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AN EXPERIMENTAL STUDY OF THE DESIGN AND OVERLOAD CAPACITY OF STRUCTURAL GRILLAGES SUBJECTED TO ICE LOADS

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ABSTRACT

The design of polar class ship structures makes use of plastic limit states where an occasional small amount of local deformation (denting) is an acceptable consequence of ice operations. The structural requirements of the IACS Unified Requirements for Polar Ships are based on closed form analytical solutions for typical frame sections subjected to lateral patch loads. Designers can easily apply a set of plastic capacity equations to check limits of a simple frame however for more complicated arrangements or to capture the response in an overload case, a more advanced analysis procedure should be employed. The finite element analysis (FEA) method is a powerful, flexible and practical structural analysis and engineering tool capable of predicting displacements and stresses for various structural failure modes and across several levels of complexity ranging from linear analysis to more advanced nonlinear analysis. This paper presents the procedure and results of an experimental study coupled with a detailed non-linear finite element analysis effort aimed at better understanding and predicting the overload response of ice strengthened structures.

Laboratory grown conical shaped ice samples (1 m diameter) were used to load structural grillages well into a plastic response domain. The scantlings of the grillages were typical of a transversely framed midbody ice belt arrangement of a 10,000 ton Ice Class PC6 ship. The maximum loads reached levels well beyond the elastic limit of the material and any acceptable plastic design point. The experiments allowed for an investigation into highly non-linear structural deformation and overload capacity considering the simultaneous failure of ice. Two separate large grillages were tested with ice specimens loaded at a quasi-static loading rate (0.5 mm/s). The first set of tests were performed in two load steps at identical loading positions at the mid-span of the central stiffener. The second set of tests were carried out in three load steps at different loading positions along the span of the central stiffener of the grillage. The experiments led to unique insight into the overload response and load carrying capacity of a structural grillage and the effect of prior plastic damage on structural response. Load-deflection curves and deformation shapes were compared with the results of nonlinear finite element analysis and showed strong agreement. The work demonstrates that nonlinear FEA is a suitable tool for the analysis of ice-strengthened ship structures subjected to extreme ice loading.

INTRODUCTION

The increased demands in the Arctic require the development of robust ice-strengthened ships which can safely transit in these harsh environments. It is necessary to advance our understanding about ice-structure interactions which can help design more efficient structures against ice interaction events. The plastic response of ship structures is gaining acceptance and has been adapted for the design of many ships and offshore structures. The International Association of Classification Societies (IACS) Requirements Concerning Polar Class (IACS Polar Rules) make use of plastic limit states for the scantling requirements of plating and framing (IACS 2007). The ability to optimize ship structures for plastic limits rather than the elastic yield point of the material, can results in a lighter and more ductile ship design. The rationale of plastic limit states is the recognition that steel structures tend to have a large reserve capacity in the post yield region. Using some portion of the reserve capacity will lead to more efficient and producible design. However, it is challenging to quantitatively estimate the level of the reserve capacity.

The present study is concerned with estimating the ultimate load-carrying capacity of a structural grillage subject to ice loading and understanding the effect of prior deformations at nearby locations on the capacity of the grillage. The objective of this study is to predict plastic response and quantify reserve capacity of structural grillages subject to ice loading through physical experiments and numerical analysis.

Previous Physical Grillage Experiments

Several research efforts have been carried out to investigate the plastic behavior of grillage structures. However, most cases used a steel plate or rigid indenter rather than real ice. The tests therefore showed certain structural response behavior that may occur differently if subjected to ice loads.

One of the largest scale physical experiments was conducted by Bond & Kennedy (1998). The authors used simple icebreaking ship structures (panels) to investigate the post-yield region. The large-scale panels used in the test were representative of a mid-body hull structure along the ice belt of a Canadian Arctic Class vessel. The tests were able to capture the post-yield stability behavior of typical icebreaker hull panels from load deformation characteristics and progression of failure from plastic hinge formation and tripping of the framing system to rupture of the plating. A finite element model was developed and validated with the experimental results. The research found that the non-linear finite element analyses can be confidently used to explore the post-yield strength and stability response of icebreaking ship structure. However, the experiments were loaded using three 500-ton jacks and two 200-ton jacks with rigid indenters rather than real ice.

Daley & Hermanski (2008a; 2008b) conducted an experimental study in order to validate the limit state equations in the IACS Polar Rules. Eight single frames and two large grillage tests were performed to investigate frames subject to intense local loads such as ice loads. A rigid steel indenter (102 x 102 mm) was used to load a structural grillage up to 1,470 kN causing punching shear in the 10 mm shell plate. The research found that the large grillages typically required much higher load levels than individual frames and both the initial and post yield capacity of a grillage is considerably higher than that for a single frame.

Also a number of researchers have developed and explored simulation models based on these tests to represent notable results. Abraham (2009) developed a regression equation using Design of Experiment (DOE) techniques for predicting capacity of frames with different stiffener forms.

The capacity of a large grillage is more than the single frame in most cases up to about 35 %. Quinton (2009) studied effect of moving ice loads on the plastic capacity of a ship's structure. The research found that the structural capacity to withstand moving loads causing progressive damage was generally less than its capacity to withstand static loads.

However, while the results of previous experiments and simulations well present post-yield behavior of the grillage with rigid indenter, there was little insight in terms of the interaction between ice and ship structures. In this study, ice specimens were produced in the laboratory and used for the grillage tests. This allowed for investigation into structural deformation considering the failure of ice. Preliminary results of these experiments were previously presented by Manual et al. (2013).

LARGE GRILLAGE EXPERIMENTS

Test apparatus

Previous experiments designed and carried out by Daley & Hermanski (2008a; 2008b) used a rigid steel indenter to load a structural grillage into the plastic regime. In the current experiments, the same test apparatus (red grillage support frame) and grillage design were adopted; however, ice samples were used to load the structure rather than rigid indenters. This allowed for investigation into structural deformation considering the failure of ice. Two large grillages were prepared and tested. The first grillage tests were intended to study the ultimate load-carrying capacity when subjected to central and symmetric loading. The second grillage was tested to study the influence of variable ice loading positions along a single frame. The test apparatus, shown in Figure 1, mainly consists of the grillage support frame (red), 700,000 lbs-capacity and 450 mm stroke length hydraulic ram (yellow), the test grillage (white) and the support frame for instruments (black).

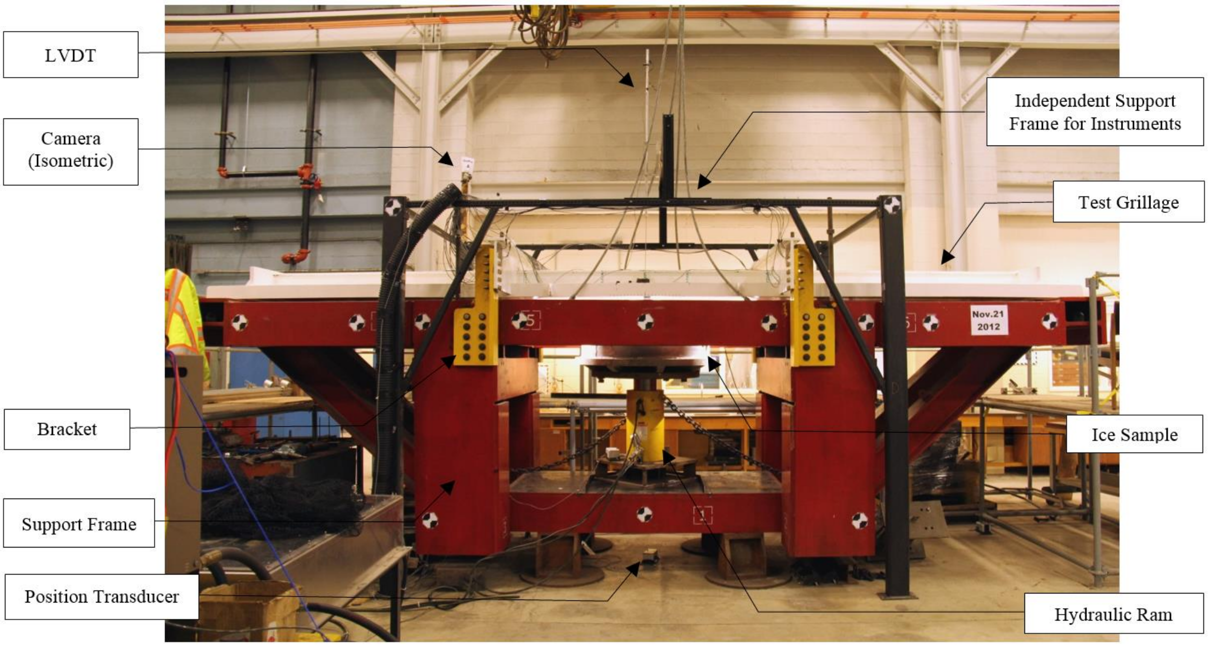

Figure 1. Grillage test apparatus

Geometry of the grillage
The structure of a ship's hull typically consists of shell plating with attached stiffeners and supporting frames. The combination of the plating and the stiffeners is a stiffened panel. The stiffened panel with the supporting frames (e.g. web frames and/or stringers) compose a large grillage. Stiffeners in a grillage can be arranged longitudinally or transversely, which are termed longitudinal and transverse frames, respectively. The geometry of the large grillage (in fact, two identical grillages named #1 and #2) is shown in Figure 2. The scantlings are a full-scale representation of a transversely framed 10,000 ton Ice Class PC 6 midbody ice belt arrangement. The grillage consists of a plate (6.756 m long and 1.460 m wide), three continuous stiffeners or frames (200 x 8 / 75 x 10), two supporting stringers (325 x 18 / 120 x 18) and two heavy side bars (100 x 30). The stringer's spacing (or the unsupported span of the stiffeners) is 2 m and the stiffener's spacing is 350 mm. The stiffeners penetrate the stringers through cut-outs with their web plates attached on a single side (see Section B-B).

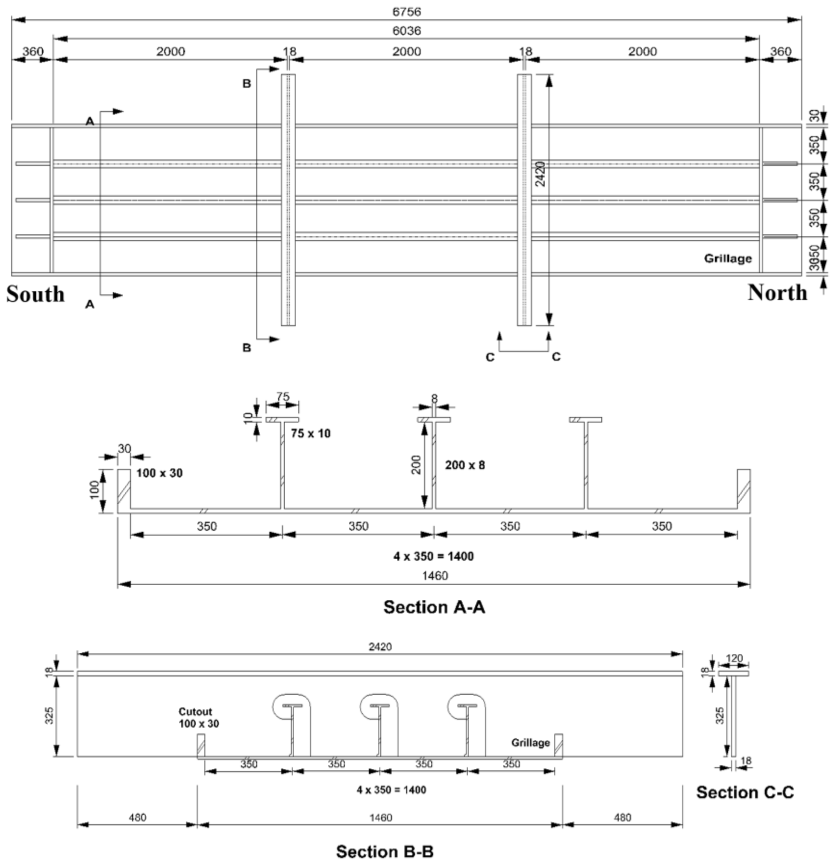

Figure 2. Geometry of the large grillage

Boundary Conditions
The boundary conditions of the longitudinal stiffeners were designed to provide full fixity. At both ends of each longitudinal stiffener a thick transverse member was fitted and the plating was bolted to the support frame as shown in Figure 3(left). The boundary condition for the central frame was designed to provide a realistic condition of a ship's side structure. Heavy side bars were added to provide additional rotational restraint at the plate's outer edges. The stringers of the grillage were bolted to the grillage support frame using brackets, also shown in Figure 3 (right). These boundary conditions were intended to restrain the ends of the stringers in all six degrees of freedom. The boundary conditions in the experiment were also modelled in the numerical simulations.

Figure 3. Boundary conditions at the longitudinal ends(left) and at the stringer ends(right)

Loading Scenarios

The tests on Grillage #1 were loaded at the mid-span of the central stiffener as shown in Figure 4(left). The first test of Grillage #1 (G1T1) was loaded until the maximum stroke of the ram was reached. Several thick steel plates were then placed under the ram to increase its stroke and perform the second test of Grillage #1(G1T2). The main purpose of these tests was to investigate the ultimate load-carrying capacity of the grillage beyond the design point.

The tests on Grillage #2 were conducted at different loading positions along the length of the central stiffener; right off-centre, centre and left off-centre. Figure 4(right) shows the test setup for G2T1, G2T2, and G2T3, respectively.

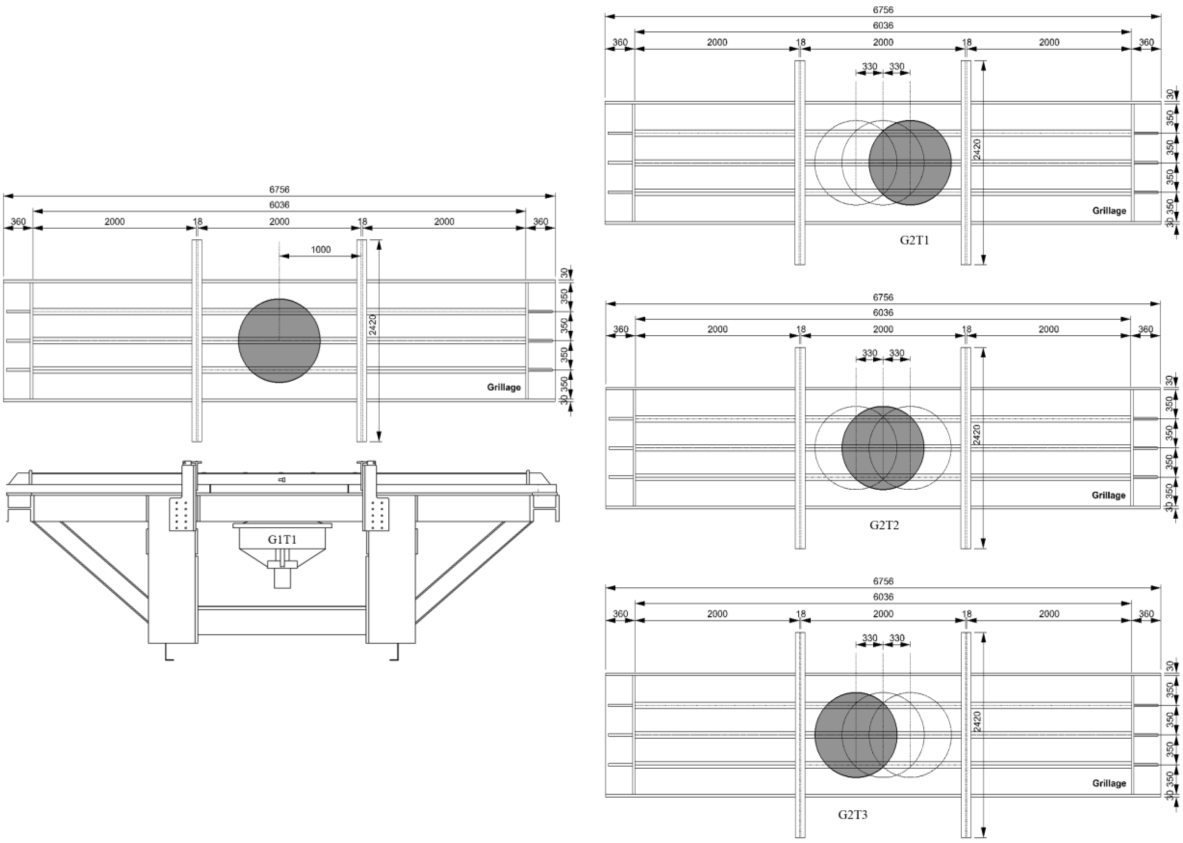

Figure 4. The loading setup of Grillage #1(left) and Grillage #2(right)

The main purpose of these tests was to investigate the influence of loading nearby the frame supports and prior deformations on the capacity of the grillage. The loading position was 330 mm away from the mid-span in G2T1. G2T2 test was conducted consecutively with structural deformation in the previous test using a fresh ice sample. There is a certain influence of the previous damage on the capacity of the grillage. G2T3 test was performed consecutively with structural deformation in the previous two tests using another fresh ice sample.

Framing Design in the Unified Requirements

This section describes a basic check for compliance with the Polar Class Unified Requirements and a sample calculation of the limit states for the offered dimensions as shown in Table 1. The calculation procedure is described for obtaining design limit loads for a transversely framed 10,000 ton Ice Class PC6 midbody ice belt arrangement. Two load cases, symmetric and asymmetric are considered.

Table 1. Sample calculations for limit loads

Transversely Framed, 10kT, Mid, PC6			
PC Class	Class		6
Displacement	Disp	kt	10
Displacement Class Factor	Cfdis		22
Crushing Failure Class Factor	CFc		1.8
Flexural Failure Class Factor	CFf		4.06
Load Patch Dimensions Class Factor	CFd		1.11
Load Parameters			
Force	F	MN	3.77
Aspect Ratio	AR		3.60
Line Load	Q	MN/m	1.68
Pressure	P	MPa	2.69
Ice Load Patch Width	w	m	2.24
Ice Load Patch Height	b	m	0.62
Average Patch Pressure	Pavg	MPa	2.69
Hull Area Factor	AF		0.45
Corrosion and Abrasion Allowance	t_wear	mm	2.00
Preak pressure factor	PPF		1.45
Pressure = Pavg * AF * PPF	P	MPa	1.76

Framing parameters						
Frame spacing	s	mm	350			
Web height	hw	mm	200			
Web thickness (net)	tw	mm	8			
Flange width	wf	mm	75			
Flange thickness (net)	tf	mm	10			
Span	a	mm	2000			
Material yield strength	σy	MPa	355			
IACS Requirements			**Req'd**		**Offered**	**Check?**
Structural stability ratio			805.00	>	471	OK
Shell plate thickness (net)	tp	mm	9.60	<	10	OK
Minimum shear area (net)	A0	cm2	9.40	<	16.8	OK
Section modulus (net)	Zp	cm3	238.80	<	325.5	OK
Limit Loads						
Pressure to asymmetric shear collapse	Ps	MPa	2.29			
Pressure to 3-hinge collapse	P3h	MPa	2.30			
Force = Ps* s * b	Fs	KN	**499.26**			
Force = P3h * s * b	F3h	KN	**502.87**			

Ice load parameters are derived taking into account the ice class, ship displacement and class dependant factors defined in the IACS Polar Rules. The design average pressure and ice load patch size obtained are 2.69 MPa and 2.24 m x 0.62 m, respectively. Considering the structure as a midbody icebelt arrangement, the average pressure is reduced by a hull area factor, AF = 0.45. In order to check the framing requirements a peak pressure factor, PPF = 1.45, is included. The minimum required shear area and section modulus can be then found by UR equations [I2-22] and [I2-23], with values of 9.4 cm^2 and 238.8 cm^3, respectively. Since the shear area and section modulus are interdependent, the minimum numbers cannot be used directly to create a unique set of scantlings for a given overall configuration consisting of frame span and spacing, load patch dimensions and pressure. Thus, iterations are generally required to find an optimum design considering weight or cost.

The scantlings of the grillage used in the experiments are known. Therefore, the shear area and modulus were calculated and then compared with the required values from the UR equations above in order to check compliance of the requirements.

The offered limit load of a single frame in the test grillage can be found using expressions which form the background behind the minimum requirements in the UR (Kendrick & Daley 2000).

Two limit states are considered; the pressure from a central load causing three-hinge collapse and the pressure from an asymmetric load causing combined shear and bending collapse. These limit pressures are 2.30 MPa and 2.29 MPa, respectively. Forces are then derived by multiplying the pressures causing collapse with the area consisting of the spacing (s) between frames and the height (b) of the ice load patch. Those forces, 503 kN and 500 kN respectively, are compared with the experimental results in the load-deflection curves to highlight the overload capacity of the grillage.

Discussion of Grillage #1 Results

Grillage #1 tests demonstrated significant overload capacity of the grillage when subject to ice loads, with deflections up to 215 mm at the peak loading condition, despite surface cracks that initiated at the ends of the central stiffener. The limit load according to the IACS Polar Rules for this particular structure is approximately 503 kN, and the load-deflection curve shows that the overload capacity of the grillage is much greater than the required rule. The maximum load applied was 2.8 MN which is greater than 5 times the design load (see Figure 5).

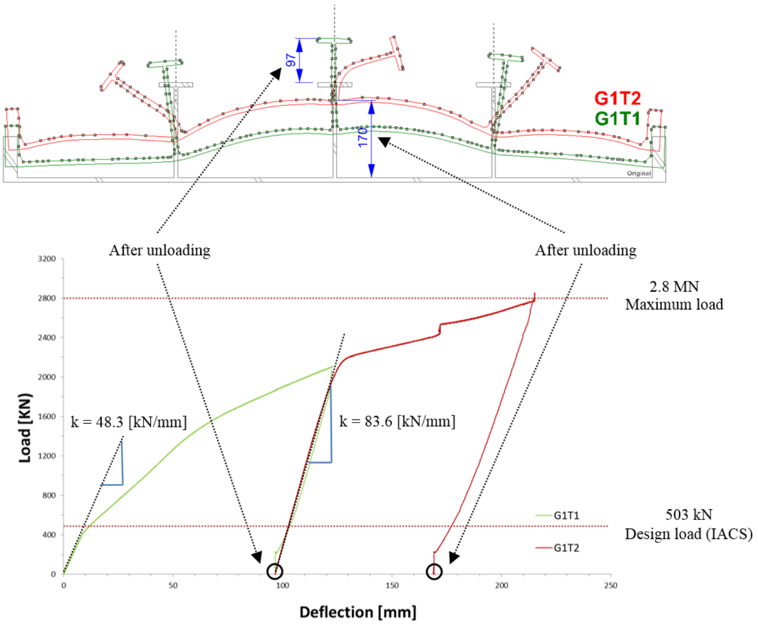

Figure 5. Load-deflection curves of Grillage #1 tests

The design load in the IACS Polar Rules is based on a single frame in isolation. These results indicate that a frame surrounded by adjacent frames can sustain higher loads beyond its design point while ice is pushing against them at extremely slow speeds (0.5 mm/s). There was no instability mechanism (e.g. buckling behaviour) observed at the 2.1 MN load level but eventually the web folded over when the load reached about 2.4 MN. Also the stiffness of the elastic portions of the load-deflection curves in the second test (83.6 kN/mm) was about 73 % higher than the first test (48.3 kN/mm). The slope of the load-deflection curve implies resisting capacity against deformation. Thus, it can be inferred that prior deformation of the frame leads to greater resisting capacity against further plastic deformation.

Minor surface cracks were detected at both ends of the central stiffener (at the stringer penetration), but there were no tears or through-thickness cracks. The longitudinal stiffeners also showed distortion near the cut-out of the stringer. Large deformation was observed in a cut-out of the stringer which is the major supporting member for the stiffeners (see Figure 6). The IACS Polar Rules do not explicitly provide criteria for stringers and other major supporting members (e.g. web frame). Each classification society's rules are expected to provide criteria for these members; however, further studies on their capacity and the influence of stiffeners and other secondary members are necessary to complete the Unified Requirements. The intention of the experiment was to study the ultimate load-carrying capacity of the grillage; however, given the limit of the hydraulic ram stroke it was not able to reach the maximum load before tearing or rupture. The deformation of ice may contribute to this lack of steel rupture since the load becomes more distributed. These experimental results suggest that the local deformations (up to 11 % of the frame span) do not necessarily compromise the overall strength of the large grillage. In fact the grillage actually gains stiffness and exhibits higher load-carrying capacity when there is prior deformation.

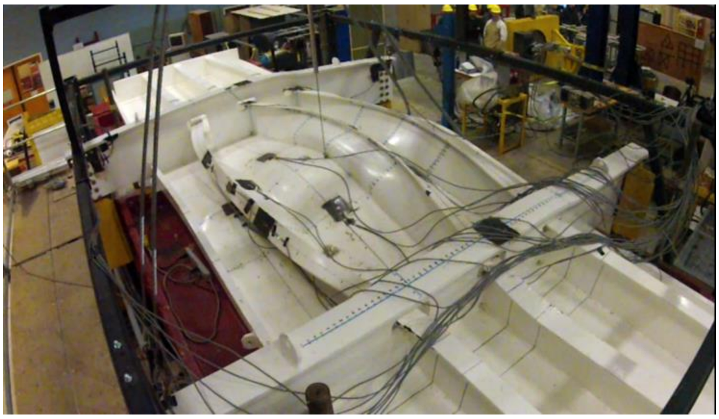

Figure 6. Isometric view of Grillage #1 at maximum load (2.8 MN)

Discussion of Grillage #2 Results

Grillage #2 load cases were carried out sequentially with fresh ice samples. It was observed that the stiffness of the elastic portions of the load-deflection curves in the second and third tests were higher than the first test (see Figure 7). The slope in load-deflection curve implies the resisting capacity against deformation. Thus, these experiments suggest that prior plastic deformations at nearby locations do not necessarily compromise the overall strength of the grillage.

The limit load for asymmetric load based on the IACS Polar Class rules for this structure is approximately 500 kN, and the load-deflection curve shows that the overload capacity of the grillage is much greater than the required rule. The maximum load applied was 2.3 MN which is greater than 4 times the design load.

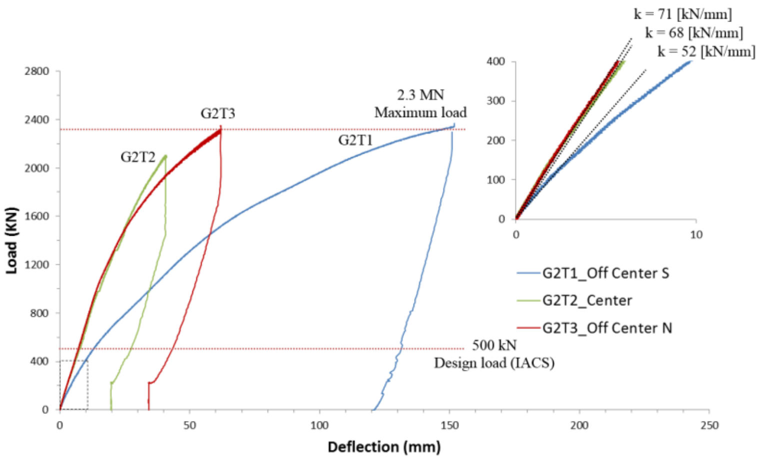

Figure 7. Load-deflection curves of Grillage #2 Tests

Pressure-area Interaction

In an attempt to capture the nominal strength of the ice and compare the crushing behaviour between different loading conditions, a nominal area calculation method was applied and process pressure-area relationships were extracted from the results. The nominal area was determined for each load step based on the indentation depth and ice/structure overlap geometry as shown in Figure 8. The pressure at each load step is simply the total force (measured from the hydraulic ram) divided by the nominal contact area. In the actual experiment the indenter (i.e. the grillage) was also deformable. This effect of structural deformation on the nominal area was not taken into account and is an area of ongoing research.

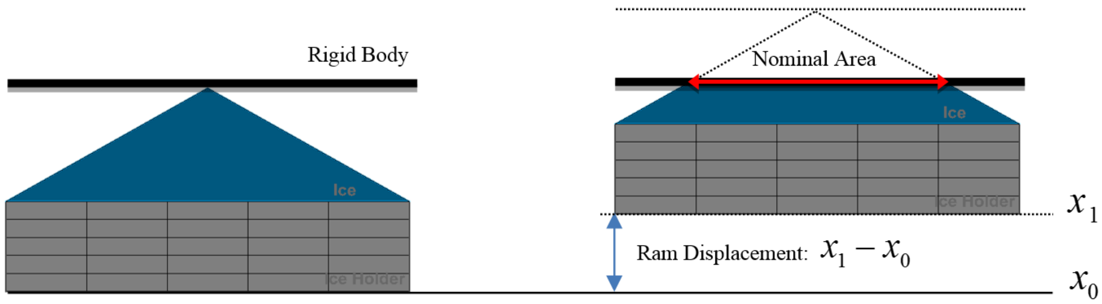

Figure 8. Schematic of the calculation method based on the nominal area

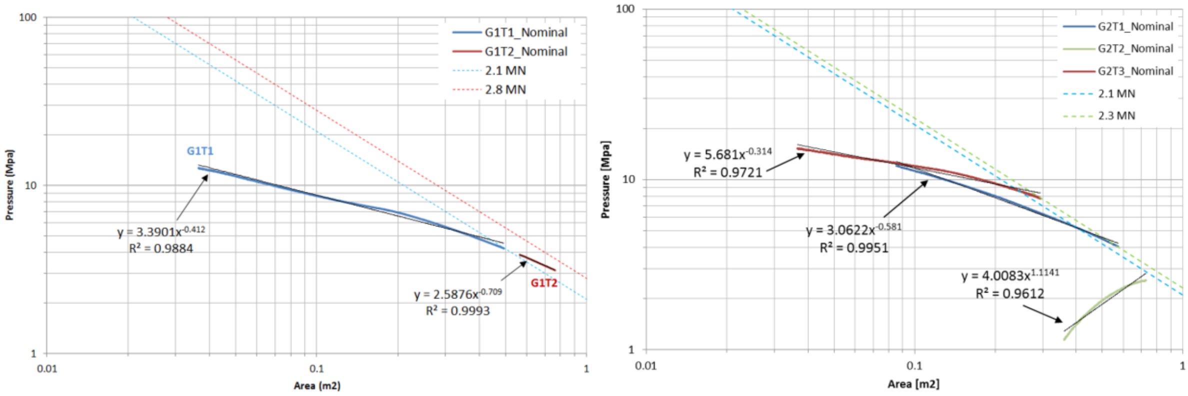

Figure 9. Nominal pressure-area curves of Grillage #1(left) and Grillage #2(right)

Figure 9(left) presents a process pressure-area relationships for Grillage #1 based on a nominal contact area method. The results show a decreasing trend of pressure as the nominal contact area increases. The highest calculated pressures are approximate 10.5 MPa for Grillage #1 tests, albeit distributed over an extremely small areas and associated with low force measurements. These peak pressures do not necessarily imply an extreme load.

Figure 9(right) presents the nominal pressure-area relationships for Grillage #2. The results show a decreasing trend of pressure as the nominal contact area increases in G2T1 and G2T3; however, an increasing trend was observed in G2T2. This is likely an effect of the over simplified nominal contact area calculation. The highest calculated pressures are approximate 10 ~ 11 MPa in both G2T2 and G2T3. Extremely small areas and low force measurements were filtered and not included in the curve. Exponential trend lines are fitted to the pressure-area data along with equations in the form of common pressure-area relationships, [$P = P_o \cdot A^{ex}$].

FINITE ELEMENT ANALYSIS

Non-linear finite element analysis using the commercial software package ANSYS® was used to simulate large deflections and plastic deformations observed during experiments. The load-deflection curves and deformation shapes measured by a MicroScribe® device were used to validate the numerical results. The entire structural grillage was modelled except for the bolt connections which were treated as boundary conditions (see Figure 10).

Abraham (2008) concluded that both shell and solid elements are suitable element types for modelling nonlinear response behaviour of frames subject to lateral loads. Thus, both plate and stiffeners were modelled using SHELL181 elements. Due to the use of nonlinear materials, full integration using five points of integration through the thickness of the shell elements was used. Each element has four-nodes, each with six degrees of freedom: translations in the x, y, and z directions, and rotations about the x, y, and z-axes.

In accordance with ABS guide notes on "Nonlinear finite element analysis of side structures subject to ice loads" (ABS 2004), the web of a longitudinal should be divided into at least three elements. In these simulations, the webs of the stiffeners were modelled with eight elements along their depth. The flanges of the stiffeners were divided into four elements across their width in order to capture the deformation of the flange. Ultimately, a 25 mm fine mesh size was applied in this simulation model. A convergence study of mesh density was initially carried out to ensure the mesh size (fineness) was adequate for the simulation. A bilinear isotropic elasto-plastic model was adopted for the material property to simplify the non-linear relationship of stress-strain in the plastic region. Young's modulus is 200 GPa; yield stress is 355 MPa, and post yield modulus is 2,000 MPa.

In reality there is a complex distribution of high and low pressure zones within the contact area. These experiments were not instrumented to capture these local pressure distributions and therefore only uniform pressures distribution over contact areas measured at different load steps during the experiments were applied.

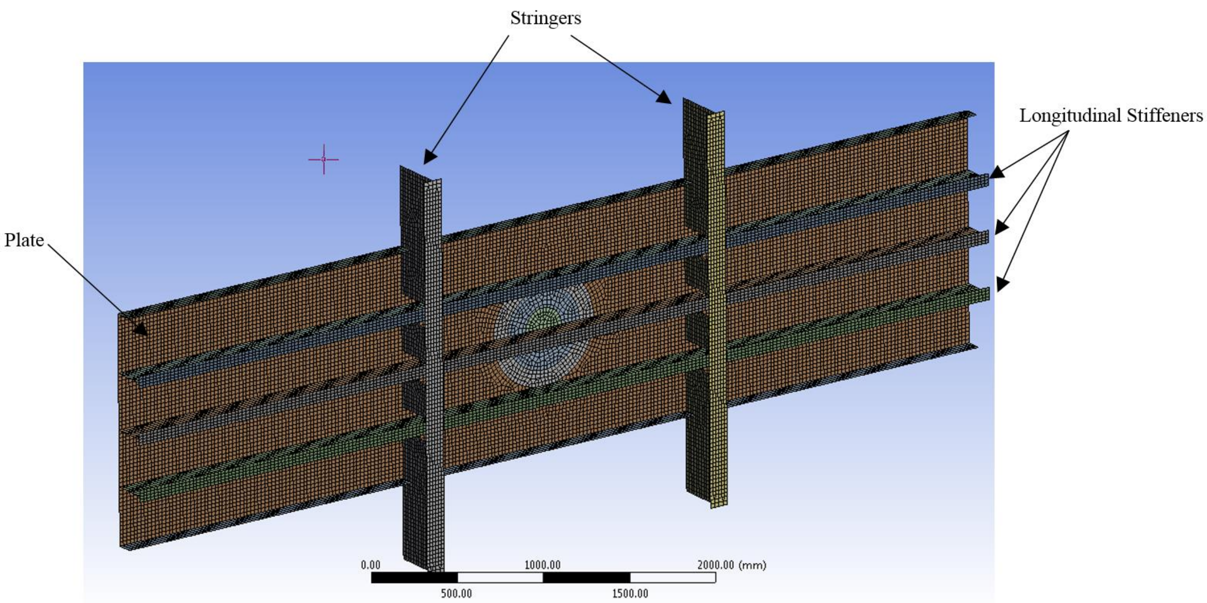

Figure 10. Extent of the structural model

A comparison of load-deflection curves from the Grillage #1 and #2 experiments and associated FE analysis are presented in Figure 11 and 12 respectively. In Figure 11, the FEA curve (black dashed line) shows excellent agreement with the experimental results of Grillage #1 and the G2T1 tests (recall the first load step of Grillage #2 is a similar central load case. The stiffness of the elastic portions of the load-deflection curves in the FEM [44.3 kN/mm] is similar to those of G1T1 [48.3 kN/mm] and G2T1 [52 kN/mm]. Also, comparisons are made showing the cross sectional views of the deformed shapes at both load steps. The deformation shape and magnitude predicted by the FEA shows strong agreement with the experimental results. Even at the final load step, the FEA quite accurately captures the progressive folding over of the central stiffener.

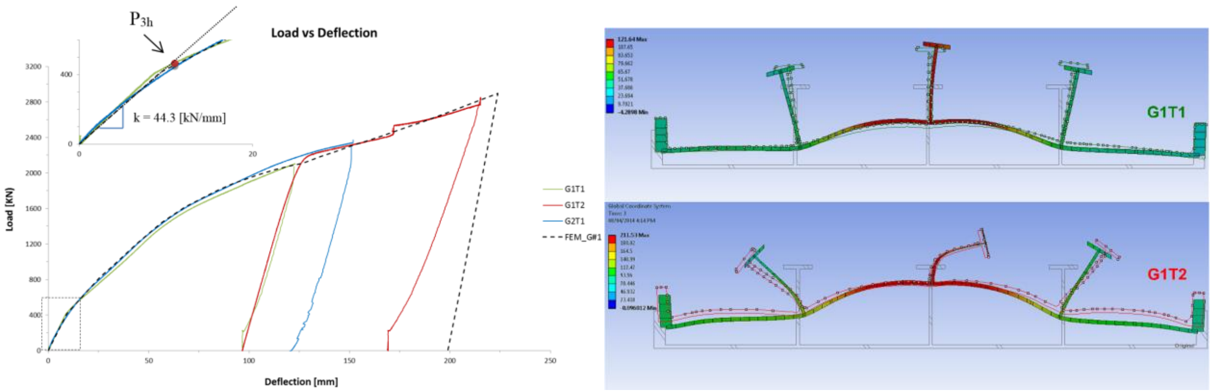

Figure 11. FEM load-deflection curves(left) and cross section views of Grillage #1(right)

In Figure 12(Grillage #2 tests), the FE analysis curves are generally stiffer than the experimental results, however the maximum deformations and permanent set show fairly good agreement with the experimental results. The stiffness of the elastic portions of the load-deflection curves also correlate well. G2T1 FEM [55 kN/mm] is similar to that of G2T1 [52 kN/mm]. Similar to the Grillage #1 tests, the deformed shapes also agree well with the experimental results. Although, at the final load step (G2T3) the FEA tends to over predict the folding over behaviour of the central stiffener.

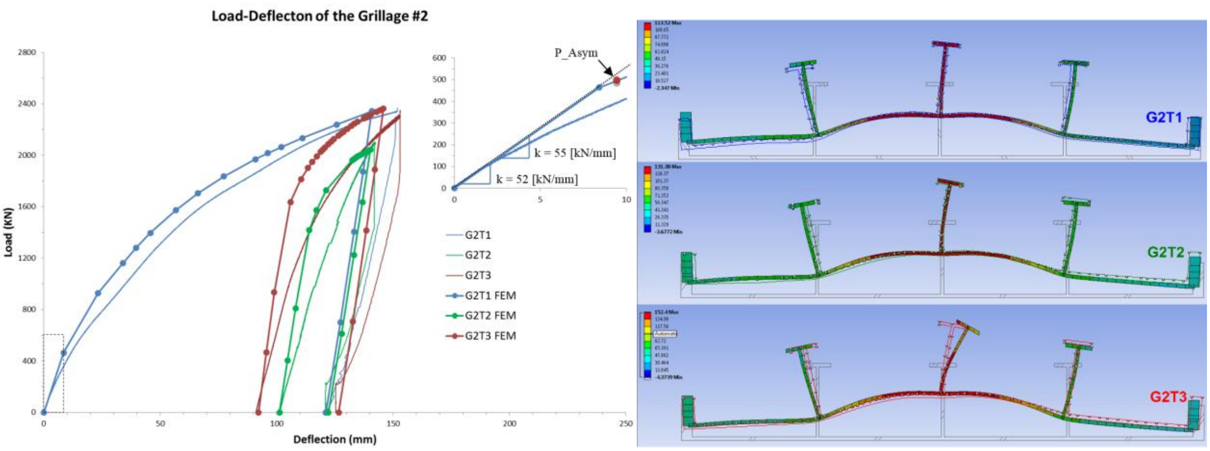

Figure 12. FEM load-deflection curves(left) and cross section views of Grillage #2(right)

CONCLUSIONS AND RECOMMENDATIONS

This paper presents the results of an experimental study coupled with a detailed nonlinear finite element analysis effort aimed at better understanding and predicting the overload response of ice strengthened structures. The strong correlation of physical and numerical results increases the confidence in our ability to predict plastic response and quantify reserve capacity. Furthermore, the results reconfirm the plastic design limits in the Polar Rules which occur at the onset of plastic deformation prior to any major loss of stiffness in the structure. Using some portion of this reserve capacity can lead to the design of safer, more efficient and lighter structures rather than using traditional working stress methods. Ultimately, the application of these findings can support a higher level of safety for ships designed for operations in ice covered water.

The results also demonstrate that nonlinear FEA is a practical tool that can be used for analysis of ice-strengthened ship structures subjected to extreme ice loading for investigation of the ultimate load-carrying capacity and the influence of variable ice loading positions on a grillage. This simulation approach has practical applications in the design and assessment of ice class ships as well as further related research.

The experimental results are quite clear and simple, and yet they raise some fundamental questions about the nature and goals of ice class ship design. When such large overload capacity exists and where the consequences of such damage are so minor (no impact on humans or the environment, only minor repair costs), one may question the value of a probabilistic treatment of design ice loads and structural limit states. Studies of local ice load statistics (take Su. et. al. (2011) as a representative example), typically show that local ice loads increase with increasing time or events, and that the magnitude of that increase is around 20 % per order of magnitude (i.e. 10 x longer testing gives 20 % increase in maximum load). In the grillage case presented here the overload (2.8 MN) was 5.57 x the design load (503 kN). This would suggest that a load of 2.8 MN is 27.8 orders of magnitude more rare than the design load. If, say, the design load represents a load one might expect annually, then one would not expect the 2.8 MN for 1,027 years. Or if the design load occurred every 10s (every impact), then the 2.8 MN would only occur every 1,024 years. Either way, focusing on structural behaviours that have meaningful consequences is more beneficial than considering the design load purely from a probabilistic perspective.

It is recommended that similar experimental and numerical analysis are carried out which consider faster loading rates (higher strain rates in both steel and ice) more realistic of ship-ice impact events and perhaps moving ice loads. Some of this work is already underway. Dynamic loading effects may introduce new structural response mechanisms and will certainly affect the ice failure modes which should be properly understood, tested and modelled.

ACKNOWLEDGEMENTS

This work was carried out as part of a large industry supported research project at Memorial University of Newfoundland called Sustainable Technology for Polar Ships and Structures (STePS^2). There were many people involved in the design and execution of the grillage tests. Physical experiments can be a strenuous and time consuming process and the dedication of everyone involved is recognized. The authors would also like to acknowledge and thank the financial support of Atlantic Canada Opportunities Agency, Research and Development Corporation, American Bureau of Shipping (ABS), BMT Fleet Technology, Husky Energy, Rolls-Royce Marine, Samsung Heavy Industries and the National Research Council Canada.

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