Response of IACS URI Ship Structures to Real-time Full-scale Operational Ice Loads

Bruce W.T. Quinton[1] (M), **Claude G. Daley**[2] (M), and **Robert E. Gagnon**[3] (M)
[1] Faculty of Engineering, Memorial University of Newfoundland
[2] Faculty of Engineering, Memorial University of Newfoundland
[3] Ocean, Coastal and River Engineering - National Research Council of Canada

Moving ice loads can incite significantly different structural responses in a steel grillage structure than can stationary ice loads. This is significant because the accepted standard for the design and analysis of ice-classed ship structures is to assume a stationary ice load (IACS URI I2.3.1). The following work utilizes the 4D Pressure Method ((Quinton, Daley, and Gagnon 2012)) to apply thirty-five of the most significant ice loads recorded during the USCGC Polar Sea trials (1982-86), to fourteen IACS URI PC1-7 classed grillages; using explicit finite element analyses. Two grillage variations for each of the seven PC classes were examined: grillages with "built T" framing and grillages with "flatbar" framing.

In short, the following simulations directly employ real-time/real-space measured full-scale ice loads, and thus provide insight into the structural capabilities of the various IACS URI polar classes when subject to actual (moving) ice loads.

KEY WORDS: *Polar Sea*; polar class; moving load; ice; 4D Pressure Method.

INTRODUCTION

Previous works by the authors have demonstrated (numerically) that the structural response of a steel grillage to a moving load is significantly different than its response to a similar stationary load . Specifically, if a load causes a local plastic response in a grillage, any subsequent lateral movement (i.e. motion in the plane of the plating) of that load will induce a significant decrease in the grillage's structural capacity to bear that load. This is true for cases where the load is supported directly by the plating; and cases where the load is supported directly by a frame. Further, moving loads have been shown to incite stiffener buckling at a much lower load magnitude than would be necessary for a stationary load.

With this in mind, it was desired to investigate the response of the various IACS URI polar classes to real ice loads; that is, real-time moving loads that were measured in the field. The 1980s USCGS *Polar Sea* trials (Daley et al. 1990; Minnick and St. John 1990) were chosen for this purpose. Data from these trials were recorded using a 9.2 m^2 (~100 ft^2) pressure panel located on the bow shoulder of the *Polar Sea*. This pressure panel consisted of 80 sub-panels; 60 of which were active at any given time. The pressure on each sub-panel was recorded in real time; thus yielding operational ice pressure loads that change in both space and time.

This paper presents the results of explicit finite element analyses in which these operational ice loads were applied to various IACS URI (IACS 2011) polar classed grillages using the *4D Pressure Method* (Quinton, Daley, and Gagnon 2012).

The *4D Pressure Method* is a general purpose algorithm, implemented for *LS-Dyna*® (Livermore Software Technology Corp.), that allows pressures that change in both time and space (i.e. $P(x(t), y(t);\, t)$) to be applied to a structure in real-time. This method allows the ice loads recorded aboard the *Polar Sea*, to be applied directly to a structure without simplification; and in (at least) the temporal and spatial resolution in which they were originally measured.

The grillages considered in these analyses were designed based on the *Polar Sea*'s particulars; with the exception of *polar class* and *frame type*. In other words, ship particulars like displacement, frame spacing, frame orientation, etc..., were kept constant, but *plate thickness*, *frame scantlings* and *frame type* were variable. Fourteen grillages were considered in the following analyses; two for each of the seven IACS polar classes, with one of each pair having "built T" frames and the other having "flatbar" frames. The results presented below provide a glimpse as to how the *Polar Sea* may have responded during the 1980's trials, had she been of a different ice class.

In the following numerical analyses, thirty-five of the largest *Polar Sea* ice trials loads (the top five from each of seven sets of trials) were applied to each of the fourteen grillages; totaling four-hundred ninety simulations. Each of these simulations was then examined to determine if the grillage behaved within design expectations, as set by the IACS URI polar class requirements.

USCGC *POLAR SEA* ICE TRIALS

During the period 1982-86, the USCGS *Polar Sea* was the subject of a suite of field trials that measured ice loads on the bow-shoulder during operations in the Antarctic, Beaufort, Bering and Chukchi seas.

Ice loads were determined by using strain gauges to measure compression in the USCGC *Polar Sea*'s transverse frames. The strain gauges were arranged in eight rows, with ten subpanels per row. Six of the eight rows were actively recording data at any given time. Each subpanel had an area of 380 mm x 410 mm. The area of the entire panel was 9.2 m^2 (~100 ft^2) Data was recorded at 32 Hz with a filter frequency of 10 Hz.

Eight sets of trials (i.e. data sets) were recorded in all. Seven of those sets (see Table 1) were used in the following simulations. The missing data set was not usable in these analyses as some of the required time-history data was unavailable.

The data in each set are separated into "load events" of approximately 5 seconds duration. Summary analyses of these data (Daley et al. 1990) provide "Total Panel Force" and "Peak Pressure on a Single Subpanel" for each load event. The largest five load events - as determined by "Total Panel Force" - from each of the seven data sets were used. The aggregate summary values for these ice trial loads are shown in Table 1. Multiyear ice was present during the "Beaufort 1982" and "North Chukchi 1983" trials, and these sets exhibit the highest total loads and peak pressures.

The unused data set mentioned above is the "1984 Beaufort and Chukchi Seas" set. The aggregate summary values for the missing data lie in the 2.6-3.7 [MN] and 4.6-5.8 [MPa] range; which approach the upper-midrange of the aggregate values for the other seven sets.

4D PRESSURE METHOD

The *4D Pressure Method* is a novel, non-contact loading method (Quinton, Daley, and Gagnon 2012) that may be used in explicit finite element analyses to apply ice pressure loads that vary in both time, and 3-dimensional space. The required input for this method is of the form of $(x, \Delta x, y, \Delta y, P(t))$. $P(t)$ is the magnitude of the pressure at time, t; x and y pinpoint the location of $P(t)$ on a given surface; and Δx and Δy define the pressure's spatial extent. This method is general in that the pressure distribution(s) applied may vary in location, size, and shape, and may consist of uniform, distributed, or a collection of discrete pressures (uniform or distributed); each of which may vary in magnitude with time. The generality of the method implies that it may be used to model everything from uniform, stationary, steady pressure loads (as is commonly done using standard finite element techniques), to custom ice pressure load models utilizing feedback response, to actual field and laboratory pressure data measured in time from a pressure sensor array. In addition, the method allows for refinement of the data's spatial resolution through the use of two-dimensional interpolation schemes. For example, given data from 6 x 10 pressure sensor array (e.g. the *Polar Sea* ice trials data), the method can refine this to any desired resolution (e.g. 11 x 19, 21 x 37, etc.) using either a nearest-neighbor, bilinear, or cubic interpolation scheme. The type of interpolation scheme utilized depends on the desired shape of the resulting interpolated data (see Figure 1). The authors suggest that cubic interpolation provides pressure shapes in line with those observed in the laboratory; however, when using the method for design purposes, the nearest-neighbor method would provide more conservative results.

Table 1: Load Particulars.

Location	Ice Type	Load Name	Speed kt	Max Single Subpanel Pressure MPa	Total Panel Force MN
McMurdo Sound Antarctica 1984	1st Year	Ant5	6.7	3.0	2.7
		Ant3	9.8	3.3	2.6
		Ant4	6.6	2.9	2.5
		Ant1	7.1	2.4	2.4
		Ant2	7.3	1.4	2.3
Alaskan Beaufort Sea 1982	Multiyear	Beau4	?	11.1	4.9
		Beau3	?	7.3	4.9
		Beau5	?	8.0	4.3
		Beau2	?	10.1	4.3
		Beau1	?	10.3	4.1
Bering Sea Ice Edge 1986	1st Year	Ber2	6.0	3.1	1.8
		Ber5	9.1	3.0	1.5
		Ber4	8.3	2.0	1.4
		Ber3	9.2	1.5	1.2
		Ber1	8.0	1.4	1.1
North Bering Sea 1983	1st Year	NBer2	?	3.7	3.6
		NBer5	?	5.1	3.6
		NBer3	?	3.8	3.6
		NBer4	?	5.0	3.3
		NBer1	?	4.0	3.0
North Chukchi Sea 1983	Mixed 1st Year & Multiyear	NChuk5	7.8	7.9	4.9
		NChuk4	3.2	9.1	4.4
		NChuk3	7.0	4.0	4.3
		NChuk2	5.6	7.0	3.9
		NChuk1	0.0	1.8	3.9
South Bering Sea 1983	1st Year	SBer3	?	1.7	2.5
		SBer1	?	3.3	2.4
		SBer4	?	2.0	2.3
		SBer2	?	1.7	2.1
		SBer5	?	1.4	1.9
South Chukchi Sea 1983	Mixed 1st Year & Multiyear	SChuk3	?	4.2	3.1
		SChuk2	?	7.0	2.9
		SChuk1	?	2.1	2.8
		SChuk5	12.4	3.2	2.7
		SChuk4	?	5.4	2.5

In Figure 1, the original input data (for a single instant in time) is shown in the top left; the other plots are the outputs of the various interpolation methods, for a given interpolation level.

The *4D Pressure Method* was developed using Matlab® (The Mathworks®, Inc.). A script reads input data, interpolates it (if desired), and then writes the corresponding *LS-Dyna®* input deck.

For the purposes of this investigation, the *4D Pressure Method* was used to spatially refine the data from the 1980s USCGC *Polar Sea* trials by a factor of 5; that is, pressure changes originally recorded between two spatial points in one dimension, were interpolated over 5 spatial points in that dimension. The cubic interpolation algorithm employed.

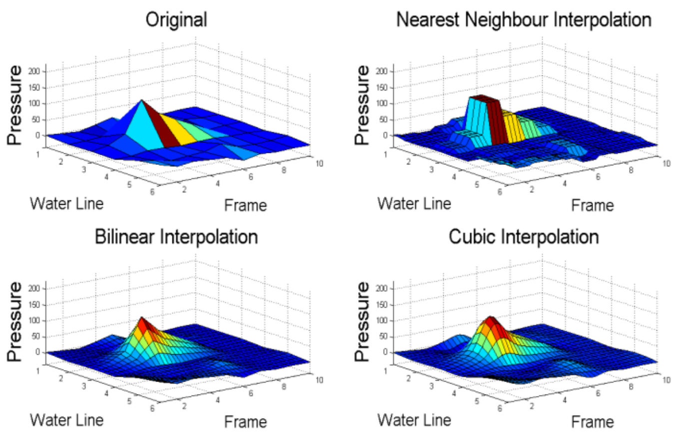

Figure 1: Top left - original 4D pressure data input; Top Right - nearest neighbor interpolation; Bottom Left - bilinear interpolation; Bottom Right - cubic interpolation.

POLAR CLASS GRILLAGES

The IACS *Unified Requirements for Polar Class* (IACS 2011), in combination with the relevant particulars of the USCGC *Polar Sea* (shown in Table 2) were used to design fourteen steel grillages. Two grillages for each of the seven polar classes were created; one utilizing "built T" frames and the other "flatbar" frames. Both frame types were explored in order to gain a better understanding of their relative behaviours in response to moving loads..

A program by C.G. Daley called *PC Design & Check* was used to calculate the plate thickness and frame scantlings for each grillage. *PC Design & Check* is essentially a Microsoft® Excel™ implementation of the IACS polar rules that has the capability to recommend minimum scantlings for frames of various configurations (e.g. flatbar, built-t, angle, etc...). The parameters shown in Table 2 were common inputs into *PC Design & Check* for all fourteen grillages:

Table 2: IACS URI grillage design parameters.

Parameter	Value	Units
Displacement	13.4	kt
Hull Region	Bi	-
Frame Orientation Angle	90	DEG
Frame Orientation Type	Transverse	-
Water Density	1.025	tonne/m^3
Frame Attachment Parameter	2	-
Yield Strength of Steel	315	MPa
Young's Modulus of Steel	207	GPa
Main Frame Span	2210	mm
Main Frame Spacing	406	mm

The variable parameters for each of the fourteen grillages were polar class, which varied between PC1 and PC7, and frame type, which varied between "built T" and "flatbar".

The primary longitudinal structure (which is actually provided by decks in the Polar Sea), was modeled for these simulations using longitudinal "built T" stringers, for all fourteen grillages. These stringers were designed to remain elastic when subject to the full load prescribed by the IACS polar rules over the frame span given in Table 2. The plating's effective width was included in these calculations, but the attached perpendicular framing was ignored. This method provides grossly oversized primary structure; which is desirable in this case as the focus of this work is on the response of the plating and transverse framing. Note that the design of primary structure is not prescribed by the IACS polar rules, but rather left to the member societies. Table 3 gives the design scantlings for each grillage.

Table 3: Grillage Particulars.

Polar Class	Frame Type	Frame Scantlings mm	Plate Thickness mm	Stringer Scantlings mm
1	built T	T 660 x 24, 200 x 24	39.0	T 1700 x 40, 200 x 40
	flatbar	F 525 x 37		
2	built T	T 500 x 20, 200 x 20	31.5	T 1300 x 32, 175 x 20
	flatbar	F 420 x 31		
3	built T	T 440 x 16, 200 x 16	25.5	T 900 x 30, 150 x 15
	flatbar	F 360 x 27		
4	built T	T 360 x 16, 190 x 16	22.5	T 900 x 23, 100 x 20
	flatbar	F 340 x 24		
5	built T	T 300 x 14, 160 x 14	20.0	T 750 x 20, 100 x 20
	flatbar	F 300 x 22		
6	built T	T 280 x 12, 150 x 12	17.5	T 650 x 18, 75 x 15
	flatbar	F 280 x 20		
7	built T	T 280 x 10, 150 x 10	15.5	T 600 x 16, 50 x 10
	flatbar	F 260 x 19		

COMPARISON OF *POLAR SEA* LOADS AND IACS DESIGN LOADS

Table 4 outlines the IACS URI design loads by polar class for these grillages. The values in each row represent the static, stationary load equivalent of a glancing collision on the bow shoulder of the vessel, for each polar class (IACS 2011).

Table 4: IACS Prescribed Design Loads for these grillages.

Polar Class	Design Ice Load F (MN)	Design Ice Line Load Q (MN/m)	Design Avg Ice Pressure P (MPa)	Load Patch Width (m)	Load Patch Height (m)
1	31.4	9.0	14.6	3.483	0.617
2	17.6	5.5	9.7	3.188	0.565
3	10.8	3.6	6.7	3.013	0.534
4	8.0	2.8	5.4	2.890	0.512
5	5.5	2.0	4.2	2.709	0.480
6	4.3	1.6	3.2	2.745	0.486
7	3.2	1.2	2.7	2.586	0.458

The IACS design *load patch* parameters from Table 4 were then used with the pressure-area relationships derived from the *Polar Sea* trials (Daley et al. 1990; Minnick and St. John 1990) to compare the *Polar Sea* ice trial loads with the IACS design loads for each polar class on the basis of average pressure. Table 5 shows the ratio, in percent, of the *Polar Sea* loads divided by the IACS design load for each polar class. This table indicates that the loads experienced by the *Polar Sea* during her 1980s ice trials are below the IACS PC5 level design loads; at least on the basis of *average load patch pressure*. Note the cells highlighted in red in Table 5. As these loads are greater than the design loads for their respective PC classes, we would expect to see significant damage to the PC7 and PC6 grillages for these loads.

Table 5: Polar Sea loads as a percentage of IACS URI design load-patch average pressure (Pavg).

Load	PC7	PC6	PC5	PC4	PC3	PC2	PC1
Ant1	40%	33%	25%	19%	15%	9%	5%
Ant2	37%	31%	23%	18%	14%	10%	6%
Ant3	32%	25%	19%	14%	10%	7%	4%
Ant4	31%	24%	18%	15%	12%	9%	6%
Ant5	34%	32%	23%	21%	17%	11%	7%
Beau1	125%	96%	75%	52%	N/A	N/A	N/A
Beau2	129%	98%	77%	53%	40%	25%	N/A
Beau3	146%	113%	88%	N/A	N/A	N/A	N/A
Beau4	143%	108%	84%	59%	45%	28%	16%
Beau5	92%	80%	60%	47%	36%	23%	14%
Ber1	21%	17%	13%	10%	7%	5%	3%
Ber2	43%	34%	26%	19%	14%	9%	5%
Ber3	28%	22%	17%	12%	9%	5%	3%
Ber4	30%	23%	18%	13%	10%	6%	4%
Ber5	27%	20%	16%	11%	8%	5%	3%
NBer1	44%	35%	27%	19%	15%	10%	6%
NBer2	82%	64%	50%	36%	27%	17%	10%
NBer3	60%	48%	37%	27%	21%	13%	8%
NBer4	75%	57%	45%	31%	23%	14%	8%
NBer5	81%	64%	50%	35%	27%	17%	10%
NChuk1	35%	29%	22%	17%	14%	9%	6%
NChuk2	74%	56%	44%	30%	18%	10%	6%
NChuk3	67%	55%	42%	31%	24%	16%	9%
NChuk4	98%	80%	61%	46%	36%	24%	14%
NChuk5	123%	94%	73%	51%	39%	25%	14%
SBer1	41%	33%	25%	19%	15%	10%	6%
SBer2	34%	29%	22%	17%	13%	8%	5%
SBer3	42%	34%	26%	19%	14%	9%	5%
SBer4	34%	28%	21%	16%	13%	8%	5%
SBer5	17%	13%	10%	7%	6%	5%	3%
SChuk1	37%	30%	23%	16%	12%	8%	5%
SChuk2	31%	28%	21%	16%	13%	9%	5%
SChuk3	61%	48%	37%	27%	21%	14%	9%
SChuk4	70%	54%	42%	N/A	N/A	N/A	N/A
SChuk5	63%	50%	39%	28%	22%	14%	8%

A similar comparison between the *Polar Sea* loads and the IACS design loads was made based on *total force*. In this case, if a *Polar Sea* load was below the design load for a particular IACS PC class, than it was classified by that PC class. These results are shown in Table 6 and agree well with those based on average pressure; that is, the largest load experienced during the *Polar Sea* ice trials was within the design limits of similar PC 5 classed vessel of similar particulars to the *Polar Sea*.

Table 6: *Polar Sea* equivalent IACS design load by total force.

Load Name	F_{max} (MN)	IACS PC Load Equivalent	Load Name	F_{max} (MN)	IACS PC Load Equivalent
Ant1	2.391	PC7	Beau1	4.115	PC6
Ant2	2.272	PC7	Beau2	4.314	PC5
Ant3	2.561	PC7	Beau3	4.872	PC5
Ant4	2.531	PC7	Beau4	4.932	PC5
Ant5	2.670	PC7	Beau5	4.324	PC5
Ber1	1.126	PC7	NBer1	2.999	PC7
Ber2	1.813	PC7	NBer2	3.577	PC6
Ber3	1.156	PC7	NBer3	3.557	PC6
Ber4	1.415	PC7	NBer4	3.288	PC6
Ber5	1.505	PC7	NBer5	3.577	PC6
NChuk1	3.856	PC6	SBer1	2.352	PC7
NChuk2	3.916	PC6	SBer2	2.112	PC7
NChuk3	4.334	PC5	SBer3	2.461	PC7
NChuk4	4.414	PC5	SBer4	2.322	PC7
NChuk5	4.892	PC5	SBer5	1.933	PC7
SChuk1	2.820	PC7			
SChuk2	2.860	PC7			
SChuk3	3.089	PC7			
SChuk4	2.531	PC7			
SChuk5	2.670	PC7			

NUMERICAL MODEL

An explicit and nonlinear finite element code is required to model moving loads. The deleterious effects of moving loads versus stationary loads are only present after the structure has plastically deformed (Quinton 2008; Quinton, Daley, and Gagnon 2012). An elastic structure will not experience any loss of capacity to a moving load; therefore, a nonlinear numerical model is necessary to predict structural response to moving loads. Further, because the deformations associated with moving loads may be large, geometric nonlinear capability is also required.

MPP-Dyna® is an explicit nonlinear finite element code that exhibits these required capabilities. It is a release of the proven and popular LS-Dyna® code that is capable of running in parallel on multiple computers in a cluster. MPP-Dyna® was used exclusively throughout this research.

The numerical models were defined at full scale, and combine the previously mentioned IACS polar class grillages with the *Polar Sea* ice trial loads using the *4D Pressure Method*.

Geometry and Mesh

The grillage numerical models were composed entirely of planar areas (see Figure 2). These areas were meshed with standard 4-node shell elements with five through thickness integration points. The Belytschko-Tsay element formulation was used for all shell elements. This element formulation includes bending, membrane and shell thickness changes.

Each grillage modeled fourteen transverse frames, three longitudinal stringers and the attached plating, and had overall dimensions of 5.896 m x 8.839 m; with a 406 mm frame spacing and a 2210 mm stringer spacing. The average element size is 50 mm x 50 mm, and the mesh density ranges from 403.5 elements/m for the "built T" PC1 classed grillage, to 505.5 elements/m for the "flatbar" PC7 grillage. An example mesh for the "flatbar" grillages is shown in Figure 3.

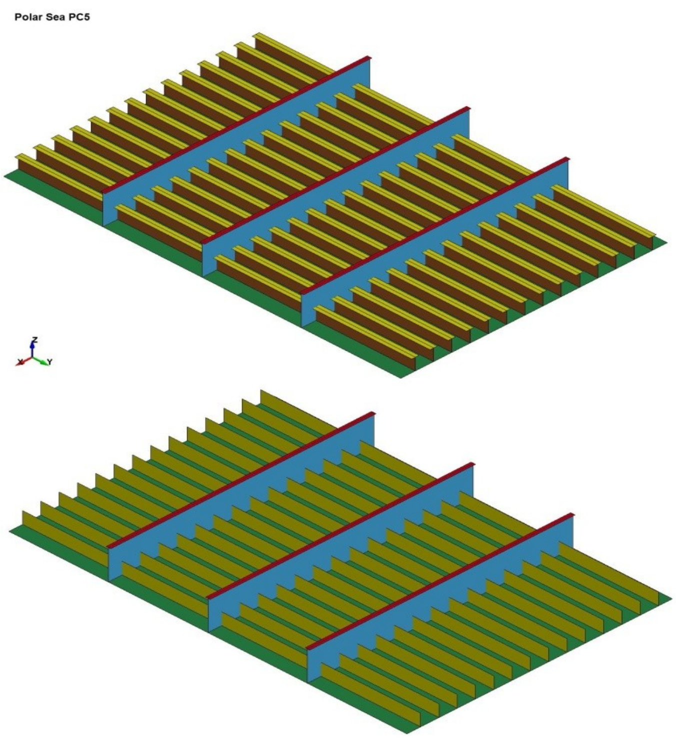

Figure 2: Example numerical model "built T" (top) and "flatbar" (bottom) grillage geometries.

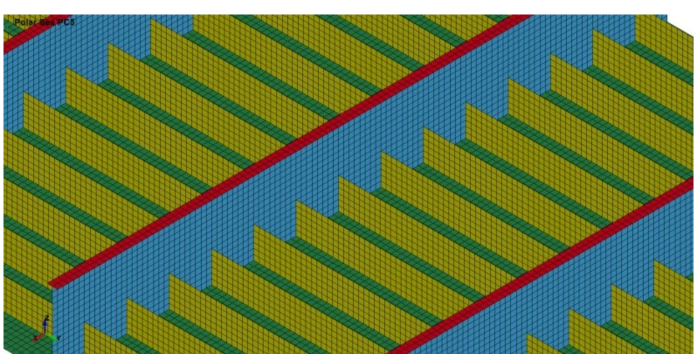

Figure 3: Example finite element mesh.

Material Model

A bilinear isotropic elasto-plastic material model was applied throughout the entire grillage model; with the inputs as shown in Table 7. The Cowper-Symonds parameters (C and p) are inputs for the Cowper-Symonds strain-rate hardening model. Since all loads in these simulations are a function of time, the Cowper-Symonds model was employed to account for the time-dependent strain-rate hardening of steel. This model scales the yield-stress of the steel by a factor of $\left[1 + (\dot{\varepsilon}/C)^{1/p}\right]$; where $\dot{\varepsilon}$ is the strain-rate. This factor is always greater than 1, thereby effectively reducing the amount of plastic damage sustained during any given load event.

Table 7: Large Grillage material model parameters.

Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio (-)	Yield Stress (MPa)	Tangent Modulus (MPa)	Cowper Symonds *C* (1/s)	Cowper Symonds *p* (-)
7850	207	0.3	315	1000	40.4	5

Boundary Conditions

All nodes perpendicular to the grillage's plating located on extents of the grillage were constrained in all rotational and translational DOF.

TEST MATRIX

The test matrix consisted of applying each of the thirty-five ice loads to each of the fourteen polar classed grillages; resulting in four-hundred and ninety simulations. A subset of the test matrix, for one of the thirty-five ice loads, is given in Table 8. Similar matrices were carried out for each of the other thirty-four ice loads.

Table 8: Text Matrix Excerpt.

Run	Load	PC Class	Framing Type
1	Ant1	1	Flatbar
2			Built T
3		2	Flatbar
4			Built T
5		3	Flatbar
6			Built T
7		4	Flatbar
8			Built T
9		5	Flatbar
10			Built T
11		6	Flatbar
12			Built T
13		7	Flatbar
14			Built T

RESULTS

It should be noted in this section that because the *Polar Sea* responded elastically to all measured ice trial loads, these results are only quantitatively valid up to the point where the structure behaves plastically. The behaviour of ice loads subsequent to the onset of plastic damage in a structure is not presently known, and it would be rash to assume that the associated pressures are not a function of the structure's plastic damage. Indeed, recent numerical results of ship/bergy bit impacts show that the loading vector and load pattern during a sliding impact scenario is strongly influenced by plastic deformation of the grillage (Gagnon and Wang 2012). Therefore deformations, reaction loads and strains subsequent to the onset of plastic behaviour in these models, while indicative of the relative responses between grillages, should not be taken as actual quantitative predictions.

Table 9 shows the percent plastic strain for each grillage when subjected to each of the thirty-five loads. As predicted earlier, the Beaufort and North Chukchi loads highlighted in Table 5 did indeed cause plastic damage to the grillages. The responses to these loads are correspondingly highlighted in red in Table 9. The responses highlighted in yellow in Table 9 show plastic strains for loads that were nominally less than the design load for each grillage. The fact that plastic strains were evident in loads less than the IACS design load is in itself not surprising, because the IACS URI polar rules employ plastic design. That is, the design point is well beyond "first yield" in the structural members, and therefore considers some permanent structural deflection to be acceptable. It is interesting to note that some of the yellow highlighted cells contain plastic strains (shown in bold red text) comparable to those in the red highlighted cells. Cells highlighted in green indicate that the structure remained entirely elastic.

Table 9: Percent plastic strain for each grillage*.

Load	Plastic Strain									
	"Built T" Frames					Flatbar Frames				
	PC7	PC6	PC5	PC4	PC3	PC7	PC6	PC5	PC4	PC3
Ant1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ant2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ant3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ant4	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ant5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Beau1	0.4%	0.1%	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%	0.0%	0.0%
Beau2	0.4%	0.1%	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%	0.0%	0.0%
Beau3	1.6%	0.9%	0.2%	0.1%	0.0%	1.5%	0.7%	0.2%	0.1%	0.0%
Beau4	2.1%	1.0%	0.3%	0.1%	0.0%	1.8%	0.7%	0.2%	0.1%	0.0%
Beau5	0.4%	0.2%	0.0%	0.0%	0.0%	0.4%	0.1%	0.0%	0.0%	0.0%
Ber1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ber2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ber3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ber4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ber5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NBer1	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
NBer2	0.2%	**0.9%**	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
NBer3	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
NBer4	0.2%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
NBer5	**0.7%**	0.2%	0.1%	0.0%	0.0%	**0.7%**	0.2%	0.1%	0.0%	0.0%
NChuk1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NChuk2	0.2%	0.1%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
NChuk3	0.2%	0.1%	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%	0.0%	0.0%
NChuk4	**0.5%**	0.2%	0.0%	0.0%	0.0%	0.4%	**0.5%**	0.0%	0.0%	0.0%
NChuk5	0.6%	0.2%	0.0%	0.0%	0.0%	0.4%	0.1%	0.0%	0.0%	0.0%
SBer1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SBer2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SBer3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SBer4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SBer5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SChuk1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SChuk2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SChuk3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SChuk4	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
SChuk5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

*Note: PC1 and PC2 grillages remained elastic for all load cases and are omitted in this table for brevity.

Table 10 gives the deformation of the plating for each grillage as a percentage of the frame spacing (i.e. 406 mm). These values are deformations "under load"; not residual deformations (i.e. they are either comprised totally of elastic deformations (green highlighted cells) or a combination of elastic and plastic deformations (yellow and red highlighted cells). As above, the red highlighted cells correspond with the loads in Table 5 that are larger than the IACS design loads.

From Table 9 we can see that the "flatbar" framed grillages generally exhibit less plastic damage than the "built T" framed grillages. Table 10 shows that the deformations for the "flatbar" framed grillages are generally higher than for the "built T" framed grillages. These results indicate that the "flatbar" framed grillages are more efficient at converting impact energy into elastic deformations than their "built T" counterparts, resulting in a more resilient structure. This finding is in agreement with the experimental observations of Daley et al. (2007; 2009). The top flange of a "built T" frame is purely the result of an elastic design space, where preventing yield in the extreme fibre of the frame is the design point. In overload conditions, the top flange of a "built T" frame provides a much stiffer reaction than the web or attached plating can support elastically. This induces plastic deformation in the web and attached plating at lower load levels than for a comparable "flatbar" frame.

Table 10.: Deformation as a percentage of frame spacing for grillages with "built T" framing**.

Load	Plate Displacment as % of Frame Spacing									
	Built T Framing					Flatbar Framing				
	PC7	PC6	PC5	PC4	PC3	PC7	PC6	PC5	PC4	PC3
Ant1	2.7%	2.0%	1.3%	0.8%	0.6%	3.0%	2.2%	1.5%	1.0%	0.8%
Ant2	2.1%	1.5%	1.0%	0.6%	0.5%	2.3%	1.6%	1.1%	0.7%	0.5%
Ant3	1.6%	1.2%	0.8%	0.5%	0.4%	1.8%	1.3%	0.9%	0.6%	0.5%
Ant4	2.7%	2.0%	1.4%	0.9%	0.6%	3.0%	2.2%	1.5%	1.0%	0.8%
Ant5	2.5%	1.9%	1.3%	0.8%	0.6%	2.8%	2.0%	1.4%	0.9%	0.7%
Beau1	1.8%	1.2%	0.9%	0.5%	0.4%	1.9%	1.2%	0.8%	0.6%	0.4%
Beau2	2.6%	1.7%	1.1%	0.7%	0.5%	2.8%	1.8%	1.2%	0.8%	0.6%
Beau3	**7.7%**	4.9%	2.7%	1.6%	1.2%	**9.8%**	**5.5%**	3.1%	1.9%	1.5%
Beau4	**8.1%**	4.8%	2.8%	1.7%	1.3%	**10.3%**	5.0%	3.0%	1.9%	1.4%
Beau5	4.3%	3.0%	1.9%	1.2%	0.9%	**5.1%**	3.2%	2.1%	1.4%	1.1%
Ber1	0.7%	0.6%	0.4%	0.2%	0.2%	0.8%	0.7%	0.4%	0.3%	0.2%
Ber2	1.8%	1.3%	0.9%	0.6%	0.4%	1.9%	1.4%	0.9%	0.6%	0.5%
Ber3	1.4%	1.0%	0.7%	0.4%	0.3%	1.5%	1.1%	0.7%	0.5%	0.4%
Ber4	1.0%	0.7%	0.5%	0.3%	0.2%	1.1%	0.9%	0.6%	0.4%	0.3%
Ber5	1.0%	0.8%	0.5%	0.3%	0.3%	1.1%	0.8%	0.6%	0.4%	0.3%
NBer1	2.6%	1.7%	1.5%	1.0%	0.6%	3.2%	2.0%	1.4%	1.0%	0.9%
NBer2	4.5%	3.1%	2.1%	1.3%	1.0%	4.9%	3.3%	2.2%	1.4%	1.1%
NBer3	3.8%	2.5%	1.5%	1.1%	0.8%	4.1%	2.6%	1.9%	1.1%	0.9%
NBer4	3.0%	2.3%	1.4%	0.9%	0.7%	3.1%	2.3%	1.7%	1.0%	0.8%
NBer5	4.9%	3.2%	2.2%	1.4%	1.0%	**5.2%**	3.4%	2.2%	1.4%	1.1%
NChuk1	3.7%	2.5%	1.7%	0.8%	0.8%	3.9%	2.7%	1.9%	1.3%	0.8%
NChuk2	3.8%	2.5%	1.7%	1.0%	0.8%	4.0%	2.2%	1.7%	1.1%	0.9%
NChuk3	4.4%	3.2%	2.2%	1.0%	0.9%	**5.3%**	3.5%	2.6%	1.4%	1.0%
NChuk4	4.9%	3.2%	2.0%	1.2%	0.9%	**6.3%**	3.4%	2.1%	1.4%	1.0%
NChuk5	4.6%	3.0%	1.9%	1.2%	0.9%	**5.4%**	3.1%	2.0%	1.3%	1.0%
SBer1	2.2%	1.6%	1.0%	0.7%	0.5%	2.3%	1.6%	1.1%	0.7%	0.5%
SBer2	1.6%	1.2%	0.7%	0.4%	0.3%	1.7%	1.3%	0.8%	0.4%	0.4%
SBer3	2.0%	1.5%	0.9%	0.5%	0.4%	2.0%	1.7%	1.0%	0.6%	0.4%
SBer4	2.0%	1.5%	1.1%	0.7%	0.4%	2.4%	1.7%	1.0%	0.6%	0.4%
SBer5	1.7%	1.0%	0.8%	0.4%	0.3%	1.4%	1.1%	0.8%	0.5%	0.4%
SChuk1	2.9%	2.2%	1.2%	0.6%	0.6%	3.1%	2.4%	1.6%	0.7%	0.7%
SChuk2	2.6%	1.7%	1.2%	0.8%	0.6%	2.7%	2.1%	1.4%	1.0%	0.6%
SChuk3	1.6%	1.2%	0.8%	0.5%	0.4%	1.9%	1.4%	0.9%	0.6%	0.4%
SChuk4	2.7%	1.9%	1.3%	0.8%	0.6%	2.9%	2.0%	1.4%	0.9%	0.7%
SChuk5	1.9%	1.3%	0.8%	0.5%	0.4%	2.1%	1.5%	0.9%	0.6%	0.5%

**Note: PC1 and PC2 grillage results omitted for brevity.

These above results generally show that when subjected to real-time, measured ice loads, these IACS polar classed structures generally behaved as predicted by the IACS URI polar rules. That is, loads near the IACS URI design load did not generally cause excessive damage, while loads larger did.

CONCLUSIONS AND RECOMMENDATIONS

Real-time, measured, spatially changing ice pressures were applied to IACS polar classed structures, and their responses were observed. In general, the polar classed structures responded as predicted by the IACS URI rules; that is, most loads that were lower in magnitude than the IACS design load did not cause unacceptable damage to the structure, while loads that were higher in magnitude did. The effect of the movement of the loads on these grillages has not been resolved, and further study involving comparison of these results with the results of simulations applying the IACS stationary design loads given in Table 4 are required.

ACKNOWLEDGEMENTS

This work was made possible through funds provided by the Memorial University of Newfoundland's Sustainable Technology for Polar Ships & Structures (STePS^2) project and its funding partners.

REFERENCES

DALEY, C., G. Hermanski, M. Pavic, and A. Hussein. 2007. "Ultimate strength of frames and grillages subject to lateral loads - an experimental study." Paper presented at 10th International Symposium on Practical Design of Ships and Other Floating Structures, Houston, Texas, USA.

DALEY, C. G., and G. Hermanski. 2009. "Ship frame research program - A experimental study of ship frames and grillages subjected to patch loads." Washington, DC, USA: U.S. Ship Structures Committee, SSC-457.

DALEY, C., J. W. St. John, R. Brown, and I. Glen. 1990. *Ice loads and ship response to ice - consolidation report.* Ship Structure Committee, SSC-340.

GAGNON, R. E., and J. Wang. 2012. "Numerical simulations of a tanker collision with a bergy bit incorporating hydrodynamics, a validated ice model and damage to the vessel." *Cold Regions Science and Technology* (Article in Press).

IACS. 2011. *Requirements concerning polar class*. London: International Association of Classification Societies.

MINNICK, P., and J. St. John. 1990. *Global ice forces and ship response to ice - A second season.* Ship Structure Committee, SSC-343.

QUINTON, B. W. 2008. "Progressive damage to a Ship's structure due to ice loading Masters." Memorial University of Newfoundland.

QUINTON, B. W., C. G. Daley, and R. E. Gagnon. 2012. "Realistic moving ice loads and ship structural response." Paper presented at The Proceedings of the 22nd (2012) International Offshore and Polar Engineering Conference, Rhodes, Greece.

QUINTON, B. W., C. G. Daley, and R. E. Gagnon. 2010. "Effect of moving ice loads on the plastic capacity of a ship's structure." Paper presented at Proceedings of the 9th International Conference and Exhibition on Performance of Ships and Structures in Ice, Anchorage, Alaska, USA.

Discussion

Jorgen Amdahl, Visitor

I would first like to compliment the authors for their substantial contributions to research and development on ice loads, load effects, structural resistance and design of polar ships over the past decades. There is no doubt that they have a unique experience and dispose of a wealth of invaluable data from laboratory and full scale measurements of ice actions.

For that reason I had great expectations upon starting to review the paper, but I must admit that I am not fully satisfied after having read it. Certainly, there is a lot of information baked into the paper, but important data are missing or not clearly explained (or it may be my failure to understand correctly the presented information), which makes it difficult to fully appreciate the results of the study.

The numerical study includes simultaneously the effects of several important factors into single analyses, and the effects of each factor on the results become disguised. If each factor had been isolated and investigated step by step, I believe a more profound understanding of their significance could have been obtained.

In my view there are at least four issues that need to be addressed when the applicability of the IACS URI rules are investigated:

1. How good are the resistance models for the plating and the frames compared to nonlinear finite element analyses?

Both the plate and the frame requirements are based on plastic analysis. I do, indeed, favor this because plastic analysis provides good estimates of the collapse resistance. Nevertheless, the collapse models are idealized and simplifications are introduced. It would, therefore, be very interesting to compare rule resistances with those predicted with LS-DYNA (which are considered "true" values). Further, what are the strain levels that are implicitly accepted by the collapse models? This could be obtained by reading strains when the collapse mode assumed in the code has been developed in the simulation with LS-DYNA. Some engineering judgment will have to be exercised, because the collapse mode is not formed gradually.

This investigation will reveal any conservatism/non-conservatism in the IACS URI rules and the implied strains would set the reference level for the strains that are obtained in later analyses, for example those in Table 9.

To include assessment of the local plate requirement I believe, but I am not sure, that the uniform pressure distribution and patch dimensions according Table 4 should be supplemented with the peak pressure factor (PPF) and hull area factor (AF) in a small area (say frame spacing squared) in order to comply with the IACS URI rules. For better judgment and to avoid uncertainties the applied AF and PPF should be given.

From the above it transpires that it is basically the cases where plastic strains are obtained that attract my interest. In my view the corresponding results for the lower class (stronger) vessels are obvious (response in the elastic domain), and deserve less space than they occupy in the paper.

2. How well do the assumed distributions comply with the measured pressure distribution?

The Beaufort Sea data are especially interesting in this case. Static or quasi-static simulations with LS-DYNA should be carried out scaling the pressure distribution from these measurements. What are the pressure levels (local and average) compared to the rule values for the same strain levels as with obtained in Pt. 1? Is the occurrence of plastic strains for loads that are nominally less than the design load for a grillage due to higher local pressure versus average pressure than those assumed in the rules?

The paper contains a lengthy discussion of methods to interpolate the measured values. In my view this should not be decoupled from the use of the pressure distributions. It is noticed that the area of the pressure panels is almost equal to the frame spacing squared of the numerical model. Local plate resistance and strains are often estimated on the basis of uniform pressures over frame spacing squared areas. I would therefore suggest using the original 4D data with a small correction as input for the LS-DYNA analysis. The pressures from Beaufort Sea are very high (> 10 MPa), so comparing this pressure with the average design pressure multiplied with AF and PPF would be meaningful. For full appreciation of the results it would be necessary to know the spatial as well as temporal variation of the pressures. Presentation of data for a few of the extreme cases would be welcomed

3. What is the effect of moving the pressure distributions using the 4D pressure method versus using the "worst " pressure distribution?

Of course the plastic deformations will spread over a larger area, but are the maximum strains/deformations different from those obtained in Pt. 2?

4. What are the effects of dynamics?

The major dynamic effects are inertia effects and strain rate. The results of true dynamic analyses should be compared with those of "static" analysis for otherwise identical cases.

It is very important that the strain rate effect be investigated by comparing otherwise identical analyss. The effect is uncertain and very much discussed. The Cowper-Symonds equation gives a significant increase of yield strength even for moderate strain rates. We do not know how much the yield strength increased during the simulations and thus affected the results. If it can be substantiated that the effect is real, shall it be included in the rules or shall it be considered a reserve strength factor?

The finite element model seems appropriate as far as mesh size and boundary conditions are concerned, the latter on the condition that plastic deformations take place some distance from the boundaries. It may be discussed whether local imperfections should be introduced for local web buckling and tripping mode for stiffeners. Fortunately, explicit programs more easily trigger buckling than implicit schemes, but do they occur at the correct load levels for the T-stiffeners and could the flat bars be susceptible to tripping? The flat bars have a substantially larger shear area, and is failure of the T-stiffener webs dominated by shear yielding?

It would be nice if the pressure-area relationships derived from the Polar Sea trials were given.

In conclusion: I really appreciate the amount of work conducted by the authors. The approach that is adopted – use of nonlinear finite element analysis along with measured ice pressure distribution – is supported. I do hope that the important effects are better separated in the future investigations so as to provide rule makers and designers of Arctic marine structures with more fundamental and in-depth knowledge of ice actions and action effects.

Roger Basu, Member

Full-scale measurements in engineering are comparatively rare especially when they involve difficult processes such as the interaction of ships and ice. Such measurements are conducted in conditions that are often difficult to control, or define. They are expensive and this is perhaps the main reason they are rare. Nevertheless, such measurements are vital since they are the only practical source of data for the critical task of calibrating and otherwise improving design equations. Notwithstanding these comments, high quality data derived using numerical analysis methods can help reduce the need for full-scale measurements, although it is difficult to imagine that such methods can completely eliminate the need for good quality experimental data especially at full scale. At the very least the results from full-scale experiments will be needed to validate numerical models. It for these reasons the work presented in the subject paper is so valuable.

It is especially gratifying to see the authors using data gathered some decades ago and applying it to examining a recently identified issue concerning the differences in structural response depending on whether the load is applied statically or as a moving load. The work seems to have uncovered new issues that may be important in considering the design of ship structure subject to ice loads. This may also be relevant for offshore structures.

A number of questions come to mind in reading the paper. It is recognized that not all the issues and questions raised could possibly be addressed in a single paper. While some of the questions can be addressed simply in the subject paper through minor additions, there are others that should be more properly addressed in subsequent studies:

1. The IACS Polar Rules assume for each class notional ship speed and ice thickness. It would be useful in interpreting the results to compare these with speeds summarized in Table 1. Are the associated ice thicknesses known?

2. Unfortunately there does not appear to be an easy way to establish what the measured loads represent in terms of how much of proportion of the lifetime extreme load they represent. Presumably the IACS loads as design loads are representative of lifetime extremes. Additional information on these aspects would be helpful in interpreting the percentages presented in Table 5 of the paper.

3. The plastic strain attained, if any, for each of the cases considered is summarized in Tables 9 and 10. For comparison purposes an indication of what "percent plastic strains" would result under the corresponding full PC design load would be instructive.

4. The 4D Pressure Method is presumably essentially a time domain analysis. What value for damping was assumed in the analysis?

5. It would be interesting to know how the fact that the load is moving influences the response. This could be done by applying the load that causes the maximum response as shown in Tables 9 and 10. In other words how would the values of percent plastic strain change for the case where the load is applied statically?

6. The study of the response of beams, and other structures, to moving loads is a well-developed field. It would be interesting to investigate whether these methods can be used to model moving ice loads. In that regard greater discussion in the paper of the dynamics of the response would be useful.

7. Similarly, in regard to the comment about stiffener buckling occurring at lower magnitudes of load if it is applied as a moving load. Again, is this a dynamic effect? If it is, then how might the speed of the ship influence the response?

8. Perhaps the authors could speculate on how the evenness in the side shell plating might influence the response?

The paper makes a significant contribution to the numerical modeling of ship structure-ice interaction and has made good use of existing full-scale data. The authors are to be commended for this and are encouraged to explore, if they have not already done so, some of the issues outlined above.

Pentti Kujala, Visitor

The authors have prepared an interesting and straightforward paper applying advanced numerical modeling of ship-ice interaction to capture the effect of real ice induced pressures on the shell structures of an icebreaker when the shell structures are designed applying various IACS PC classes. I have mainly two topics for which I await some further clarification. First is the calibration of the pressure measuring system onboard USCGC *Polar Sea*. As the system is based on the measurements of compressive stresses on the web of the installed frames, it would be interesting to know how these compressive stresses are calibrated to capture the pressure distribution induced by ice. Secondly, it would be interesting to hear the authors' opinion of proper limit states to be used on ice-strengthened structures. In Table 9 and 10 are given the calculated plastic strains and permanent deflections occurring on the modeled structures. It seems that plastic strain higher than 0.3% is selected as "red" area and similarly 1.9% of permanent deflection is selected as "red" values. Can the authors clarify somewhat more in detail why these values have been selected? In addition, it would be interesting to know whether the conducted analysis gave any new insight to the proper limit states that should be used when designing shell structures of ships for various operations in ice.

Dan Masterson, Member

I have read the paper carefully and have discussed it with colleagues who have knowledge in the field. The work itself has been done carefully and well. It shows by extrapolation of past ship ram tests that the lower classes of the Polar Class code are reasonably correct. We already knew this but confirmation is always helpful.

The real problem lies in the sideshell pressures specified by Polar Class for PC1 and PC2. All evidence from various kinds of tests supports the thesis that these pressures are not reasonable but are excessively and unjustifiably high. Thus a real problem is created for higher class icebreaking ship hull design. This work does nothing to address the issue. This problem will surely be addressed in future editions of the IACS standard.

Takahiro Takeuchi, Visitor

The paper provides useful field data based on USCGC *Polar Sea* trials. Authors indicate that some of data as shown in Table 5 exceed IACS URI design load. Through a large number of simulations by FEM using these field data, plastic deformations of the structure were correspondingly obtained. These findings will clearly contribute to the design of the polar ships.

I think the following information will enhance the value of the paper:

1. More explanation of ice conditions for each trials.

2. Description of typical ice failure observed in each trials, and corresponding ice-load (histories).

Could you prepare further information?

Authors' Response

The authors would like to thank **Professor Amdahl** for his in depth discussion of our paper. We greatly appreciate his knowledgeable comments; however, we believe that our purpose in writing this paper was somewhat different than he interpreted. The four major parts of Dr. Amdahl's discussion are preceded by the assertion "*In my view there are at least four issues that need to be addressed when the applicability of the IACS URI rules are investigated.*" It was not our aim to address the applicability of the IACS URI rules. The goal of the paper was to explore the effects of the movement of the load on ship structures. We chose both the *Polar Sea* data and the IACS Polar Rules as bases for our study, and we took both as givens. While one might question either of these items, this was not our goal. The current standard approaches to the design of ice class ships (or offshore structures) view the ice load as acting at a single location on the outer shell. Most actual ice loads do not remain stationary with respect to a ship's hull, and our prior work suggests that a moving load causing a plastic structural response incites more damage to the structure than an equivalent stationary load. With the exception of the assumption that loads are applied quasi-statically at a single location, none of the premises inherent in the IACS URI rules are in question (in this paper).

Dr. Amdahl raises the concern that several important factors are simultaneously included in this study. He is correct that we did this. In particular, strain rate effects; load movement; varying pressure amplitudes, distributions, and trajectories; and dynamic (inertial) effects are all combined. This was done intentionally, though we agree that we might have looked at the effects in isolation. We took our approach so as to model, as close as is possible, real-world ship-ice interactions. Strain-rate effects, commonly included in crash simulations in other industries (e.g. automotive and aerospace), were included in these simulations using the Cowper-Symonds model. The Cowper-Symonds model is a standard for simulations that ignore temperature changes, for which there are accepted parameters for common steels. The *Polar Sea* trials data provided us with real world pressure data that varied in amplitude, time and space, and thus permitted us to examine realistic moving ice loads. We accept that the Polar Sea data is imperfect, but until we have data of better temporal and spatial resolution, we feel comfortable in using it for our purposes.

We would like to emphasize a point about our simulation's validity. We used ice loads measured on an elastic structure. Obviously we have not considered the various dynamic and rate-dependent effects that would occur when the structure begins to behave plastically. There is a lack of data regarding ice loads on a plastically deforming structure. This latter point is why the authors point out (in the paper) that the results are not quantitatively valid after plastic yielding begins.

Dr. Amdahl raises many interesting points in his discussion of our paper. And although we did not intend to discuss the applicability of the IACS URI rules, we agree that this is an important issue. We will address his comments in the order he presented them:

Regarding the resistance models for the plating and framing, the authors have investigated experimentally and numerically various PC classed grillage structures. Laboratory experiments involving a full sized PC6 classed grillage structure were performed by Daley and Hermanski (2008a; 2008b). The results of both the experiments and the numerical models agreed very well with the IACS capacity formulations, though not necessarily with the exact failure geometry. We would agree that additional study examining the IACS formulations would be valuable.

Regarding the pressures given in Table 4, we did not include the peak pressure factor (PPF) because we compared the average pressure over the whole patch with the average for the same area from the Polar Sea data. Comparing the more localized peaks would be a different exercise. We did not include the area factor (AF), because the Polar Sea panel was in the bow and the area factor was 1.0.

Assuming that Dr. Amdahl is referring to the measured Polar Sea pressure distributions in comparison to the distributions assumed in the IACS Polar rules, we feel that such a comparison would be done with caution. The Polar Rules have a pressure distribution as one part of a complete design process and meant to be used in that way only. Actual pressure measurements reflect a variety of effects and specifics. We would find such a comparison interesting but we would expect that it would be quite challenging to interpret.

Regarding the suggestion that the Polar Sea data be "corrected", the authors agree that the Polar Sea data is not perfect. Certainly, increasing the magnitude of the pressures would have resulted in greater damage to the grillage structures, but given the novelty of the investigation of the response of ship structures to moving loads, the authors did not want to add this additional level of speculation at this stage. This is for the same reason the strain-rate effects were not omitted, that is: obtaining results that are possibly unduly conservative could warrant unnecessary alarm at this point in the research. Prior work by the authors has shown that the deleterious effects of moving loads causing plastic damage to the structural capacity of a ship's grillage can be substantial. Depending on the load type and trajectory, the authors have observed structural overload capacities drop to less than half their assessed value for equivalent stationary loads. The authors believe that much more research is necessary in order to more fully understand the effects of moving loads.

This comment gets to the essence of our paper. We do say that moving loads not only spread the response over a greater area but that the movement leads to a change in the plastic response mechanism and results in greater maximum plastic deformations and strains.

The issue of the two types of dynamic effects (strain rate and inertial) is important. We included the inertial effects because they are necessarily included in an LSDyna Explicit analysis. We suspect that actual inertial effects were quite minor in the present study. It is debatable whether we should have included the strain-rate effects (i.e. the Cowper-Symonds model for rate enhanced material strength). As mentioned above, strain-rate effects were included in this work because these effects are real and are commonplace in crash analysis in other industries. While the Polar Rules and all other ice class rules do not account for this beneficial effect, neither do the rules account for the deleterious effect of the moving load. We included both in an attempt to get a picture of the likely true behavior. We do not disagree that looking at the various aspects singly would be useful. The one key additional dynamic effect that we did not study was the influence of structural plastic response on the ice failure and consequent loads. We intend to examine this in the coming months and years.

Regarding Dr. Amdahl's assessment of our numerical model, we appreciate his endorsement. We concur that explicit finite element programs do not generally require a "trigger" to induce buckling. While this numerical model was not specifically calibrated against laboratory experiments, it is largely based on similar models that were. Regarding the issue of the response of T-stiffeners and flat bars, our experience is that the failure modes are plastic mechanisms that only resemble elastic buckling phenomena (tripping, shear buckling), but are actually quite different. To speculate for a moment, and in hopes of sparking some further discussion among our readers, in our view we are dealing with behaviors that might best be termed auto-plastic mechanisms. As the structure deforms, the plastic deformations form to adapt to the changing internal load balance. This is not like the instability phenomena that constitute various types of elastic buckling. In most cases a good non-linear analysis will exhibit the main plastic behaviors quite well. The key error will typically be that analysts will not properly define the full strain hardening behavior.

We again wish to thank Dr. Amdahl again for his excellent discussion. His pragmatic questions and recommendations are much appreciated.

ADDITIONAL REFERENCES

DALEY, C. G. and G. Hermanski. 2008a. Ship Frame Research Program - an Experimental Study of Ship Frames and Grillages Subjected to Patch Loads, Volume 1 - Data Report: Ship Structure Committee.

DALEY, C. G. and G. Hermanski. 2008b. Ship Frame Research Program - an Experimental Study of Ship Frames and

Grillages Subjected to Patch Loads, Volume 2 - Theory and Analysis Reports: Ship Structure Committee.

The authors appreciate **Dr. Basu's** discussion of the issues surrounding, and possible implications of the subject of this paper; which focuses on the plastic response to moving ice loads on steel stiffened panels. The authors will attempt to respond to Dr. Basu's comments in the order he presented them:

1. Ice conditions data for the Polar Sea trials were generally recorded every one-half hour, and were neither specific to impacts, nor very precise. Ice thickness, for example, was only estimated in a general way. Ice edge shape was not observed. So, while the authors agree that this would provide a useful base for interpreting the results of this paper, it would still leave many questions (see below). We will attempt to provide this sort of cross comparison in future papers.

2. The issue of the probability level for the Polar Rules design load and for the Polar Sea measurements is an interesting but difficult topic. The Polar Rules design point can be thought of in deterministic terms (i.e. a collision at a certain speed into ice of a certain shape and strength). It can also be seen in probabilistic terms because such a collision will be quite rare for a cautiously operated vessel. Unfortunately, the Polar Sea data is not ideal for either a deterministic or a probabilistic validation of the IACS Polar Rules. The reason is that a number of significant parameters were not precisely measured during the trials. We would like to echo Dr. Basu's comment on the value of field data, and the difficulty of gathering it. We would like to add that future field trials should pay more attention to accurate characterization of the precise ice geometry and properties in each impact. As expensive as field data is, researchers and sponsors should understand that spending much more may be a wise investment.

3. The "percent plastic strain" of the full PC design load is presently under consideration by the authors, and will be presented soon. The authors are examining the cases where the IACS design load is applied both statically and moving along the hull.

4. Damping was not actively employed in these simulations. While structural "ringing" was not observed to be a problem in these simulations, the authors agree that damping should be considered in future work. In cases of plastic response, the response is heavily damped due to the irrecoverable plastic work done.

5. In previous works, the authors have compared non-moving and moving loads causing quasi-static plastic damage. For loads causing large plastic deformation of the structure, the movements have been found to strongly and detrimentally influence the response. When there is no plastic deformation, slow movement is not significantly different from the cases of no movement. We did not consider dynamic effects and responses. Whether or not a difference in structural response will exist for the load cases causing the maximum structural response in this paper, is an important question. Dr. Basu's suggestion to investigate this is well taken, and is presently under consideration.

6. The authors agree that much work has been accomplished in the field of moving loads in other industries. Considerable work by civil engineers on the effects of moving loads on bridges, roads, and train tracks has been done, though normally for elastic responses. Analytical models for moving loads causing a plastic response in beams exist, however their applicability to ship structures needs to be examined. The same cannot be said for plates. The only publically available literature on the subject of the plastic response of a plate to a moving load is Sokol-Supel (1985). This paper is an attempt to develop the theory for rigid-plastic plates under a concentrated moving load. The theory developed does not consider the damage in the wake of the moving concentrated load (see Figure 1). This implies that the damaged material on the trailing side of the moving load (shown as a dashed line in Figure 2) instantaneously recovers to an elastic undamaged state. This formulation is the reason that the author claims that a rigid-plastic plate can sustain a larger moving load than a quasi-static (or stationary) load; and that the higher the speed (up to some critical speed), the larger the sustainable load before plastic collapse. These findings are in direct conflict with the results of the numerical model presented in Quinton (2008), where it was predicted that moving loads causing plastic damage incite a reduced structural capacity when compared with stationary loads. There is no evidence of validation of this theory presented in Sokol-Supel's paper.

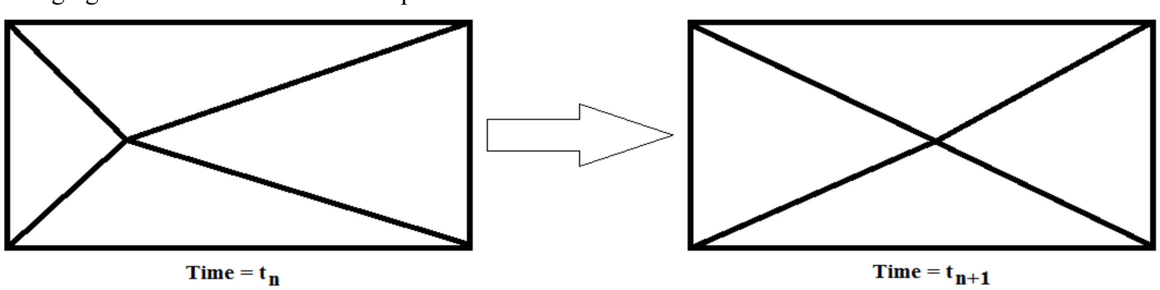

Fig 1. Example concentrated moving load on a rigid-plastic plate where damage due to the passage of the load is ignored.

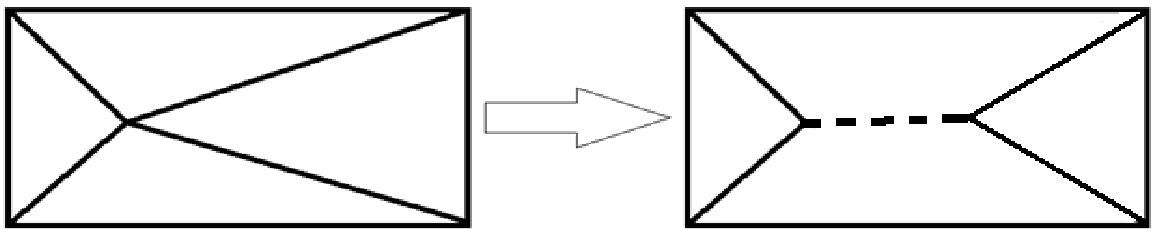

Fig 2. **Example concentrated moving load on a rigid-plastic plate showing line of prior damage (dashed).**

7. First, for clarification, the term "buckling" should be discussed. For the purposes of this response, the authors would like to define "buckling" as an elastic instability. By this definition, the authors have misused the term "buckling" in their previous works, as the "buckling-like" behaviour observed in experiments and simulations to date was not in any way an elastic instability. It was a stable and progressive plastic response. It is the opinion of the authors at this time that the essence of the "buckling-like" behaviour observed under lower load magnitudes (than for stationary loads) is not a dynamic effect, and (ignoring strain-rate effects) the speed of the ship should not influence the structural response. We intend further work on this issue.

8. We believe Dr. Basu, when saying “evenness” is referring to small deformations in the hull plating. As we believe that the behaviours we are observing are progressive, possibly self-reinforcing, plastic mechanisms, we suspect that initial deformations are not significant. However, this is only speculation and should be checked.

Again the authors would like to thank Dr. Basu for his questions, comments and general discussion.

ADDITIONAL REFERENCES

Quinton, B. W. 2008. "Progressive Damage to a Ship’s Structure due to Ice Loading." Masters, Memorial University of Newfoundland.

Sokol-Supel, Joanna. 1985. "Rigid Plastic Plates Under a Concentrated Moving Load." Journal of Structural Mechanics 13 (1): 77-93.

We thank **Professor Kujala** for his comments and questions. While our work was not meant to be a review of either the *Polar Sea* data (nor the IACS Polar Rules), it is very understandable that the reader would ask about the basis of the background material. In the case of the *Polar Sea* the rationale for the use of compression stresses to assess the ice pressures is interesting. One of the authors happens to have designed that system, and so knows the background in detail. The answer to the question is that *Polar Sea* frames are quite unique, being essentially full bulkheads with stiffened cutouts. Because of this, the ‘standard’ approach to ice load instrumentation (which is shear difference along frames) was not feasible. The only structural response that was found to be reasonably uniquely related to the ice loads was the compressive stress. The Ship Structure Committee reports referenced will provide further detail on this point. While this has little direct bearing on the present paper, it does remind us of the need for accurate ice load data. The authors believe that the *Polar Sea* data is as good as any data sets from that generation (i.e. from the 1980s and 90s), but we would all benefit from the much higher quality load data that could be gathered today with newer technology.

As to the question of the basis for designating certain values in Tables 9 and 10 as "red", the answer may be found explicitly in Table 5 and implicitly in Table 6. The "red" shaded cells in Table 5 denote cases where the loads applied (based on average pressure) to the PC classed grillages are larger than their IACS design load. Table 6 characterizes the measured *Polar Sea* loads (based on total panel force) as IACS design loads (for the *Polar Sea*). Consequently, any simulation involving a PC7 classed grillage would be overloaded when loaded with any loads characterized as PC6 or larger (on so on for the other PC classed grillages). It should be pointed out that the characterization of the *Polar Sea* loads as IACS design loads agrees very well when based on average pressure or total panel force. When viewing Tables 9 and 10, the "red" shaded cells simply denote cases where the applied load was larger than the IACS design load. We would expect to see larger than normal plastic deformations in these cases. In other words, the "red" shading of cells was not based on some quantitative floor value. Further, there is "red" bold text in some of the "yellow" shaded cells. "Yellow" shading denotes cases where the applied load was less than the IACS design load, however there was still plastic damage evident. The "yellow" shaded cells containing bold, "red" text show plastic strains that are as high, or higher than some of the overloaded (i.e. "red" shaded) cases. Again, the marking of these values using "red" was not based on some quantitative floor value.

The issue of which limit states should be used for structural design is an excellent question and is really at the core of the work done in this paper. The standard approaches to limit states in ice class rules take either the yield point (elastic design) or the formation of a plastic mechanism (plastic design) as the design limit state. The authors know, as most specialists do, that ice class structures are very ductile and are capable of exhibiting substantial capacity beyond yield and beyond the first plastic mechanism. There are no observable consequences of first yield and no practical consequences of small plastic distortions. Our focus should be on how to prevent serious consequences which occur in overload situations. The paper is an exploration of one effect that only occurs when the loads are well above even the plastic design point. We believe this is important because we believe that the real concern in ice class design is about what occurs during overloads. We do not mean that we should change the design point to some extreme limit state. Rather we suggest that the design should consider the whole range of responses, so that structures are ensured to have both good initial strength and good overload capacity. In this way we hope that real safety and capacity can be achieved in the most cost effective manner. We realized that a plastic overload assessment, which is normally done without consideration of movement along the hull, is strongly influenced by such movement as has been shown in our prior work, and needs to be studied further. We wrote this paper to communicate this point to anyone who is similarly interested in the overload capacity of ice class ships.

We appreciate **Dr. Masterson's** comments. We do agree that our paper does not address the issue of the correctness of the Polar Rules. We did not examine side shell pressures, so it is somewhat difficult to address Dr. Masterson's points and concerns. It may be useful for us to say what we do feel the data shows, in terms of the Polar Rules. Our analysis examined the hypothetical case of a set of vessels of different ice classes, all of which being the same size and shape (and power) of the *Polar Sea*. We took the highest loads measured on the bow panel on the *Polar Sea* and examined what the response might have been had the structure been of any of the Polar Classes. Now while our aim was to study the effects of moving loads, the exercise can be seen as an examination of how various ice classes would have performed during the ice impacts that the *Polar Sea* experienced in her ice trials. What is obvious is that a PC5 class vessel would have been fully capable of the impacts. We view this as showing that the trials resulted in PC5-type ice interaction scenarios, and not that PC1 is over-specified. We should also note that our analysis included a structural behavior that adds capability to a structure, but that is normally not considered. As a result, we were less conservative than many would be. The effect we are describing is real, and helps ships resist ice impacts. This effect is the strain rate enhancement of yield strength (implemented via the Cowper-Symonds model). Most analysts would not have included the effect and it is not considered in the design rules. Had we left out this effect, we would have found that the plastic responses would have been greater and that higher ice classes would have been required to resist the various load cases. This may partly explain why the loads caused the relatively low responses in the structure. We would suggest that the issue of the level of PC1 side shell pressures is a matter for further study and debate.

The authors would like to thank **Professor Takeuchi** for his discussion and endorsement of our paper. We certainly appreciate his request for clarification of the relevant ice conditions for each of the trials.

The ice impact data for all of the Polar Sea trials were generally broken down into 5 second increments. In some cases, the ice conditions for a particular event are available, but otherwise the ice conditions were recorded in general, at specific time intervals. The most relevant cases for this paper are the Beaufort 1982 and the North Chukchi Sea 1983 impacts, the details of which are summarized below (St. John, Daley, and Blount 1984). For further information, interested readers are referred to Daley et al. (1990b; 1990a).

Case	Ice Conditions	Speed
Beau1	Multi-year fragments in first-year ice	<3 knots
Beau2	Not Available	Unknown
Beau3	Steady running through multi-year and first-year ice	Unknown
Beau4	Backing & Ramming into multi-year ice	3-4 knots
Beau5	Backing & Ramming into multi-year ice	2-3 knots
Nchuck-All	Multi-year ridges in relatively small multi-year floes surrounded by first-year ice cover of ~ 5 feet (1.5 m)	Unknown

Regarding the typical ice failure modes, record of this information was impractical during the trials through methods other than direct observation. All impacts occurred at the bow, which has a significant slope. Generally speaking, multi-year ice failed through crushing, and first-year ice failed though crushing followed by flexural failure.

ADDITIONAL REFERENCES

DALEY, C., J. W. St. John, R. Brown, and I. Glen. 1990a. *Ice Loads and Ship Response to Ice - Consolidation Report*. Washington, D.C.: Ship Structures Committee.

DALEY, C., J. W. St. John, R. Brown, J. Meyer, and I. Glen. 1990b. *Ice Loads and Ship Response to Ice - A Second Season*. Washington, D.C.: Ship Structures Committee.

ST. JOHN, J. W., C. Daley, and H. Blount. 1984. *Ice Loads and Ship Response to Ice*. Washington, D.C.: Ship Structures Committee