POAC'17
Busan, KOREA

Proceedings of the 24th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 11-16, 2017, Busan, Korea

Arctic LNG Carrier Structural Risk Analysis for Iceberg Collisions

R. Gagnon[1], J. Wang[1], D. Seo[1], H. Ki[2], J. Choi[2] and S. Park[2]
[1] Ocean, Coastal and River Engineering, National Research Council Canada, St. John's, NL, Canada
[2] Daewoo Shipbuilding & Marine Engineering (DSME), Seoul, Korea

ABSTRACT

Structural risk analysis for a new 172,600 m^3 Arctic LNG Carrier was carried out. Finite element software, LS-DYNA, was used for the analysis. Three different iceberg masses were used: 3,320 ton, 6,640 ton and 10,000 ton. Six impact simulations were conducted for the condition where no water was present where the vessel forward speed was ~19.5 kt and the iceberg speed was 5 kt perpendicular to the tracking line of the ship. Impacts were targeted on specific areas of the vessel's bow section. Bell-shaped icebergs, specified by DSME, and more realistic vase-shaped icebergs, developed by NRC, were used for the simulations. The maximum contact force that was measured was in the 80 - 90 MN range for the 10,000 ton iceberg for either shape. The maximum deflections of the outer and inner hulls for these cases were -263.9 mm and -29.5 mm respectively. Two simulations using the 10,000 ton NRC vase-shaped iceberg and DSME bell-shaped iceberg were conducted where water, and associated hydrodynamics, was included. For these wet-case simulations the vessel speed was ~19.5 kt and the maximum impact force was in the same approximate range as the dry-case simulations. The outer and inner hull deflections for the wet-case simulations were significantly higher than those for the dry case because the deformable hull section was less constrained and consequently more flexible than the actual case corresponding to the dry-case simulations. Ice contact areas and average pressures were determined for seven cases. All of the simulations generated sliding-load impacts. No rupturing/tearing of the outer hull was observed for any case.

KEY WORDS: Ship-iceberg collisions; Numerical simulations of ice impacts; Ice impact damage to ships; Ice impact loads and pressures.

INTRODUCTION

The objective of this study was to perform numerical simulations to evaluate the structural integrity of the new 172,600 m^3 Arctic LNG Carrier for various iceberg collision scenarios. Most of the simulations did not include water (dry case) because the results were of value to the client for comparative reasons since similar simulations had been conducted before. Two more realistic simulations were conducted where water was included (wet case). The validated ice model used for all the simulations in this study was developed by NRC. The simulations presented here involving the highly detailed ship mesh, provided by DSME, for the cases where water and hydrodynamics are included represent the most advanced simulations ever conducted of a ship sustaining damage from a collision with an iceberg. The methods used in these simulations can be applied to a wide range of scenarios.

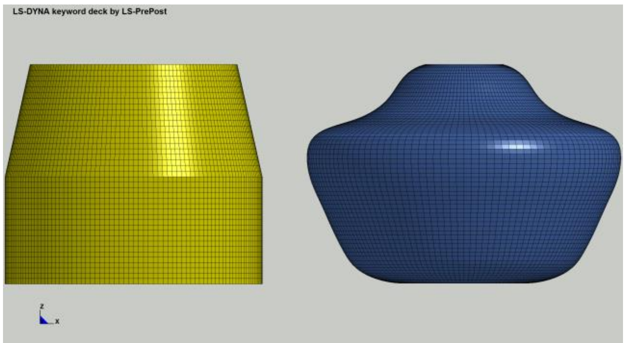

Figure 1. Iceberg shapes: (left) DSME bell-type; (right) NRC vase-type.

SIMULATION SCENARIOS

Two different-shaped icebergs were used: one had a bell shape (specified by DSME) and the other had a vase shape (generated by NRC). Figure 1. shows images of the two iceberg shapes. Three different iceberg masses (3,320 ton, 6,640 ton and 10,000 ton) were used for each shape for the dry-case simulations. Only the 10,000 ton icebergs were used for the two wet-case simulations.

Simulation scenarios are shown in Table 1. There are two contact locations of interest on the vessel, i.e. at FR. 131 and FR. 125 + 1400 mm as shown in Figure 2., where the intention is that the maximum load for any particular impact simulation occurs at either of these locations. It is important to note that the scenario Cases 1- 6 are not realistic since these scenarios could not occur under real circumstances where water is present. These simulations were conducted at the request of the client so that comparisons could be made with earlier simulation results that they had acquired.

HARDWARE, SOFTWARE AND ICE MODEL

The simulations were run on a HP Z820 Workstation that has two Intel Xeon Processors E5-2660 v2, where each has 10 cores running at 2.20 GHz (up to 3 GHz). The system has 28 GB of DDR3 RAM. 8 CPU's with SMP (single memory processing) were used for each simulation. The software used was LS-Dyna^{TM} version Ls971d Dev, Revision 101132, double precision. It uses LS-Dyna's ALE formulation to handle fluid hydrodynamics and it has a number of contact algorithms and a large suite of material types that can be chosen for the interacting structures. ANSYS Workbench V12.1 with ANSYS DesignModeler^{TM} was used for the modeling and generation of meshes for the study.

A crushable foam model (Gagnon and Derradji, 2006; Gagnon and Wang, 2012) was used for the ice that made contact with the vessel during the simulations. The isotropic foam model crushes one-dimensionally with a Poisson's ratio that is essentially zero, as described by Hallquist (1998). Unloading is elastic to the tension cutoff stress. Subsequent reloading follows the unloading curve. Application of a pressure, prescribed by the user, on a block or layer of such foam that is rigidly supported from below causes it to irreversibly compress in the direction of the applied load.

Table 1. Simulation Scenarios.

Case Number	**Contact Location**	**Iceberg Mass (metric ton)**	**Iceberg Speed (kt)**	**Iceberg Shape**	**Ship Speed (kt)**
Case 1	FR. 131	10,000	5	Bell type	19.44
Case 2	FR. 131	10,000	5	Vase type	19.44
Case 3	FR. 125 + 1400 mm	6,640	5	Bell type	19.44
Case 4	FR. 125 + 1400 mm	6,640	5	Vase type	19.44
Case 5	FR. 131	3,320	5	Bell type	19.44
Case 6	FR. 131	3,320	5	Vase type	19.44
Case 7-ALE*	FR. 131	10,000	0	Bell type	19.44
Case 8-ALE*	FR. 131	10,000	0	Vase type	19.44

* Note that Cases 7-8 use ALE (Arbitrary Lagrangian Eulerian) methods to simulate hydrodynamic effects with the presence of water.

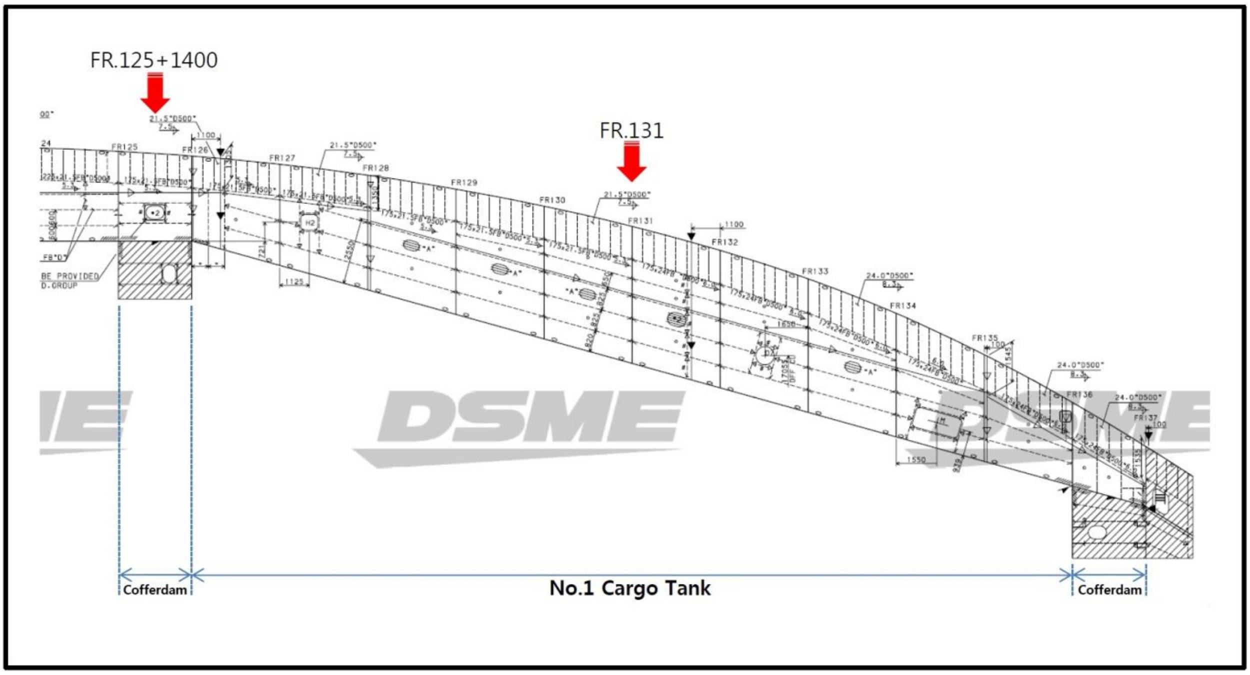

Figure 2. Top view of a portion of the vessel showing the cargo tank region. Two contact locations on the vessel hull are indicated by red arrows where, during any particular simulation, the ice impact load will reach its approximate maximum value at one or the other location.

The ice model has been validated using data from growler impact tests conducted in NRC's Ice Tank facility (Gagnon, 2004) and from full-scale measurements (Gagnon et al., 2008). Properties of the icebergs used in the simulations are given below in Table 2. As mentioned above, for the present study iceberg shape was investigated by using two shapes. The bell-shaped iceberg model was supplied by DSME and the vase-shaped iceberg model, deemed to be more realistic than the bell-shaped one, was generated by NRC. The vase shape is very roughly based on observed shapes of icebergs where underwater protrusions are common and the protrusions are generally rounded and smooth due to melting.

SHIP MODEL

The ship model used for the simulations was supplied by DSME. The full meshed model is shown in Figure 3. The portion of the cargo section of the vessel where the simulated ice impacts occurred is shown in Figure 4. The double-hull design structure of the vessel is evident.

ICEBERG SHAPE EFFECT ON LOCAL PRESSURE, GLOBAL LOAD AND DAMAGE

Table 2. Iceberg Properties.

Density	870 kg/m^3
Young's modulus	9.0 GPa (for deformable portion)
Poisson's ratio	0.003 (for deformable portion)
Element type	*SECTION_SOLID (brick)
Typical element dimension in contact region	0.48 m – 0.50 m (DSME Iceberg) 0.50 m – 0.78 m (NRC Iceberg)
Material properties	*MAT_CRUSHABLE_FOAM (for the deformable portion)
Number of elements for Cases 1-8	DSME 10,000 ton: 88,640 DSME 6,640 ton: 66,700 DSME 3,320 ton: 32,880 NRC 10,000 ton: 186,714 NRC 6,640 ton: 132,120 NRC 3,320 ton: 70,128

Generally speaking, in the results below, the more rounded and protrusive aspect of the vase-type iceberg leads to more concentrated forces in the contact region that result in higher pressures and ultimately more local damage (plastic strain) than in the case of the bell-type iceberg. A related consequence of this is that the peak loads will be somewhat less for the vase-type iceberg impact because more energy is absorbed by the vessel as plastic deformation, as opposed to elastic deformation, than the case of the bell-type iceberg. One can appreciate this issue more clearly by imagining the extremely unlikely scenario of an iceberg shape virtually matching the shape of an extensive area of the hull of a vessel during a collision and see that the load would be distributed over a very large area leading to low local pressures and very little or no plastic damage on the one hand and a high resultant force on the other hand because the vessel response would be fully elastic. Similarly one would expect lower pressures and less damage to the ice itself when the iceberg shape conforms to the shape of the vessel in the contact region.

RESULTANT IMPACT FORCES AND HULL DEFLECTIONS (DRY-CASE)

In order to run a simulation where the maximum load would occur at the specified frame, that is, either frame 131 or frame 125 +1400 mm, it was necessary to run a few trial simulations that involved adjusting/offsetting the initial collision contact point by a suitable amount. Figure 5. shows the resultant forces for the simulations where the offset adjustments were made. One can see

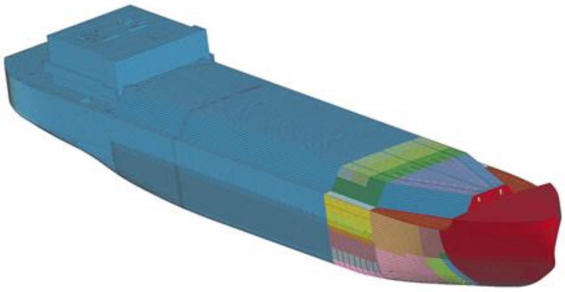

Figure 3. Full FE model of the ship. The multicoloured length segment between the red forward-bow section and the large blue main-body section had deformable properties during the dry-case simulations.

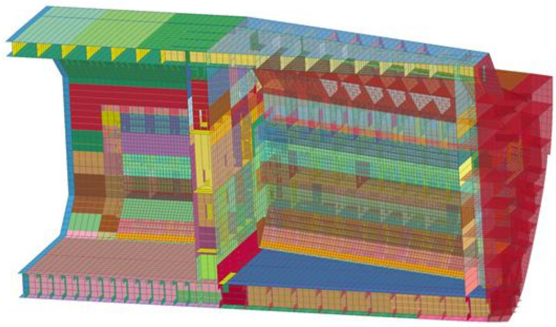

Figure 4. Sectional view of the FE ship model showing inner portions of cargo holds 1 and 2 where details of the mesh structure of the outer and inner hulls are evident. The simulated ice impacts occurred on the outer hull of this portion of the vessel.

that the peak loads for the DSME and NRC icebergs were fairly close to one another for the more massive ones, that is, the differences were about 10% for the 10,000 ton iceberg, 15% for the 6,640 ton iceberg. Since the bergs exhibited similar degrees of rotation during the impacts we might attribute the higher load exerted by the bell-type iceberg to the fact that it had less curvature (i.e. less protrusiveness) than the NRC iceberg and therefore presented a larger contact area, thereby resulting in greater loads due to the wider load distribution and less plastic damage, as previously discussed.

For the case of the 3,320 ton icebergs the DSME iceberg was subject to considerable rotation

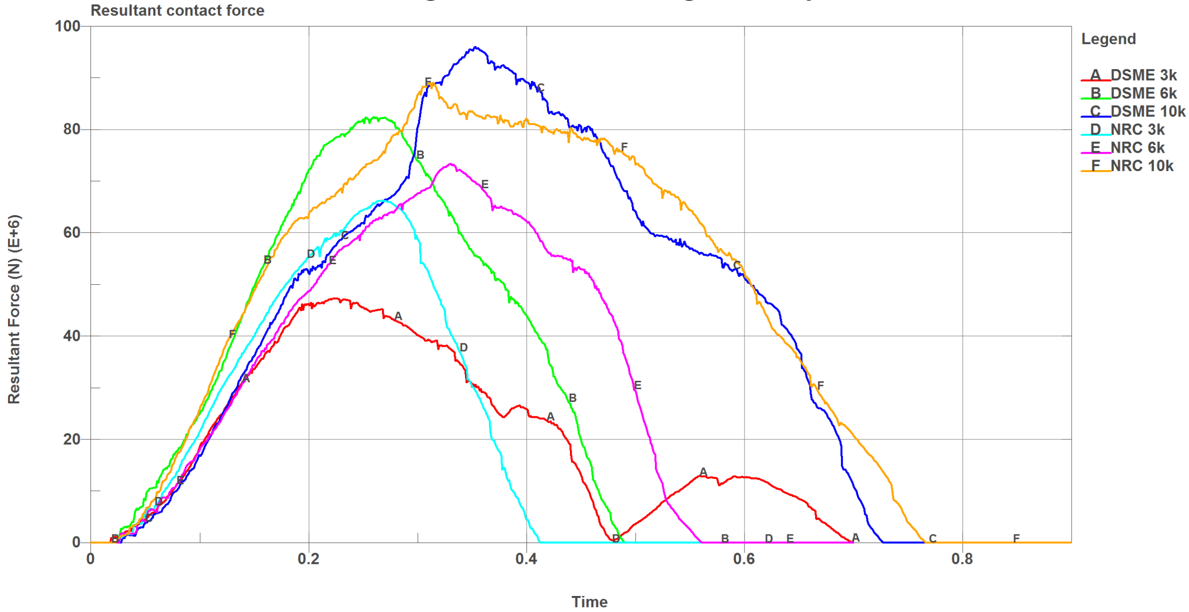

Figure 5. Resultant force time series for the impacts where load reaches its approximate maximum value at FR.131 for the 3,320 ton iceberg cases (traces A and D) and the 10,000 ton cases (traces C and F), and at FR. 125+1400 for the 6,640 ton case (traces B and E). The unit on the X axis is 'second'.

when the impact occurred (i.e. the force vector passed far from the iceberg's center of mass) because of where the vessel contacted it. The NRC iceberg experienced less rotation during the impact and consequently exerted more force on the vessel. We also note that the DSME iceberg experienced a secondary hit.

Figure 6. shows the maximum hull deflections for all the dry cases (Cases 1- 6). The higher outer hull deflections exhibited by all three NRC icebergs support the earlier conjecture that the NRC iceberg's protrusiveness leads to greater local damage than the DSME icebergs. The inner hull deflections are similarly greater for the NRC icebergs for the two lower-mass cases, however the pattern switches for the largest iceberg mass. The implication is that much more crumpling of the webbing occurs in the NRC 10,000 ton iceberg case than for the DSME 10,000 ton iceberg case.

NRC 10,000 TON ICEBERG WET-CASE (ALE) SIMULATIONS

Some of the simulations where water was included were for the NRC 10,000 iceberg. The methods used to set up and run the simulations are similar to those described by Gagnon and Wang (2012). These simulations took considerably longer to run than the dry cases (Cases 1-6, Table 1) because of the inclusion of the large number of water elements in the mesh. The full-run simulation using the NRC iceberg took 167 hr. The dry-case simulations, on the other hand, typically took approximately 23 hr to run. Furthermore, a number of preliminary simulations had to be run in order to locate the correct initial position of the iceberg, relative to the tracking line of the vessel as it moved forward, to facilitate an impact occurring near frame 131.

To continue, a series of short and simple simulations were run where the vessel was given a certain speed (19.44 kt) to determine the required initial position of the ice mass in the water in order to get a ‘hit’ at the desired location on the bow of the vessel. For these simulations all solid components (the vessel and the ice mass) had rigid-body designations and the contact definitions for both objects applied only to the water so that the simulations could run quickly. That is, during the relatively long real-time portion of the simulation where the ship is transiting over a distance of ~130 m, in order to generate a realistic bow wave, the simulation runs with a reasonably long time step. This procedure took about 4 simulations to perform, where each took 8 hr to run, corresponding to 13 s of simulated time.

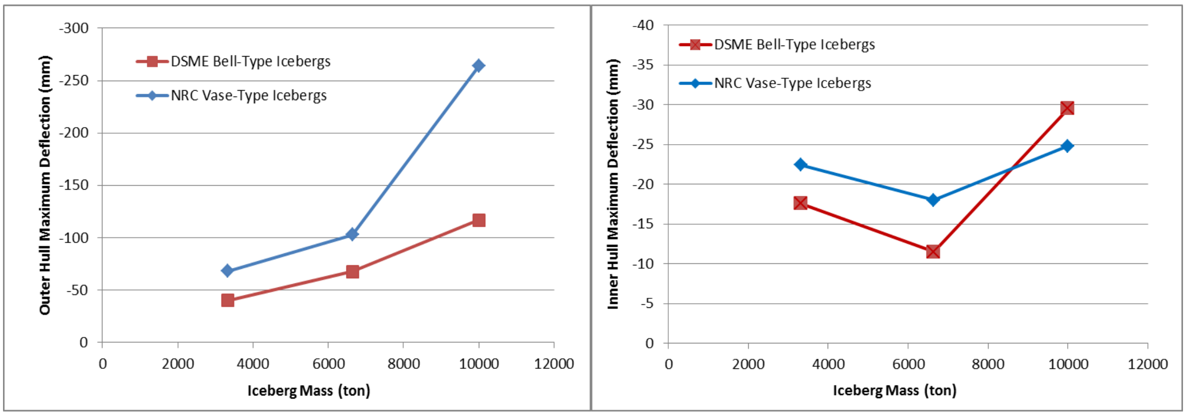

Figure 6. Maximum outer hull (left) and inner hull (right) deflections.

So far what we have described will get a wet-case simulation to the point where the vessel is at a close approach to the ice mass and the mass has begun to respond significantly to the hydrodynamics associated with the ship's bow wave. This takes about 8 hr of run time. To this point, as previously mentioned, the ice mass and vessel have been treated as rigid bodies interacting only with the water. But just before the actual collision occurs it is necessary for these components to be activated, that is, their properties need to be changed to realistic ones rather than simple rigid body ones. In LS-Dyna this can be done ‘on the fly’ during a simulation. This is facilitated by using the LS-Dyna command ‘*RIGID_DEFORMABLE_R2D’ to activate the ice mass portion (i.e. the half of the mass facing the vessel) and vessel portion (the large section of the hull encompassing the impacted region) as deformable parts. This command enables one to specify the activation time, i.e. the time just before contact occurs (at time = 13 s), prior to running the simulation. Once activated, the formerly rigid components now have realistic deformable properties that they maintain throughout the rest of the simulation. Now, however, the computations are much more intensive due to the large numbers of deformable elements of portions of the ship and ice mass, where the portions interact with the water and with each other, so the simulation runs much more slowly, i.e. for the NRC iceberg case it takes ~160 hr for the remaining simulation time segment from 13 s to 14.35 s. Note that the simulations ran on only 8 CPU's. Workstations are presently available with several times this number of CPU's, and Beowulf computer clusters have even more. Consequently simulations like the present ones can be run in much shorter time periods.

Figure 7. is an image from the simulation showing the full view of the ship/ice collision scenario that includes water waves associated with the ship and iceberg motions. The time series load record for the simulated collision is shown in Figure 8. The time series deflections of the inner and outer hull are shown in Figure 9.

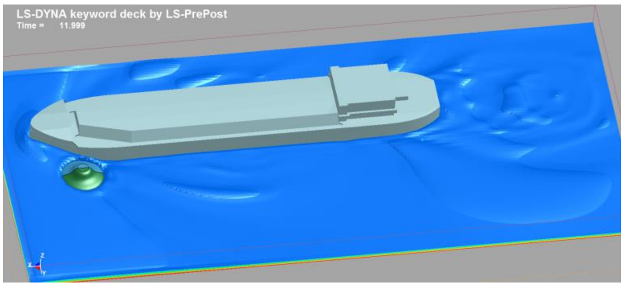

Figure 7. An image showing the full view of the ship/ice impending collision (~ 1.3 s before impact) that includes water waves associated with the ship and iceberg motions for the case of the NRC 10,000 ton iceberg. The deformable portion of the iceberg is the half (light blue in color) that faces the side of the ship. The ship speed was 19.44 kt. (Case 8, Table 1)

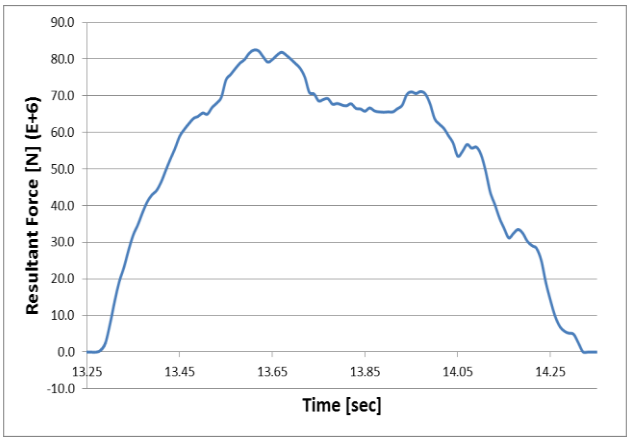

Figure 8. Resultant force time series for the NRC 10,000 ton iceberg (wet-case). (Case 8, Table 1.)

Now it is important to draw the reader's attention to certain aspects of the ALE wet simulations that signal caution in terms of reliability of the results. During the dry-case simulations (Cases 1-6) the deformable segment of the vessel, as shown in Figures 3. and 4. above, was large and included all the strengthening components in that length segment. This was somewhat intensive computationally but was handled within reasonable amounts of time for the simulations to run. At that earlier stage of the work it was understood that wet-case simulations would take a relatively long time to run if that whole section of the vessel was given deformable properties. So it was decided to use a smaller deformable section than what was used for the dry-case simulations, as shown in Figure 10. This was attached to the rest of the vessel at the fore and aft ends of the segment. That implied that the structures at the top and bottom of the segment, such as the deck, did not impart their strength to it. Consequently the segment was more flexible elastically than would normally have been the case.

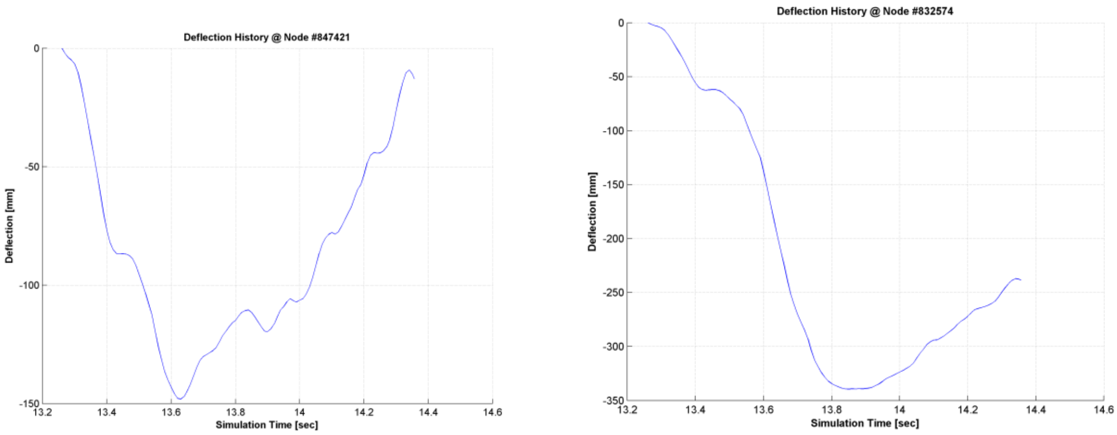

Figure 9. Deflection history for the node showing the maximum deflection of the inner hull (left) and outer hull (right) where the NRC vase-shaped 10,000 ton iceberg (wet-case) interacted with the ship during a sliding-type impact. The small bumps on the plots, most prominent at the right of the left plot, likely correspond to resonant oscillations (~ 9 Hz) of the hull. (Case 8, Table 1.)

Hence, it is our opinion that the wave patterns and iceberg motions during the wet-case simulations were not affected much by this issue. Similarly the impact load data should still be reasonably accurate, indeed they seem to be in the same range as the dry-case values. The deflection data for both the outer and inner hulls would be inaccurate, that is, the deflections would be greater than what they should be due to the extra flexibility of the affected deformable hull section, i.e. for comparison the dry-case and wet-case maximum deflections of the outer hull are -263.9 mm and -339.4 mm respectively for the NRC 10,000 ton iceberg. The maximum deflection values of the inner hull suffer a much greater relative discrepancy since those deflections are normally considerably smaller than those of the outer hull, i.e. for comparison the dry-case and wet-case maximum deflections of the inner hull are -24.8 mm and -148.1 mm respectively. The issues discussed above can fairly easily be remedied by either using the full deformable segment of the hull that was used in the dry-case simulations or by judiciously attaching the top and bottom edges of the smaller deformable section to the rest of the rigid vessel. Time ran out under the present contract to perform such alterations.

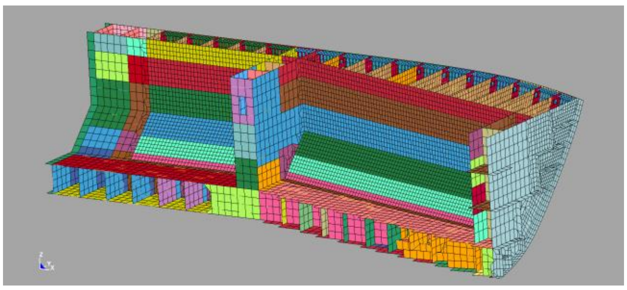

Figure 10. Hull portion that was given deformable properties for the NRC 10,000 ton iceberg (wet-case) simulation. (Case 8, Table 1.)

INTERFACE CONTACT PRESSURE AND AREA

The following discussion primarily regards the simulation results from the wet-case vase-type 10,000 ton iceberg. Figure 7. shows the whole vessel and iceberg to give the reader some perspective of the scale of the ice/ship interaction for the NRC 10,000 ton case. Figure 11. is an expanded view of the inside of the hull and shows detail of a typical interface pressure pattern during the impact. The 'qualitative' aspect of the pressure patterns is discussed below.

One thing that is noteworthy is that the pressure is highest on the plating that is backed by the frames. This characteristic is intuitively sensible and is similar to the results of an earlier study of a tanker collision with a bergy bit (Gagnon and Wang, 2012). Another aspect is that the pressure distribution in the ice contact zones is generally characterized by high pressures in the central contact regions and considerably lower pressures surrounding the high-pressure zones. Both these characteristics are visible in the expanded view shown in Figure 11. These characteristics arise because the NRC ice model was designed to reflect the pressure distributions observed when real ice is crushed at strain rates in the brittle regime. During crushing the high-pressure zones in real ice correspond to relatively intact ice whereas the low-pressure zones correspond to softer crushed ice. Details of the physics involved in ice crushing have been discussed extensively before (Gagnon, 1999).

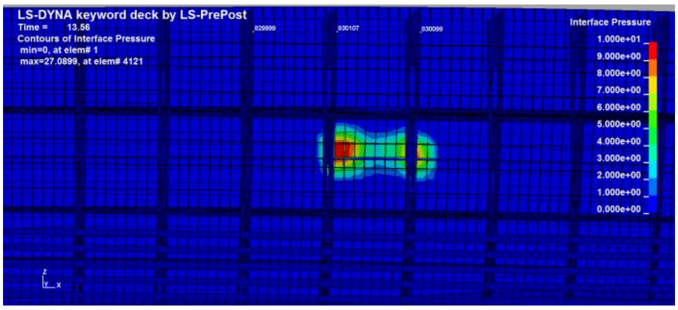

Figure 11. Image showing the iceberg-ship 'qualitative' interface contact pressure where the NRC vase-shaped 10,000 ton iceberg interacted with the ship during a sliding-type impact in water. Similar patterns occurred for dry-case simulations. The view is from the inside of the outer hull so that structural members are visible. The scale for the colored contours of pressure is at the right of the image. Pressure is elevated in contact regions where the ice contacts hull plating that is supported by structural members on the inside of the hull. (Case 8, Table 1.)

We may also determine the contact area and average pressure. This was done by first counting the elements that experience contact at the particular instant in time during the interaction in order to get the contact area. An element was considered to be experiencing ice contact if it registered at least 0.1 MPa for the interface pressure. The average contact area was determined by dividing the resultant force by the measured contact area. The time series contact area and average contact pressure are shown in Figure 12. The contact areas and average pressures determined in this way are considered to be reasonably accurate. The same method was used by Gagnon and Wang (2012).

Here we note that while the correct patterns of pressure are qualitatively presented in images such as Figure 11, the magnitudes of the actual interface pressures are higher than what is reflected in the scale at the right because not all of the resultant force that generates the pressure patterns is accounted for in this LS-Dyna rendering. This occurred because the shell-plating elements of the outer hull share some nodes with the structural members behind the plating. One can roughly estimate to what extent the pressure scale should be upwardly adjusted by comparing the approximate perceived average pressure from any image with the actual average contact pressure in the plot below in Figure 12.

It is noteworthy that for the majority of the impact duration the average pressure tends to level off at around 9 MPa. This relative lack of dependence on contact area has been observed before in other cases of ice/structure interaction. Gagnon (2014) reported a fairly constant average pressure for a wide range of contact area for collisions of the CCGS Louis St. Laurent with sea ice. Frederking and Sudom (2008) and Gagnon (2014) reported similar results for indentation experiments at Hobson's Choice Ice Island. Furthermore, numerical simulations by Gagnon and Wang (2012) and Gagnon (2007) showed qualitatively similar trends.

In all the simulations of this study a specific strain criteria for failure had been assigned to the deformable ship elements, depending on the type of metal. For the larger icebergs, in particular, there were generally a few elements that reached the plastic strain criteria (e.g. effective plastic strain = 0.1) during a simulation so that those elements eroded.

CONCLUSIONS

Eight scenarios of iceberg collisions with the DSME 172,600 m^3 Arctic LNG Carrier have been conducted using LS-Dyna software that involved two iceberg shapes and three sizes for each shape. Six of the simulations did not include water and associated hydrodynamics. For the largest ice mass a full-run simulation was conducted for the NRC 10,000 ton iceberg where water was included using LS-Dyna's ALE formulation. For the wet-case simulations motions of the icebergs prior to contact with the vessel (data not shown here), due to hydrodynamic effects, appeared to be realistic. Ice/ship contact area and average contact pressure were determined for seven impact simulations. Average pressure appeared to be independent of contact area for significant portions of the time series records and was in the approximate range of 6-11 MPa.

Impact loads for the largest icebergs were in the ~ 80-90 MN range. Deflections of the outer and inner hulls in the impacted areas of the vessel's bow were in the ranges -116.6 mm to -263.9 mm and -24.8 mm to -29.5 mm respectively for the largest ice masses for the dry-case simulations. No ruptures of the outer hull (side shell) were observed.

The wet-case simulations are the most sophisticated ship/iceberg impact simulations ever conducted. The techniques and methodology utilized have been shown to be robust, suggesting the usefulness of such simulations for vessel design and for testing/improving of codes in general.

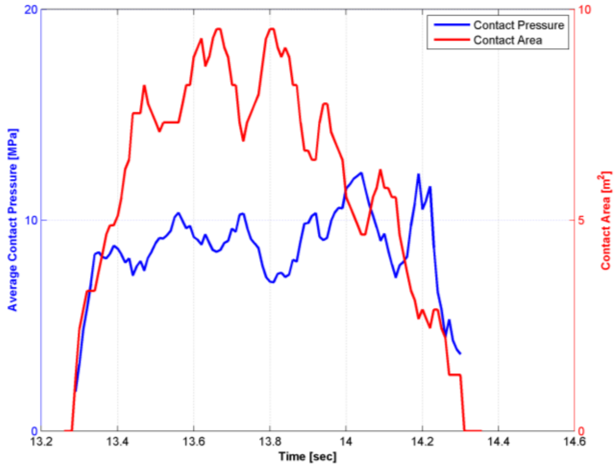

Figure 12. Average contact pressure and contact area for the case of the NRC vase-shaped 10,000 ton iceberg interacting with the ship during a sliding-type impact (Wet-Case). The average contact pressure was calculated by dividing the resultant force by the measured contact area (determined by counting contacted elements) assuming that the surface is flat, whereas the surface is usually deforming, i.e. becoming concave due to damage to the hull. Hence the actual average contact pressure is somewhat higher depending on the degree of concavity of the surface. However, the discrepancy amounts to < 5% even in the most extreme cases. (Case 8, Table 1.)

REFERENCES

Frederking, R. and Sudom, D., 2008. Local Ice Pressure Distributions during 1990 Hobson's Choice Ice Island Multi-Year Ice Indentation Tests. Proc. 19th IAHR International Symposium on Ice, Vol. 2, 815-827.

Gagnon, R.E., 1999. Consistent Observations of Ice Crushing in Laboratory Tests and Field Experiments Covering Three Orders of Magnitude in Scale. Proceedings of the 15th International Conference on Port and Ocean Engineering under Arctic Conditions, 1999, POAC-99, Helsinki, Finland, Vol. 2, 858-869.

Gagnon, R., 2004. Analysis of laboratory growler impact tests. Cold Regions Science and Technology 39, 1–17.

Gagnon, R., 2007. Results of Numerical Simulations of Growler Impact Tests. Cold Regions Science and Technology 49 (2007) 206–214.

Gagnon, R., 2014. Re-analysis of Load and Pressure Data Acquired from Ice Impacts During the CCGS Louis St-Laurent 1994 Arctic Voyage. Proceedings of the 22nd International Symposium on Ice, IAHR 2014, Singapore.

Gagnon, R.E. and Derradji-Aouat, A., 2006. First Results of Numerical Simulations of Bergy Bit Collisions with the CCGS Terry Fox Icebreaker. Proceedings of IAHR 2006, Sapporo, Japan.

Gagnon, R., Cumming, D., Ritch, A., Browne, R., Johnston, M., Frederking, R., McKenna, R., Ralph, F., 2008. Overview accompaniment for papers on bergy bit impact trials. Cold Regions Science and technology 52, 1–6.

Gagnon, R.E. and Wang, J., 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 81 (2012) 26–35.

Hallquist, J.O., 1998. LS-Dyna Theoretical Manual. Livermore Software Technology Corporation. May 1998.