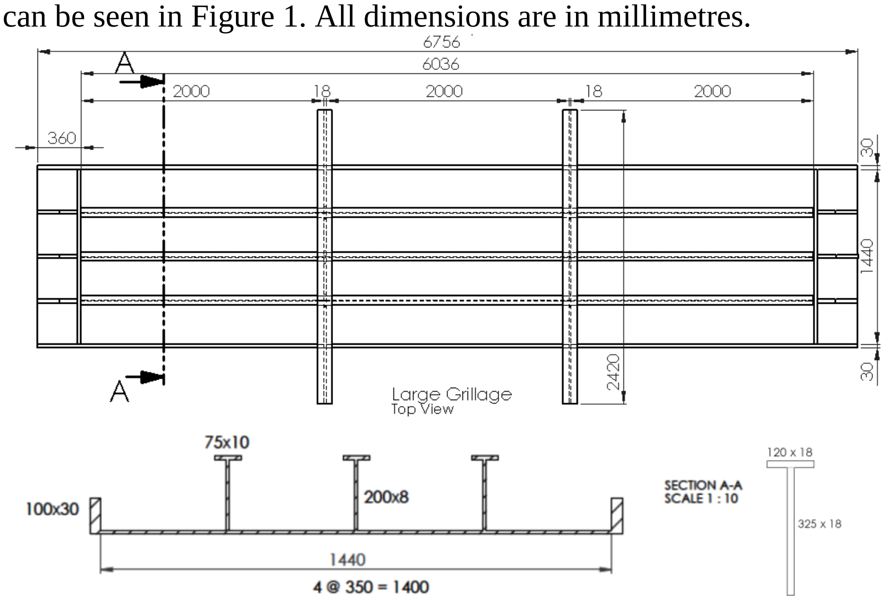

Figure 1: Large grillage scantling

The grillages were loaded with cones of lab-grown seeded ice. The cones are 1 m in diameter, with a 30 degree tip angle. The growth methods used for the ice cones are based on the results from earlier experiments where ice cones of different properties were loaded against a high-resolution pressure panel (Reddy Gudimetla et al, 2012).

Figure 2: Physical experiment at point of maximum load

The grillage was loaded centrally in three steps (Setting load, Test 1, and Test 2). The loading rate of 0.3 mm/s provides quasi-static structural response during the interaction. The low strain rate also allows the ice to be deformed in a ductile fashion. The purpose of this low strain rate is to allow for higher loads than if the ice failed in a brittle way due to higher strain rates. A ductile response may not be a realistic ice failure mechanism for a ship transiting through ice, but the focus of this research is on the structural response to the ice loading, not the mechanics of the ice failure.

During the setting test, the ice cone was loaded into the grillage up to 393 KN, and the load was subsequently removed. Next, during Test 1, the ice cone was loaded into the grillage up to 2.07 MN, and then unloaded. During Test 2, the ice was loaded into the grillage up to a maximum of 2.73 MN (480% of design load). The grillage response was recorded using a network of 74 strain gauges, several string potentiometers, and an LVDT. The presented grillage displacement data is the maximum displacement as recorded by the LVDT at the centre of the top of the flange of the middle stringer. The final deformed shape of Grillage A is shown in Figure 3. A load-displacement plot for the grillage A experiment is shown in Figure 4.

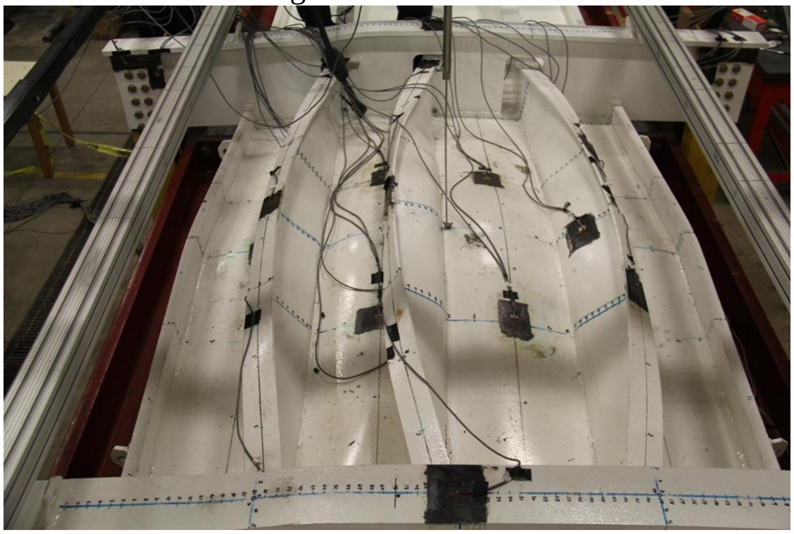

Figure 3: Grillage A after Test 2

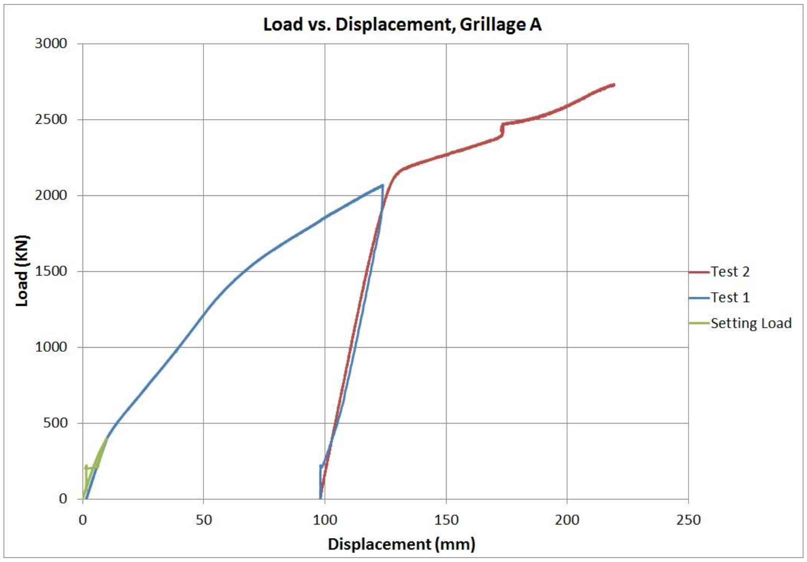

Figure 4: Grillage A load vs. displacement plot

NUMERICAL SIMULATION OF PHYSICAL EXPERIMETNS

Validation of the numerical model presented in this work is done by comparing the laboratory results of the large grillage experiments with the results of ANSYS nonlinear FE analysis of the grillage. A model representative of the large grillage was developed and subsequently analysed in ANSYS. A numerical model of the Grillage experiment is used to validate the FE analysis described later in this report.

During the laboratory experiment, the real-time spatial pressure distribution was not (and could not have been) observed. As well, at no point during the experiments was the exact area of ice-structure interaction known. This makes the task of achieving a high-fidelity FE simulation of the experiments quite challenging in that the form of the pressure distribution applied by the ice has to be assumed. Without knowing how the contact area changes with time, or knowing how the pressure distribution changes with load level, there is no way to exactly model the grillage experiments. Therefore, a reasonable representation of the patch load size and pressure distribution within the patch size must be made. Through preliminary FE analysis, while experimenting with different circular patch load diameters and pressure distribution patterns, it was observed that using a single, uniformly loaded patch size produced quite reasonably accurate results. Using a gradually increasing load patch size had little effect on the recorded results in either the elastic or plastic range. For the analysis, a circular uniform load patch with a diameter of 40 cm was used to represent the ice. The resulting maximum pressure during the simulation is therefore 16.3 MPa. This is a similar maximum nominal pressure to what has been recorded in previous experiments using similar cones. The maximum nominal pressure recorded in Reddy Gudimetla et al, 2012, was 16 MPa. In ship trials in ice, pressures in the 20-30 MPa range are not unheard of. For example, in the 1991 *Oden* expedition, local pressures as high as 23 MPa were recorded (Science & Technology Corp., 1993).

This load was applied in the center of the grillage shell plating. The size of the load patch did not change during the simulation. This is in contrast to the physical experiments, where the diameter of the ice-structure interaction area went from about 5 cm at the beginning of the experiment to 50 cm at the end of the experiment.

A bilinear isotropic material model was used for the analysis. To ensure accurate mechanical material properties, destructive tensile testing was performed on the 350W steel used in the grillage. Ten specimens were taken from the undeformed sections of the grillage sample after testing and were machined to ABS standards (ABS, 2012). The tensile tests were carried out using an INSTRON testing machine. The resulting average yield strength was 409 MPa, significantly higher than the published minimum of 355 MPa. The Young's modulus was confirmed to be 200 GPa, and a post-yield tangent modulus of 1.5 kPa was used in the analysis. A typical stress-strain curve for a tensile test is shown in Figure 5.

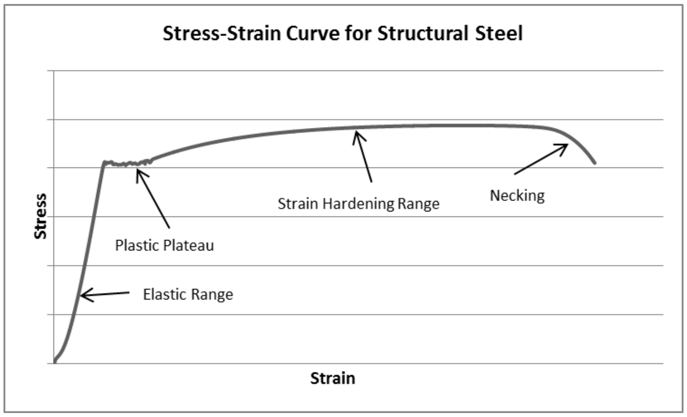

Figure 5: Stress-strain curve for structural steel in axial tension

The boundary conditions for the FE model were an idealized version of the physical conditions. Bolted connections were not modelled; the areas of the bolted connections were fixed in translation and rotation. The idealised boundary conditions can be seen in Figure 6.

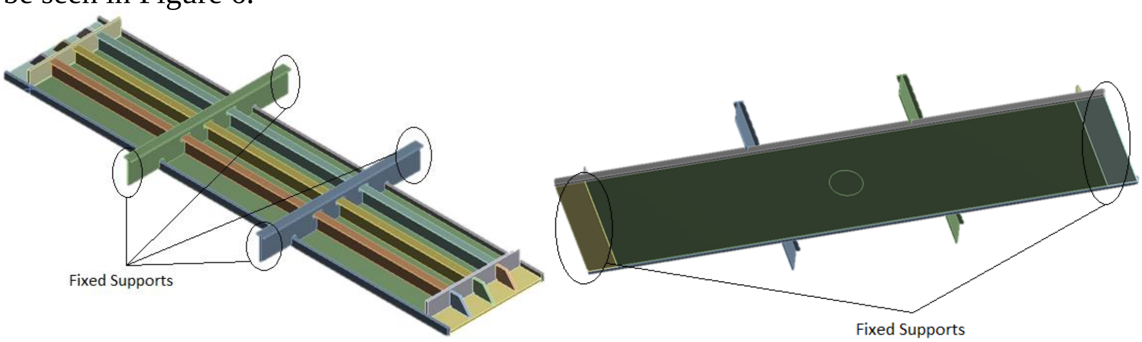

Figure 6: FE boundary conditions

A finer mesh typically means more accurate and refined results. However, there is a balance between element sizing and model accuracy at which an acceptable result can be achieved while keeping the computation time to a reasonable level. A convergence study was done to find the point at which increasing the mesh size no longer improved the results, with the results converging on a solution as the mesh continued to be refined. The mesh uses SOLID186 elements. This is a solid element with midbody nodes along each edge. Mesh statistics are shown in Table 1.

Table 1: Large grillage mesh statistics

Large Grillage Mesh Statistics	
Total Nodes	56626
Total Elements	18051
Nodes along shell plate between each stiffener	11
Nodes through thickness of stiffeners	5
Nodes through thickness of shell plate	5
Nodes through thickness of web frames	5
Nodes along stiffener between web frames	46

Figure 7 shows the total loading and unloading of Grillage A, Test 1 laboratory results and FE analysis results. The results show greater discrepancy in response as the load increases. At a peak load of 2050 KN, the FE model had 111 mm of total deflection, while the laboratory results displayed 124mm of total deflection. This represents a 10.5% error in deflection (or capacity) in the FE model compared to the laboratory results. When unloaded, the FE model has 92 mm of permanent deformation, while the laboratory results showed 98 mm of permanent deformation. The FE model therefore had 6.1% less permanent plastic deformation after the load was released. Figure 8 shows the shape of the deformed grillage in the simulation. This is a close match to the deformed shape in the physical test (Figure 3).

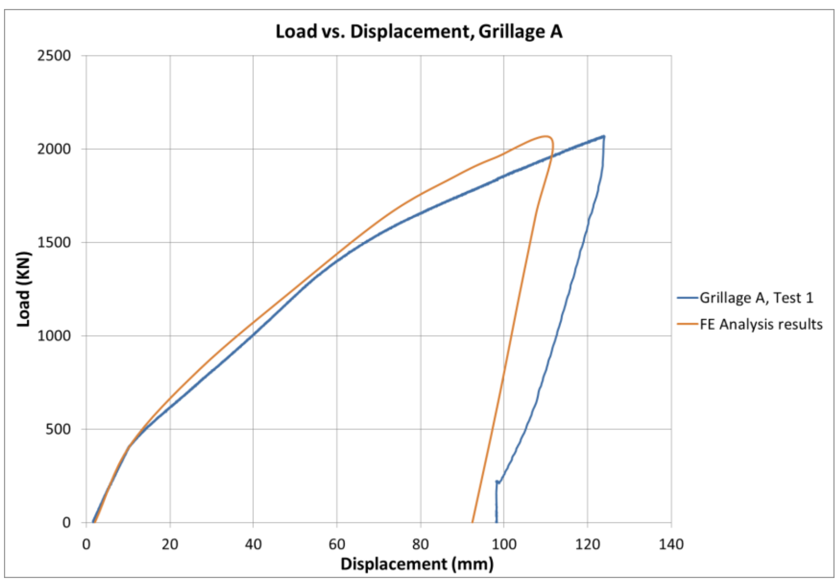

Figure 7: Laboratory results and FE analysis results of large grillage experiment

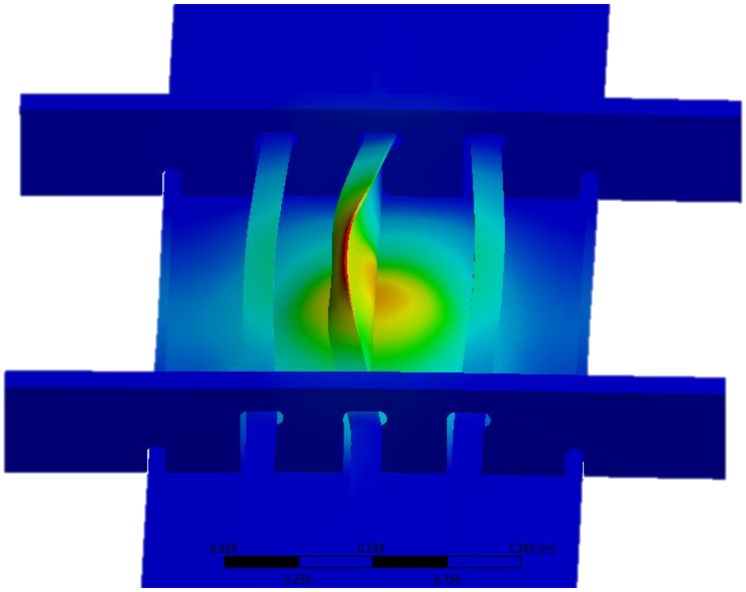

Figure 8: Deformed shape of grillage in simulation

Areas of uncertainty in the simulation of the experiment lie mostly in the representation of the structure-ice contact as a single, uniform load patch. Since the material properties of the grillage steel were physically tested and confirmed, there is little uncertainty associated with that aspect of the simulation. It is possible that fabrication tolerances or welding issues play a role in simulating the experiment, although upon inspection of the fabricated grillage there were no noticeable issues.

CONCLUSION & RECOMMENDATIONS

The large grillage test results provide practical, real-world scale information about ship-ice interaction with a degree of reliability that cannot be achieved with in-situ ship testing, particularly in ice. These tests are useful as a validation of existing ship design rules. They provide insight to the actual ice load a grillage structure can withstand without catastrophic structure failure (ie. tearing or puncture of the shell plating). Although the structure was not pushed to the point of failure, and it is not known at what load level that might happen, it is a testament to the reserve capacity of structural grillage arrangements that it withstood nearly 500% of the design load with deformation but without failure.

The lateral boundary conditions in this experiment may not accurately represent the continuous nature of a ship hull, and consequently, the results are not necessarily indicative of the actual fracture limit of a ship structure, but the results do provide useful data on the response of a grillage structure under ice load. The point of the experiment was not to evaluate the fracture limit of ship structure, but to explore the reserve capacity beyond yield, and beyond the design load of polar ship structure.

In the results, it can be seen that the slope of the elastic portion of the unloading phase is steeper than the slope of the elastic portion of the loading phase. This demonstrates that, in addition to strengthening through strain hardening, the grillage becomes stiffer as a result of the plastic deformation.

A limitation of these experiments is that due to the size, hours, and cost involved, it was not possible to repeat the test for more experimental runs. Ideally, the large grillage tests would be repeated several times to determine the repeatability of the structural response to the ice loading.

The fidelity of the FE analysis is quite good. Having less than a 10% discrepancy between laboratory results and FE analysis results is quite reasonable when the pressure distribution of the ice-structure interface is not known exactly. Using a uniform pressure distribution resulted in acceptable fidelity, and therefore in this case, it was not necessary to use a non-uniform pressure distribution. If one wanted to achieve a higher fidelity FE simulation of structural response to ice loading, there would have to be a focus on achieving an accurate estimate of the ice spatial pressure distribution.

Overall, the analysis of ship structures for ice loading is an area where there could be an enormous amount of experimental work done. Full-scale laboratory experimentation is a useful method for testing ice-structure interaction in a controlled environment. Both continued quasi-static and dynamic ice loading experiments on stiffened panel structures would contribute to furthering the understanding in this area. However, the magnitude and cost makes it unlikely that a great number of full-scale laboratory ice-structure tests will be completed in the near future. FE analysis is a much faster way of analyzing structural response to ice loading, however, the model should be validated by real-world, or close to real world, results in at least a representative number of cases.

The results of this work have demonstrated a practical approach to analyzing local ice loads on floating structures. Having a validated FE analysis methodology for the analysis of full-scale ship structure is a very useful tool for the analysis and development of an optimized structural arrangement for floating structures in ice.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support of Atlantic Canada Opportunities Agency, Research and Development Corporation, American Bureau of Shipping, BMT Fleet Technology, Husky Energy, Rolls-Royce Marine, Samsung Heavy Industries and The National Research Council Canada.

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