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Encl: (1) NSWCCD-65-TR-2018/13, Modeling and Simulation of Ice Floe/Ship Structure Collision with Inelastic Structural Deformation, Ice Crushing, and Ice Flexural Fracture, Apr 19

1. Reference (a) requested Naval Surface Warfare Center, Carderock Division (NSWCCD) to develop capabilities, using advanced computational structural dynamics modeling and simulation methods, for simulation of dynamic response and failure of non-ice-classed ship structures subjected to collision with sea ice in the marginal ice zone. Enclosure (1) documents the results of this work.

2. Enclosure (1) documents parametric numerical simulations of ice floe collisions with notional non-ice-classed surface ship hull structure, including permanent set damage in the structure and crushing and flexural fracture failure mechanisms in the ice. Enclosure (1) identifies trends with respect to structure/ice friction, structural impact point, and ice crushing material models; it also identifies influences of ice flexural fracture as a function of ice floe thickness. Finally, enclosure (1) documents limited studies of the criticality of relative structure/ice collision speed and of multiple lower-level impacts compared with a single high-level impact.

3. Refer comments or questions to Mr. Douglas E. Lesar, Code 651, at (301) 227-1803 or douglas.lesar@navy.mil.

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NSWCCD-65-TR-2018/13 April 2019

Platform Integrity Department

Technical Report

Modeling and Simulation of Ice Floe/Ship Structure Collision with Inelastic Structural Deformation, Ice Crushing, and Ice Flexural Fracture

by

Douglas E. Lesar



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Enclosure (1)

**Naval Surface Warfare Center
Carderock Division**

West Bethesda, MD 20817-5700

NSWCCD-65-TR-2018/13 April 2019

Platform Integrity Department

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14. ABSTRACT This report documents a series of numerical simulations of ice slab impact on notional naval surface ship hull structure. These simulations exploit modeling methods for ice crushing and flexural fracture, and they demonstrate the shared-energy collision mechanics regime where local structural damage extent may be dependent on and limited by ice slab failure. Inelastic material behavior and development of permanent set deformation is allowed in the impacted hull structure. For the range of parameters considered, ice flexural failure does not consistently limit structural permanent set damage, even for relatively thin ice slabs. For this reason, reliance on a "flexural limit" for limiting ice impact loading on relatively wall-sided non-ice-classed hulls is not recommended. Structural modeling methods are refined to minimize the influence of structural vibration responses that are artifacts of imposed relative structure/ice movement and structural boundary conditions, and a method for simulating repeated ice impacts is developed. Repeated ice slab impacts inflict cumulative structural damage, but permanent set strain increments generally decrease with repeated loadings.					
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Preface

The Structures and Composites Division (Code 65) of the Platform Integrity Department at Naval Surface Warfare Center, Carderock Division (NSWCCD) performed the work described in this report between January 2018 and September 2018. Funding was provided by Office of Naval Research (ONR), Sea Warfare and Weapons Department, Ship Systems and Engineering Research Division (ONR 331). The work was performed under funding document N0001418WX00135, program element 0602123N.

ONR requested NSWCCD to develop capabilities, using advanced computational structural dynamics modeling and simulation (M&S) methods, for simulation of response and failure analysis of non-ice-classed ship structures subjected to collision with sea ice in the marginal ice zone. This work is motivated by two needs: (1) a need to advance U.S. Navy (USN) ability to quantify the risk associated with operating surface combatants in ice-infested polar waters and (2) a need to develop surface combatant operating guidance minimizing risk to hull structural integrity during polar-region operations. This document is a continuation of a prior NSWCCD report (Lesar, 2017), which documents initial structure and ice collision simulation development efforts and describes technical needs and long-term research objectives in this technical area.

The author thanks Dr. Paul Hess III of ONR for, starting in 2010, having the foresight to restore USN science and technology (S&T) attention to this increasingly important technical area. The hardware and software resources of the Department of Defense (DoD) High Performance Computing Centers were essential to timely completion of the several hundred simulations performed in the course of this effort.

1. Summary

This report documents a series of numerical simulations of ice slab impact on notional naval surface ship hull structure. These simulations exploit modeling methods for ice crushing and flexural fracture, and they demonstrate the shared-energy collision mechanics regime where local structural damage extent may be dependent on and limited by ice slab failure. The simulations reported here also allow inelastic material behavior and development of permanent set deformation in the impacted hull structure. For the range of parameters considered, ice flexural failure does not consistently limit structural permanent set damage, even for relatively thin ice slabs. This result discourages reliance on a “flexural limit” for limiting ice impact loading on relatively wall-sided, non-ice-classed hulls. Refinement of structural modeling methods in these studies minimizes the influence of structural vibration responses that are artifacts of imposed relative structure or ice movement and structural boundary conditions. A method for simulating repeated ice impacts is also developed. Repeated ice slab impacts inflict cumulative structural damage, but permanent set strain increments generally decrease with repeated loadings.

2. Introduction

Existing semiempirical toolsets are adequate for design and assessment of ice-classed hull structures for ships that are completely dedicated to icebreaking or must routinely operate in ice-infested waters. However, these toolsets assume robust hull structural configurations incompatible with constraints of warship design. Numerical modeling and simulation (M&S) methods accounting for ice crushing, ice fracture, large hull structure deformation, plasticity, tearing, and rupture are needed for the shared-energy collision and damage physics phenomena that are likely when non-ice-classed hull structure collides with floe or glacial ice.

The earlier NSWCCD report (Lesar, 2017) surveys numerical M&S methods that have been used in past ice-structure interaction studies and more novel methods that have potential for this technical area. Very few analytical ice-structure collision simulation studies (and even fewer physical experiments) have, to date, been carried out for non-ice-classed (e.g., naval combatant) surface ship hull structures. One recent exception is an M&S effort (Dolny, Daley, Quinton, & Daley, 2016, 2017) using both semiempirical/analytic and finite element (FE) methods in an attempt to define “safe speed” ranges for a notional naval surface ship hull operating in ice. However, the FE studies reported by Dolny et al. were intended to inform adjustments to the semiempirical/analytical ice loading calculation tools. Depending on their purposes, the FE analyses considered the ice as flexible and the hull as rigid, or vice versa, and did not account for full compliant structure/crushable ice interaction, with the possibility of ice slab flexural failure that might limit structural load.

The earlier report (Lesar, 2017) also documents a series of FE-based ice beam flexural fracture simulations, which, through comparisons with a limited experimental data set, validated usage of a properly tuned inelastic material model in the LS-DYNA explicit nonlinear dynamics analysis code for modeling this mode of ice failure. This model was combined with an inelastic LS-DYNA material model for simulating ice crushing in the immediate ice/structure contact zone in an analysis series demonstrating ice slab fracture distant from the crushing zone. The bimaterial ice slab was loaded by a moving rigid wall sloped at a 10° angle with respect to the vertical and an 80° angle with respect to the impacted slab. Physically plausible radial and circumferential crack patterns developed, though the LS-DYNA element deletion process may not have been optimally managed. The strong influence of structure/ice contact surface friction on the ice slab failure process was evident.

In this report, the same ice- and ice-failure-modeling methods used previously (Lesar, 2017) are used in a new LS-DYNA M&S series considering collision interaction between one of the same notional local surface ship hull structural models used by Dolny et al. (2016, 2017) with large ice slabs of varying thickness. Better-managed LS-DYNA element deletion criteria produced cleaner ice flexural fracture patterns, and inelastic deformation levels in the structure are tracked and compared for analysis variations where ice fracture is either allowed or prevented. Ice slab thicknesses considered are in the 0.14-m-to-0.35-m range (roughly 5.5 inches to 13.75 inches) and typify the lower levels of ice thickness that should be expected in the Arctic marginal ice zone (MIZ) at 10 % ice concentration or lower (Schultz, 1988). The initial analysis sets considered an almost static ice/structure approach rate (somewhat more than 1 kn relative speed), consistent with 2016 and 2017 analyses by Dolny et al. Baseline analyses did not allow

fracture anywhere in the ice, and parallel simulations allowed fracture in the great bulk of the ice beyond a small crushing-only zone near the structural contact area. Cases were also run with and without static and dynamic contact surface friction with a coefficient of 0.10.

Even for these quite-thin slabs and with ice floe motion constrained by a fixed far-field boundary, ice flexural fracture did not consistently limit the peak loads imparted to the structure. Effectively, the non-ice-classed structure was the “weak link” in the coupled ice-structure system. The effect of ice/structure contact friction was more significant, with peak loads and inelastic structural damage in nonzero-friction cases consistently increased above companion simulations with zero interface friction.

LS-DYNA analysis scope included impacts on (1) a longitudinal frame and (2) a transverse web frame. Although inelastic damage patterns in the structures differed for these two impact locations, the trends of increasing permanent set with increasing ice thickness and contact friction were similar. Another simulation set addressed web frame impact at a faster approach rate (4 kn). Peak loads and inelastic structural responses tended to be higher for the more rapidly developing collisions, and in cases where ice flexural fracture occurred, the fracture was cleaner and more complete. However, ice flexural failure did not consistently lower peak loads and inelastic structural strains.

Most analysis cases used a tuned LS-DYNA elastic-plastic structural material description used in the Dolny et al. 2016 and 2017 studies for the small crushing-only region of the ice floe in immediate contact with the hull structure. An alternative LS-DYNA crushable-foam ice crushing material model (Gagnon, 2006, 2012) was assumed in a web frame impact case set for higher-rate loading, and the results compared with those obtained with the Dolny et al. elastic-plastic model. The Gagnon ice crushing material model, developed and calibrated for glacial (bergy bit) ice (which tends to be stronger and harder than seawater or floe ice), produced consistently higher loads and greater structural damage than the Dolny et al. ice crushing model.

An LS-DYNA slow-speed longitudinal frame impact analysis set was also conducted with identical ice slabs successively impacting the structure, allowing permanent set deflections to accumulate. The majority of the permanent set was induced by the initial impact, with considerably less damage taking place in both of the later impacts.

A key engineering conclusion supported by these studies is that when considering ice/structure interaction for relatively wall-sided non-ice-classed and nonicebreaking hull forms, a “flexural limit” that limits level ice and ice floe loading at lower ice thicknesses cannot be relied upon.; As a result, loadings presuming that no flexural fracture occurs are not likely to be overly conservative for structural risk assessment or design efforts.

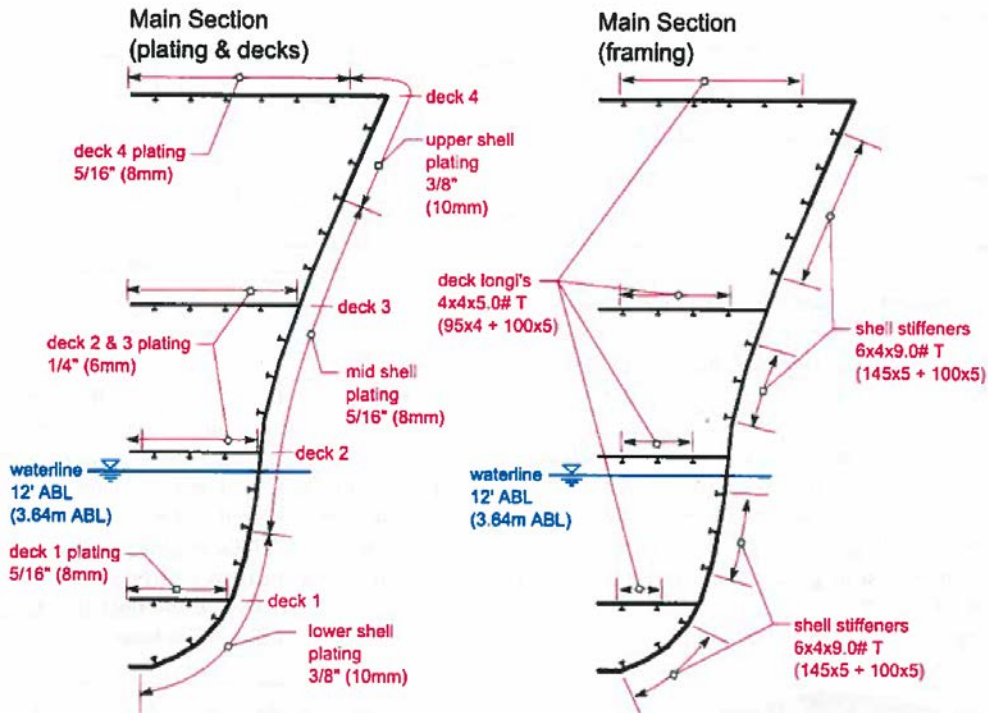
3. Methods, Assumptions, and Procedures

LS-DYNA is a general-purpose, three-dimensional (3D), nonlinear finite element analysis (FEA) code, developed and maintained by the Livermore Software Technology Corporation (LSTC, 2015). This code is primarily intended for high-rate dynamic problems in which large deflections, complex evolving mechanical contacts, nonlinear material behavior, and material failure are predominant. It addresses static and dynamic problems involving solids and structures, possesses adjunct fluid domain modeling capabilities, and enables treatment of various fluid-structure interactions. It uses explicit time-integration methods, but it can also carry out implicit solution of low-rate or static problems. Several LS-DYNA applications to problems in the ice mechanics and ice/structure impact areas may be cited (Das, Polić, Ehlers, & Amdahl, 2014; Gagnon & Derradji-Aouet, 2006; Gagnon & Wang, 2012; Kim, 2014; Kim, Storheim, Amdahl, Løset, & von Bock und Polach, 2016; Liu, Amdahl, & Løset, 2011a; Sazidy, 2015).

Numerous LS-DYNA FEMs, developed under contract to ONR by a team composed of the American Bureau of Shipping (ABS) and Memorial University (MUN), were made available to the USN (Dolny et al., 2016, 2017). ABS and MUN included a detailed local structural idealization of a generic Naval surface ship based on the notional “Hull 3000” (H3000) hull form. The hull plating, longitudinal and transverse stiffeners, decks, and bulkheads in the resulting FEM were developed by NSWCCD, based on USN structural design practice. The scantlings of this representative structure, located in the bow region of the ship centered 18.3 m aft of the forward perpendicular, are listed in Table 1 and illustrated in Figure 1.

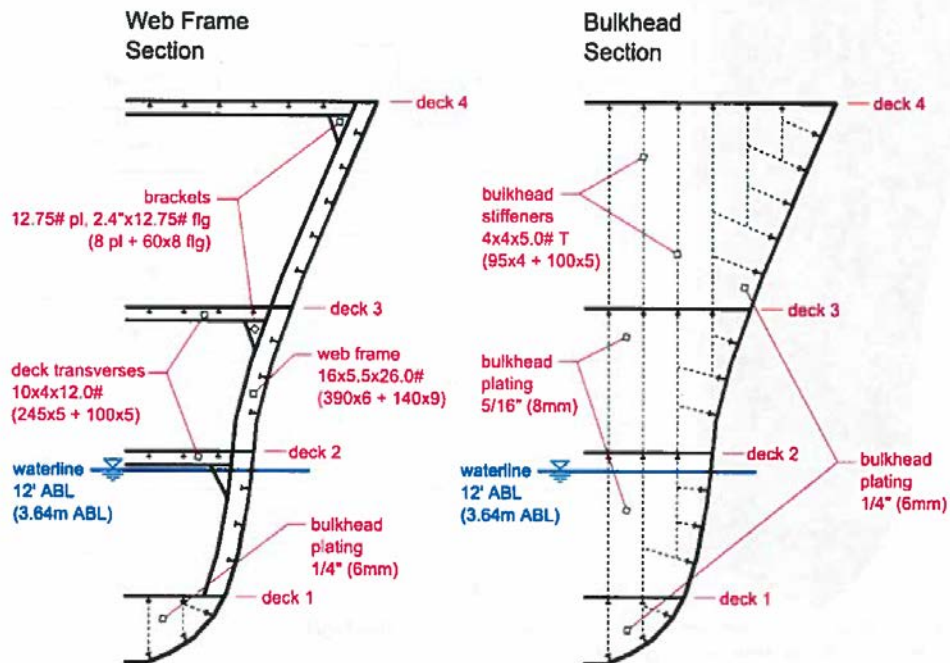
Table 1. H3000 Plate and Stiffening Frame Properties

Components	Plate Thicknesses (mm)	
Upper and Lower Hull Shell	10.0	
Middle Hull Shell and Deck 1	8.0	
Other Decks, Bulkheads, and Floors	6.0	
Parameters	Frame Type and Dimensions (mm)	
	Longitudinal	Transverse
Frame Span	2032	2500
Frame Spacing	685	~ 1000
Web Height	145	390
Web Thickness	5.0	6.0
Flange Width	100	140
Flange Thickness	5.0	9.0



NOTE: structural material = HY-80 steel

(a) Sections Between Transverse Frames

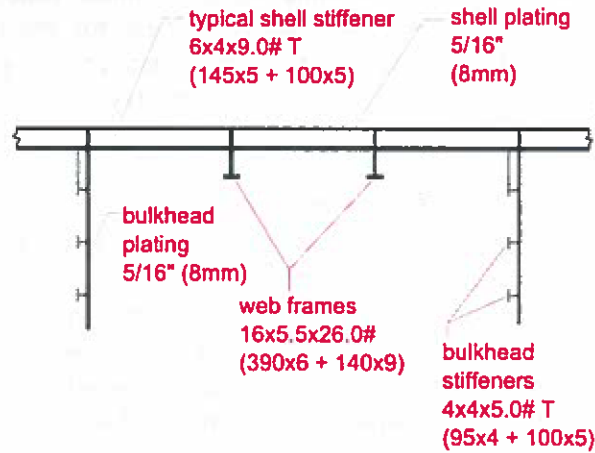


NOTE: structural material = HY-80 steel

(b) Sections at Web Frames and Bulkheads

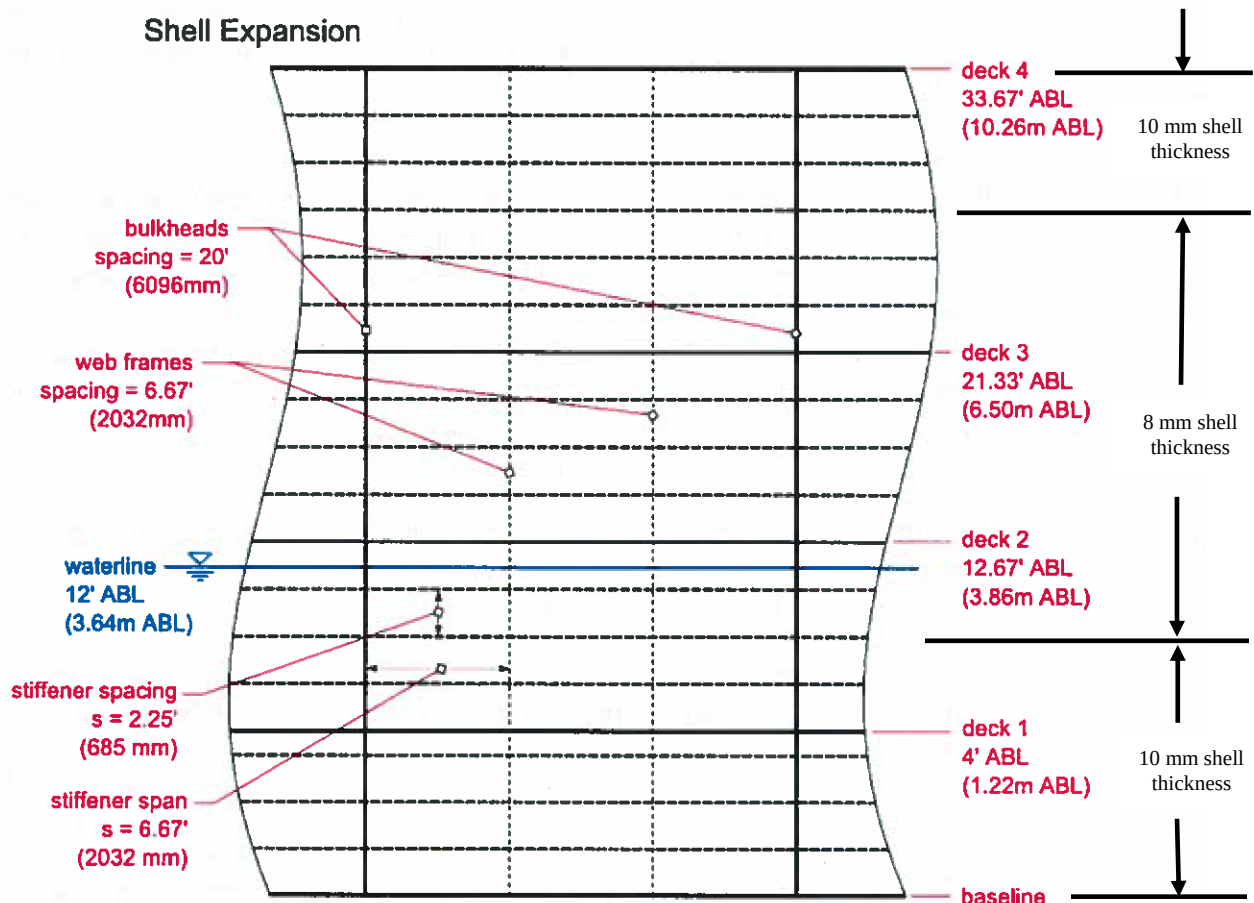
Figure 1. H3000 Structural Scantlings

Typical Longitudinal Frame



(c) Longitudinal Framing Detail

Shell Expansion



(d) Framing Arrangements on Hull Shell

Figure 1. H3000 Structural Scantlings (cont'd)

The hull section material is HY-80 steel; appropriate material properties for an LS-DYNA bilinear elastic-plastic strain-hardening material, MAT PLASTIC KINEMATIC (MAT3), are listed in Table 2. Rate dependency of these properties is not taken into account, though the loading rates considered in the present study are relatively low.

Table 2. H3000 Structural Material Properties

HY-80 Material Property	Value in US (Imperial) Units	Value in SI (MKS) Units
Mass Density	0.283 lbf/in ³	7833 kg/m ³
Elastic Modulus	29.6 Msi	204 GPa
Poisson's Ratio	0.3	0.3
Yield Strength	80 ksi	551.6 MPa
Ultimate Tensile Strength	100 ksi	689.5 MPa
Ultimate Tensile Strain	0.2	0.2
Bilinear Elastic-Plastic-Kinematic Hardening Model Parameters*		
Tangent Modulus*	101 ksi	0.7 GPa
Hardening Parameter	0.0	0.0

Note: * Tangent modulus is derived from yield strength, ultimate tensile strength, and ultimate tensile strain.

Dolny et al. used the H3000 structural idealization (with case-dependent FE model extent adaptations) in five ice/structure impact studies:

- Development of structural-deformation-based adjustments to the spreadsheet-based ice loading computation tool DDePs (Direct Design of Polar Ships, developed by BMT Fleet Technology and the American Bureau of Shipping)¹, which normally presumes a rigid structure
- Analysis of structural response to stationary, increasing patch loads
- Analysis of structural response to a moving rigid indenter
- Analysis of structural response to moving and spatially-varying (“4D”) patch loads based on USCGC Polar Sea (WAGB 11) ice loading field measurements (Daley, St. John, Brown, & Glen, 1990)
- Analysis of structural response to impact by crushable ice slabs

The last listed study is the only one in which *flexible* structure interaction with a *deformable* ice medium is considered. FEMs of uniform-thickness ice slabs were developed for that study, with constraints preventing out-of-plane ice slab flexure imposed. These slabs were pushed into the structure at a constant imposed approach velocity until a chosen indentation level was reached. The ice material model was restricted to simulation of macro-scale crushing in the immediate vicinity of the ice/structure contact surface. Since the study focused on the question of the effect of structural deformation on ice crushing loads, ice slab flexure and failure of the slabs through flexure-induced cracking was not considered.

¹ There is no one report documenting DDePS, but Dolny et al. (2016) lists several contributing references.

The present effort exploited selected FEMs constructed by the ABS/MUN team, using ice slab models amended to allow for ice slab flexure and flexure-induced cracking during the ice/structure interaction process. Their ship structural FEMs were also altered to attain better-controlled kinematic responses of the structure relative to the ice slab. These amendments are described subsequently.

3.1 Hull Structure Modeling

The LS-DYNA discretization of H3000 hull structure used in the present studies, based on the plate and stiffener scantlings shown in Figure 1, spans three transverse hull frame spacings and is bound on its fore-and-aft ends by continuous transverse bulkheads. The discretization extends from the keel to the third deck level and includes deep floors, first deck (tank top), second deck, transverse tee frames, and longitudinal tee stiffeners on both side shell and decks. Bulkhead stiffeners and brackets are also included. Only one (port or starboard) side of the hull is modelled, and waterline angles of the hull form are not considered, i.e., the sectional areas of each frame location are the same, and transverse dimensions from centerline do not vary fore and aft. Figure 2 illustrates the LS-DYNA idealization, based on the ABS/MUN-developed FEM designated with LS-DYNA input file name `structure_h3000_long.k`, used in LS-DYNA runs H_101 through H_105, as reported by Dolny et al. (2017, section 4.3). The left-hand view of Figure 2 shows plating and stiffener outlines, while the right-hand view displays the shell element mesh. The model is composed of 18 parts, distinguishing between side shell, longitudinal stiffener, transverse frame webs and flanges, deep floors, bulkheads, and decks. The mesh is composed of 28639 nodes, 29061 shell elements, and zero beam elements, with all stiffeners discretized as shells².

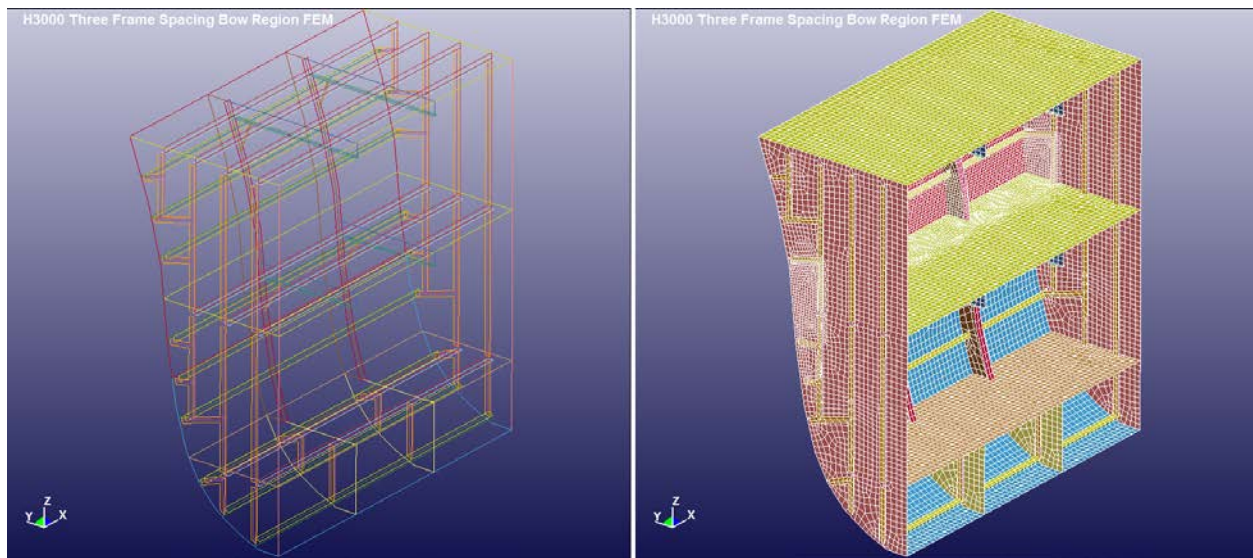


Figure 2. LS-DYNA Structural Idealization of H3000 Bow Region Structure

Dolny et al. (2017, section 4.3) document the preliminary mesh convergence and optimization studies that justify the modeling of three hull frames, the representation of all

² The ABS/MUN team has provided structural modeling guidelines for hull structure/ice collision modeling (Quinton, Daley, Gagnon, & Colbourne, 2017).

stiffeners with shell rather than offset beam elements, shell element edge lengths of ~ 5 cm, and the usage of LS-DYNA's Hughes-Liu (H-L) shell elements throughout the FEM.

The idealization of Figure 2 differs from the ABS/MUN-developed FEM in several ways to overcome initial difficulties associated with structure and ice slab kinematics. The fracture-and-out-of-plane-flexure-enabled ice slab tended to break prematurely near the curved outer boundary of the slab when moved toward the structure that was constrained against rigid body movement with the fixed boundary constraints originally specified by ABS/MUN. To circumvent this problem, the outer boundary of the ice slab was fixed in all degrees of freedom (DOF), and the structure was moved toward the slab at a constant approach velocity. This was initially accomplished by specifying imposed velocities on all structural FEM nodes in the port/starboard symmetry plane and constraining all other DOF at these nodes. Although this approach eliminated the premature ice fracture problem, the structural FEM tended to vibrate excessively during motion startup. This anomaly was minimized by constraining the forward and aft ends of the model with stiff bulkheads and reinforcing the upper limit of the model with the third deck. Imposition of a constant approach velocity in the transverse direction and constraint of all other DOF were extended from the port/starboard symmetry plane to all nodes on the two bounding bulkheads and the second deck. Although not completely eliminated, preimpact vibration was reduced to what was judged to be nuisance level³. Constrained structural nodes on the H3000 FEM periphery are highlighted with tick marks in Figure 3.

H3000 section showing nodes constrained against all DOF except Y translation

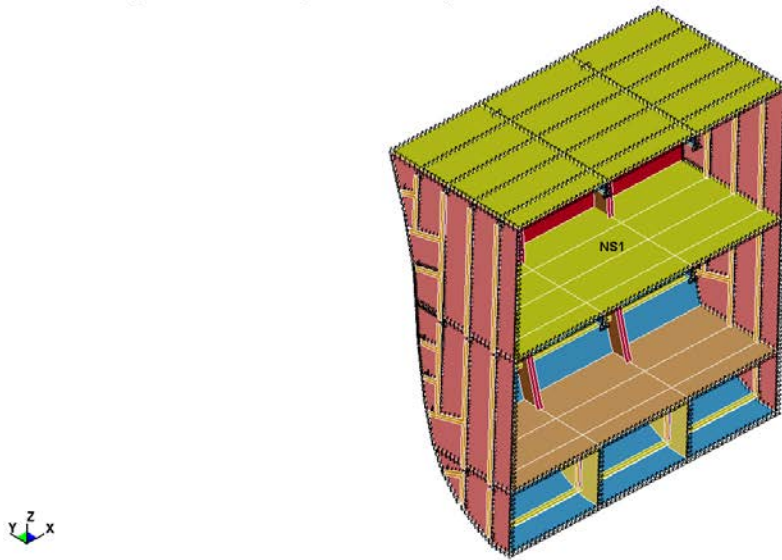


Figure 3. Nodal Constraints Applied to H3000 FEM

³ Imposition of LS-DYNA-implemented Rayleigh-style structural damping in the hull section material was experimented with, but the resulting energy dissipation was found to adversely compete with (reduce) material deformation energy dissipation during inelastic structural response.

3.2 Ice Slab and Ice Material Modeling

Figure 4 is a schematic of the ice slab considered in this study. The slab has a radius of 30 m and a wedge angle of 150° . Recent thin-ice mechanics studies focusing on ice slab buckling used a slab of this size and shape (Dolny et al., 2017, sections 2.4 and 2.6). It covers a surface area of 1214.3 m^2 (13070.6 ft^2), and three thicknesses, 0.14 m, 0.21 m, and 0.35 m (5.51 in, 8.27 in, and 13.78 in), are considered in this study. The corresponding floe masses, assuming 900 kg/m^3 mass density, are 150.6 long tons, 225.9 long tons, and 376.5 long tons. The floe thicknesses and area are in the lower bound of the ranges expected for first-year ice in the Arctic MIZ⁴.

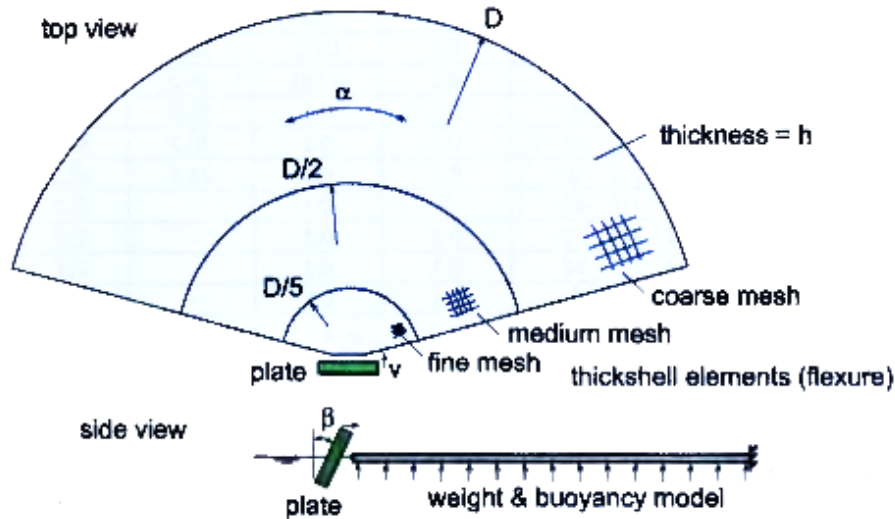


Figure 4. Schematic of Ice Slab for H3000 Collision Interaction Studies

The only nodal constraints applied to the ice slabs are full fixity on all nodes on the “far field” boundary at 30-m radius, as shown in Figure 5.

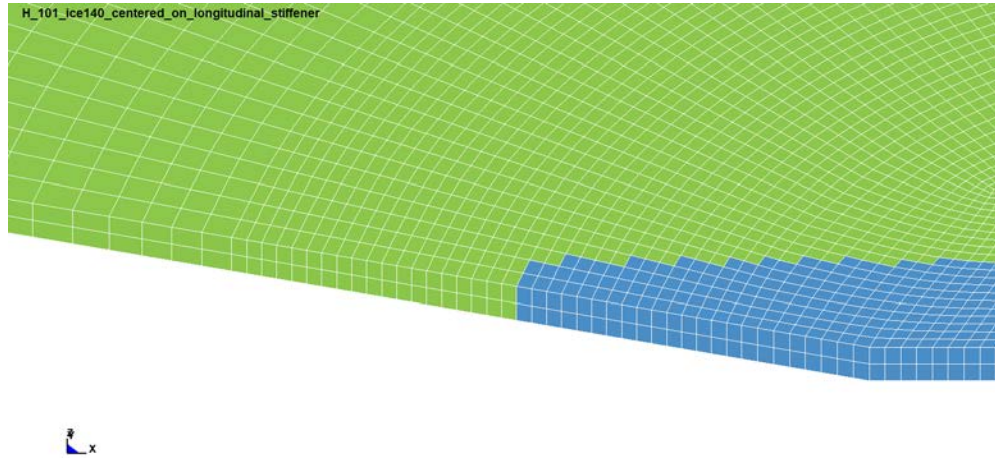
⁴ Appendix A contains size-, thickness-, and mass-based comparisons of the ice bodies considered in this report, with WMO categorizations and ice bodies considered in related studies.

Ice slab showing nodes constrained against motion in all DOF

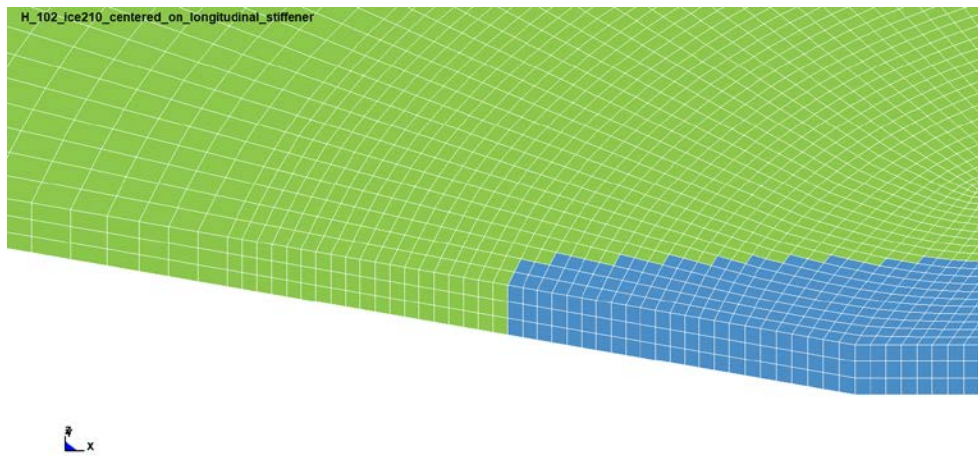


Figure 5. Nodal Constraints Applied to Ice Slab FEMs

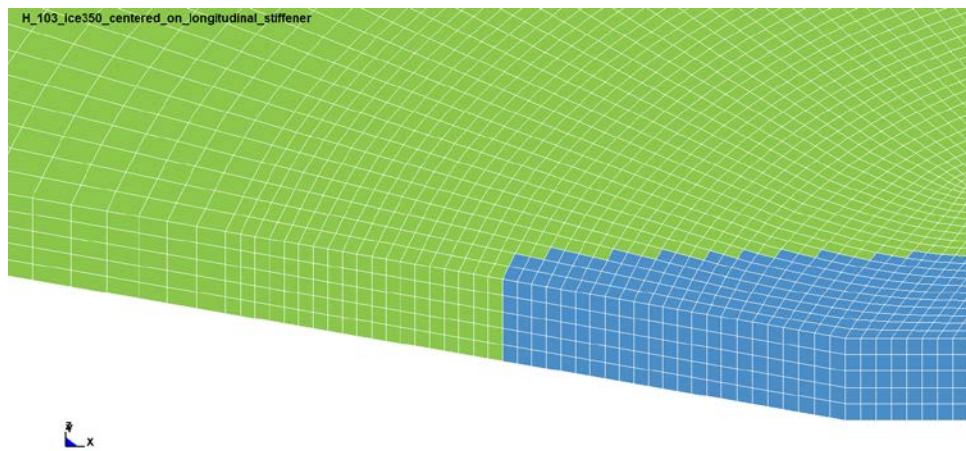
All three floe thicknesses are discretized with LS-DYNA thick-shell elements, which allow superior resolution of through-thickness stress and strain gradients than is possible with 3D solid elements. The LS-DYNA thick-shell formulation used is type 1, which uses the Reissner-Mindlin kinematic assumption where through-thickness planes remain planar during deformation but may rotate with respect to the element normal vector. The constitutive law is plane-stress-based, and thickness change is based on Poisson's ratio. One-point quadrature is used in the shell plane, but five integration points are specified through the thickness of each thick shell. The 0.14-m, 0.21-m, and 0.35-m thicknesses are represented with two, three, and five elements through the thickness, respectively. This element disposition provides equal element depths and equal distances between integration points for all models. Closeup views of the ice slab mesh, showing aspect ratios of the stacked thick-shell elements, are shown for the three slab thicknesses in Figure 6.



(a) 14-cm Thickness



(b) 21-cm Thickness



(c) 35-cm Thickness

Figure 6. Ice Slab Thick-Shell Element Meshes

Weathered ice floes will always have irregular outlines, and ship/ice floe contact will usually occur with respect to a floe edge “feature,” i.e., at the apex of a distinct angle along the outline if not an outright protrusion or knob. The prior thin-ice study (Dolny et al., 2016, section 2.6), considered a range of wedge angles between 90° and 150°. This study used the 150° angle, as that angle tended to produce the highest collision loads.

A key difficulty of modeling ice slab collision interaction with structures is the lack of a material response and failure model for ice that accommodates two factors: (1) the near-field crushing damage behavior predominant near the ice/structure interface and (2) the possibility of flexural fracture in the far field of the slab more remote from the interface. The approach taken is to assign a fracture-enabled material model to elements in the majority of the ice slab, with a relatively small non-fracture-enabled region near the contact zone assigned to a material model specialized for crushing simulation. The next section discusses details of the crushing and flexure material models.

3.2.1 Ice Crushing Modeling

Macro-scale modeling of ice crushing phenomena with limited account of fracturing and spalling during the crushing process has been treated with two LS-DYNA material models:

- a) Isotropic crushable foam (MAT63): This simple model presumes elastic-perfectly-plastic behavior and requires only yield stress as a function of volumetric strain and a tensile pressure cutoff value.
- b) Kinematic/isotropic elastic-plastic material (MAT3): This is a conventional J2 flow theory elastic-plastic material model with choice of kinematic or isotropic hardening and optional ability to account for rate dependency.

LS-DYNA MAT63 has been successfully used in simulation of full-scale ship/iceberg collision (Gagnon & Derradji-Aouet, 2006; Gagnon, 2010), in simulation of laboratory-scale ice crushing tests (Kim, 2014), and in conceptual ice wedge/indenter collision studies (Sazidy, 2015). Crushing response of ice has also been successfully modeled (Dolny et al., 2017; Liu, Daley, Yu, & Bond, 2012) using LS-DYNA MAT3, whose parameters can be optimized so that contact pressures and contact areas develop according to full-scale, experimentally-verified pressure/area relationships. Neither of these material models have a “failure” criterion, but one may be introduced via the MAT_ADD_EROSION keyword. MAT63 works only for 3D solid finite elements.

In this study, LS-DYNA MAT3, with parameters tuned according to ice slab thickness as designated by Dolny et al. (2017), was used in the ice slab crushing zone. A comparative study (Storheim, 2016, section 7.4) of the Gagnon ice models and an alternative elastic-plastic ice material model with hydrostatic pressure dependence (Liu, Amdahl, & Løset, 2011b) motivates this choice. Storheim (2016, Figure 7.24) showed that the Gagnon crushing models, as originally calibrated for glacial ice impact, provided pressures as a function of contact area highly contrary to expectations of the International Standards Organization (ISO, 2010) for crushing of an ice sphere against a rigid plate. Even so, MAT63 in the crushing zone, using the Gagnon calibration parameters for yield stress versus volumetric strain and tensile stress cutoff, was briefly examined in one collision scenario with MAT3-based results.

Table 3 lists the assumed MAT3 material parameters for crushing-zone ice. The only slab-thickness-dependent parameter in the crushing property calibration (Dolny et al., 2017) is the yield stress, which in MAT3 is the same in tension as in compression. This is not an issue in

modeling of ice where compressive stresses are predominant. For reference, the yield stress values in Table 3 are those presented previously by Dolny et al. (2017, section 4.3, Table 9).

Table 3. LS-DYNA MAT3 Parameters for Ice in the Crushing Zone

Parameter	Value
Mass Density	900 kg/m ³
Elastic Modulus	9 GPa
Poisson's Ratio	0.33
Yield Stress (depends on slab thickness; see note)	1.2805 MPa (t = 0.14 m) 1.2719 MPa (t = 0.21 m) 1.2551 MPa (t = 0.35 m)
Plastic Hardening (Tangent) Modulus	10 MPa

Note: Yield stress values adapted from *ONR Ice Capability Assessment and Experimental planning, Deliverable #2: Advanced Modeling and Re-Assessment of NSWCCD Hull 3000* [Technical report], by J. Dolny, C. Daley, B. Quinton, and K. Daley, 2017, Houston, TX: American Bureau of Shipping.

3.2.2 Ice Flexure and Fracture Modeling

Following the works of Ehlers and Kujala (2013) and Sazidy (2015), the LS-DYNA material MAT_PLASTICITY_COMPRESSION_TENSION (MAT124) has been extensively exercised for simulation of ice beam and ice slab flexural failure (Lesar, 2017). This is a J2 flow theory-based, elastic-plastic material model that accepts yield-stress-versus-effective-plastic-strain curves that differ for tension and compression. This feature accommodates the important tensile/compressive strength differential effect typical of ice. Flexural fracture of the slab is modeled using the element erosion technique applied in simulation of ice beam fracture (Ehlers & Kujala, 2013) and ice slab fracture (Sazidy, 2015). In this method, the stress and/or strain condition at integration points of MAT124 elements are tracked against a user-specified failure parameter (e.g., effective plastic strain, maximum principal stress, mean stress, or pressure). Elements reaching the specified failure condition are then deleted from the model, and in this way, “cracks” initiate and propagate dynamically. In the model’s basic form, failure by element erosion can be triggered by attainment of (an effective plastic) “failure” strain; however, this criterion does not differentiate between tensile and compressive regimes. Fortunately, alternative failure criteria (e.g., failure pressure or maximum principal stress) can be specified via LS-DYNA’s MAT_ADD_EROSION keyword, enforcing failure only if tensile conditions prevail at element integration points. LS-DYNA identifies whether the compressive or tensile stress-strain curves apply at integration points based on the algebraic sign of mean stress (pressure). This can lead to numerical artifacts when dynamic loading is rapid and the algebraic sign of pressure fluctuates rapidly. To alleviate this problem, a blending of the compressive and tensile stress-strain curves can be specified. Alternatively, the user can force the code to use compressive and tensile stress-strain curves verbatim if this problem is not encountered. By comparison of LS-DYNA simulations with ice beam fracture test data of Ehlers and Kujala (2013), the previous NSWCCD study (Lesar, 2017) established the validity of using verbatim unblended tensile and compressive stress-strain curves and the maximum principal stress failure criterion with

MAT124. The MAT_ADD_EROSION failure metric used throughout this study was maximum principal stress (input parameter SIGP1).

Another aspect of the material failure modeling approximation using the element erosion technique is the number of integration points required to reach the chosen failure condition before the element is “failed” and removed. The previous study (Lesar, 2017) presumed the most permissive choice; that failure condition attainment at only *one* integration point is sufficient for element deletion. This is a moot point if modeling uses one-integration-point 3D solid elements, but it becomes a key assumption if thick-shell elements with several integration points through the thickness dimension are used. After publication of the previous study (Lesar, 2017), some ice slab fracture simulations documented therein were revisited with more stringent element deletion specifications. The contents of Appendix B show that greatly cleaner and physically plausible ice slab crack patterns ensue when more than one integration point must reach failure conditions before element deletion. As a result, in the simulations that follow, element deletion proceeds only when *all* integration points in an element reach failure conditions.

Table 4 lists the MAT124 parameters used in this study for flexural zone ice, with comparison to the final parameter set used in earlier work (Lesar, 2017). The initial parameter set for the present study is partly based on the values listed for crushable ice in Table 3 in section 3.2.1, with consistent mass density and elastic parameters. For MAT124, the tangent modulus is the same for both tension and compression responses. For MAT124, the slab thickness-dependent tensile yield stresses are the same as those specified in the MAT3 crush zone, and the compressive yield stresses are set to be ten times higher, as was done previously (Lesar, 2017). The tensile yield stresses are roughly a factor of two higher than in the previous study (Lesar, 2017); but since Dolny et al. presumed low and high yield strength limits of 0.5 and 1.5 MPa in the crushing model calibration study, all of these values are reasonable. A notable difference in the present study is the maximum principal stress value at failure, which is specified as being considerably higher with respect to the tensile yield stress than was specified previously. The greater offset with respect to tensile yield helps to alleviate what appeared to be great sensitivity of failure load prediction to effective inelastic strain when a low tangent modulus is combined with a near-unity ratio of failure strength to yield strength.

In the early stages of the present study, notable discontinuities of compressive stress levels occurred near the boundary between MAT3 and MAT124 ice. Examination of plastic strain contours indicated that the stress discontinuity was an outcome of the factor-of-ten difference between compressive and tensile yield in the MAT124 ice, with a resulting factor-of-ten difference in compressive yield between MAT3 and MAT124 ice. Since maximum principal stress is the failure criterion in the MAT124 ice instead of the tension-compression-agnostic effective plastic strain, a factor-of-ten difference in tensile and compressive yield, imposed partly to suppress any possibility of failure by plastic strain under compression, was thought to be excessive and unnecessary. Consequently, the compressive/tensile yield stress ratio for the MAT124 ice was relaxed from 10 to 2. This change practically eliminated artificial stress contour discontinuities between MAT3 and MAT124 regions and still provided a physically reasonable tensile/compressive strength mismatch.

The (initial) yield stresses and the plastic hardening modulus are not input directly, but they are reflected in the effective-plastic-strain-versus-stress curves that are input as LS-DYNA “load

curves.”⁵ An ice mass density of 900 kg/m³ was assumed, with no (upward) mass density adjustment as an ad hoc method for imposing hydrodynamic added mass incurred due to ice movement in the supporting water medium. Given the slow relative velocities assumed in these simulations and the greatly simplified collision kinematics assumed, added mass modeling was felt to be an unnecessary embellishment.

Table 4. LS-DYNA MAT124 Parameters for Ice in the Flexural Response Zone

Parameter	Previous Study Value*	Present Study, Initial Value	Present Study, Final Value
Mass Density	900 kg/m ³	900 kg/m ³	900 kg/m ³
Elastic Modulus	9 GPa	9 GPa	9 GPa
Poisson's Ratio	0.3	0.33	0.33
Yield Stress in Compression	5.0 MPa	10x tensile yield; 10.2-10.3 MPa	2x tensile yield; 2.4-2.6 MPa
Yield Stress in Tension	0.5 MPa	Variable, depending on slab thickness; 1.2-1.3 MPa (see Table 3)	Variable, depending on slab thickness; 1.2-1.3 MPa (see Table 3)
Plastic Hardening (Tangent) Modulus	10 MPa	10 MPa	10 MPa
Maximum Principal Stress at Failure (SIGP1)	0.505 MPa	1.5 MPa	1.5 MPa

Note: * Previous study values adapted from *Modeling and Simulation of Ice Failure Modes during Ice Floe/Ship Structure Collision* (NSWCCD-65-TR-2017/12), by D. E. Lesar, 2017, West Bethesda, MD: Naval Surface Warfare Center, Carderock Division.

3.3 Collision Kinematics

A glancing blow of an ice slab on the bow region of a ship is a ship/ice collision scenario of significant operational interest. Figure 7, taken from the work of Dolny et al. (2016, section 4.5), schematically illustrates the scenario, many variations of which were analyzed for the H3000 hull form with the ABS/MUN-developed spreadsheet-based ice load calculation tool, DDePS, as reported by Dolny et al. (2016, section 4.5).

However, existing H3000 FEMs developed by ABS/MUN do not represent this collision scenario. The discretized structural section has constant athwartship dimensions as a function of ship section fore-aft length; consequently, the FEM's wetted surface lacks waterline angle variation. Since the present study focusses on establishing the likely importance of ice slab flexural failure when the impacting structure is limber and nearly wall-like, the collision scenario

⁵ The first coordinate pair of effective plastic strain-versus-stress curves must be (0.0, initial yield stress).

is instead defined by lateral relative movement of the hull structure and the ice slab along a vector perpendicular to the ship's vertical midship plane, as shown in Figure 8.

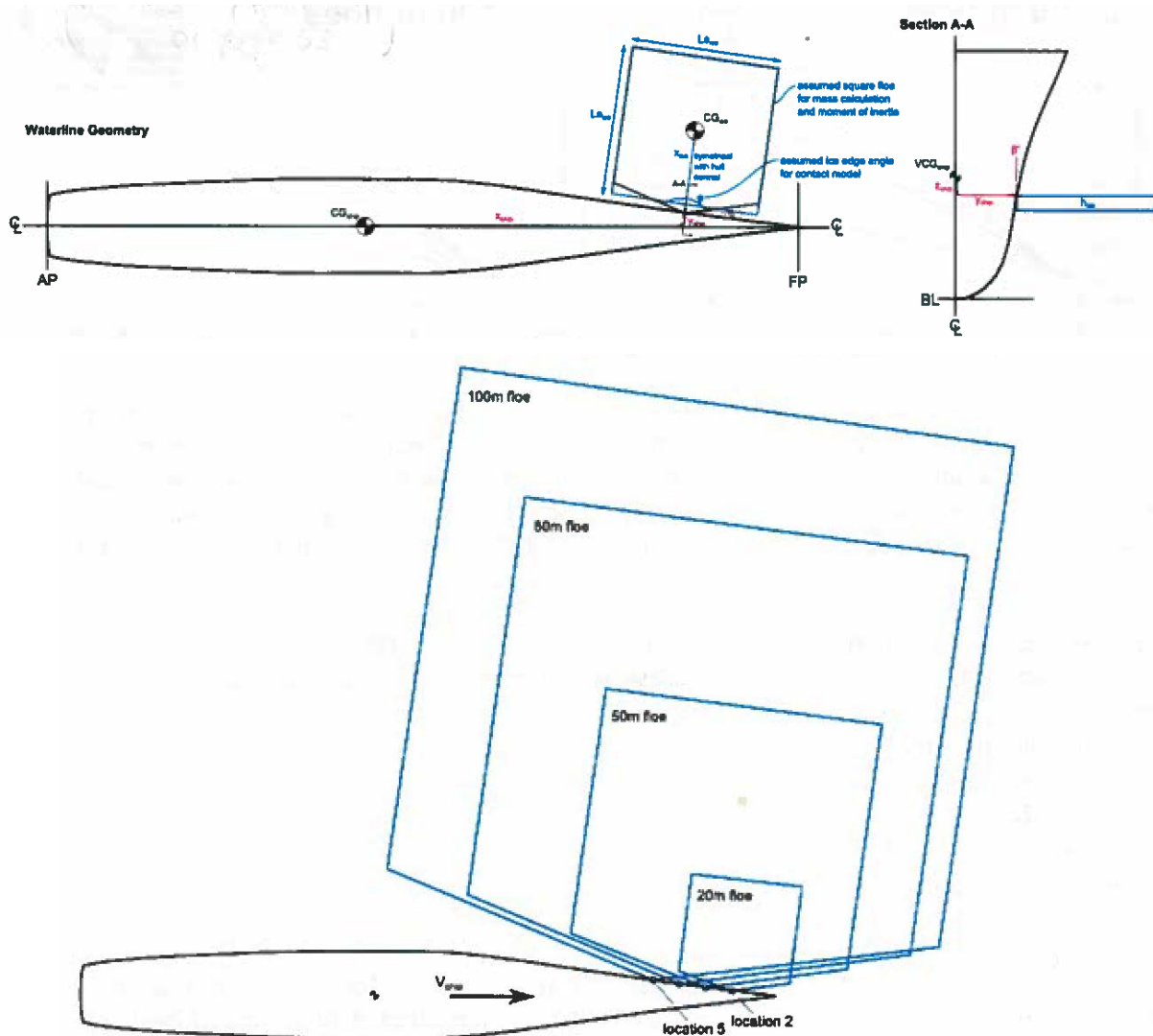


Figure 7. Ship/Ice Floe Collision Scenario Considered in DDePS Studies.
From ONR Ice Capability Assessment and Experimental Planning, Deliverable #1:
DDePS SafeCheck Technical Background and Safe Speed Assessment of NSWCCD Hull
3000 [Technical report], by J. Dolny, C. Daley, B. Quinton, and K. Daley, 2016, Houston,
TX: American Bureau of Shipping.

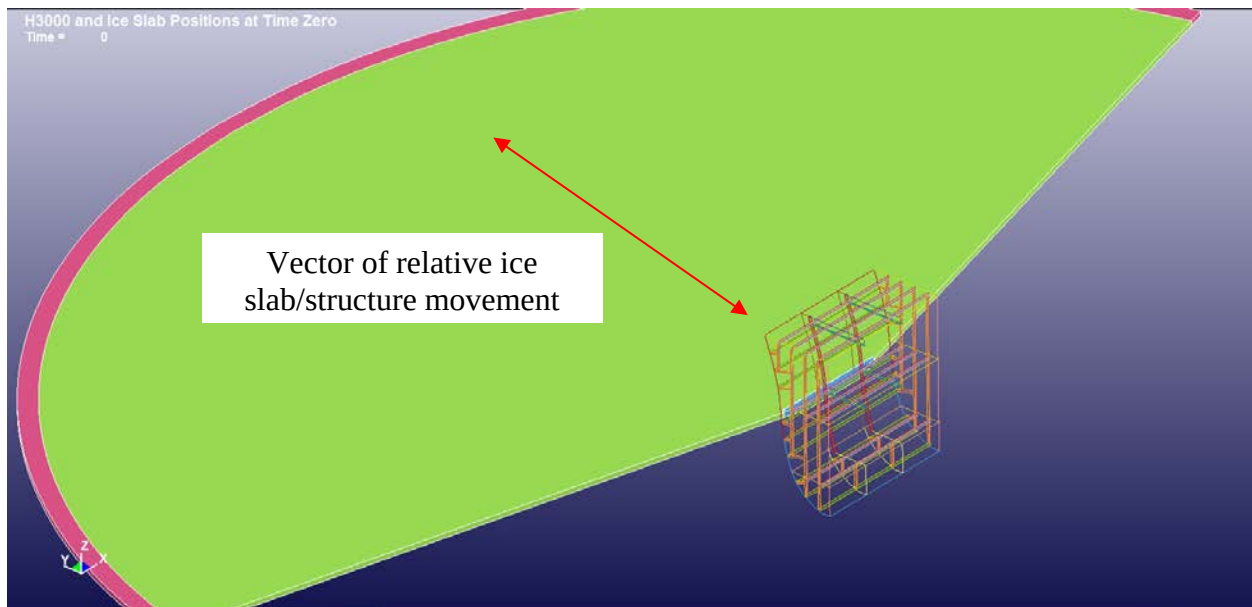


Figure 8. Ship Structure Section/Ice Slab Collision Scenario Considered in the Present Study

For reasons described in section 3.2, the relative structure/ice movement is represented by translation of the structure into the initially stationary ice rather than vice versa. The H3000 FEM is driven into the ice slab at a translational velocity of 0.58824 m/s (slightly over 1 kn). This very slow approach velocity was assumed in the ice crushing calibration studies (Dolny et al., 2017). Structural motion is ramped up from zero to the terminal value in 0.016 s, prior to impact with the ice. The effect of faster relative motion is examined in a simulation assumption variation set. The timespan of simulation is 0.5 s. For most simulations, this timespan allowed development of peak interaction force. The outer boundary of the slab is fixed against displacement for most simulations, but that constraint is relaxed in one modeling assumption variation set.

3.4 Simulation Assumptions

The LS-DYNA contact entity `CONTACT_AUTOMATIC_SINGLE_SURFACE` was used to detect and track ice/structure contact. With this contact algorithm, all free faces of all elements in the model are candidates for contact and sliding. However, since all structural elements are shells, it makes little sense to include all interior structural elements (decks, floors, stiffeners) as candidate contact surfaces. Therefore, the structural contact surfaces are restricted only to the parts comprising the water-exposed side shell.

Nonzero contact surface friction can be modeled in LS-DYNA with classical Coulomb friction assumptions. Distinct static and dynamic friction properties can be optionally assigned. In this effort, both frictionless contact and contact with a static coefficient of 0.10 are assumed, with the nonzero-friction input following that presumed by the ABS/MUN team (Dolny et al., 2016, 2017).

The LS-DYNA contact entity `CONTACT_FORCE_TRANSDUCER_PENALTY` recovers forces on all structural contact surface faces, which are summed to obtain the total load exerted on the H3000 side shell. Time histories of this force are fundamental bases of comparison between the many simulations.

As described by Dolny et al. (2017, section 2.4.1), the ABS/MUN team exploited the `DEFINE_FUNCTION` feature of LS-DYNA to devise modeling of gravity- and immersion-depth-dependent buoyancy loading on the deforming ice slab. The loading function provides time-dependent distributed-pressure loadings to each element face on the bottom of the discretized ice slab. The present effort used their method; however, for the buoyancy force function to work as formulated, the position of the $z = 0.0$ coordinate plane needs to be located at the static waterline of the floating ice. The assumed ice material density of 900 kg/m^3 and the implied water density of 1000 kg/m^3 imply that the $z = 0.0$ plane must be positioned at 90 % of the slab depth above the slab bottom. To avoid maintaining distinct FE models for the differing ice thicknesses, all structure and ice parts are positioned in LS-DYNA by `PART_MOVE` commands in an ice-thickness-specific master LS-DYNA execution control file prior to dynamic analysis.

LS-DYNA's default viscous hourglass control scheme was used, with an imposed coefficient of 0.10. Initial runs with stiffness hourglass control did not minimize hourglassing energy as effectively as viscous control. Hourglassing response was visually evident at and near one deep-floor/tank-top intersection in way of an adjoining stiffener intersection. This anomaly remained localized to those components, which were of little structural deformation interest. Curiously, this nonphysical response did not occur at an identical joint at the second companion frame location.

Text-format (ASCII) data for time-history plotting (principally contact surface forces) was saved at 0.0005-s intervals (1000 samples in 0.5 s) and binary whole-model data is saved at 0.005-s intervals (100 samples in 0.5 s). The resultant contact force (RCFORC) file contained required contact surface force and moment time histories. The binary datasets provided inelastic strain contours and animations of structure and ice deformations including development of ice slab fractures.

3.5 Simulation Software and Hardware

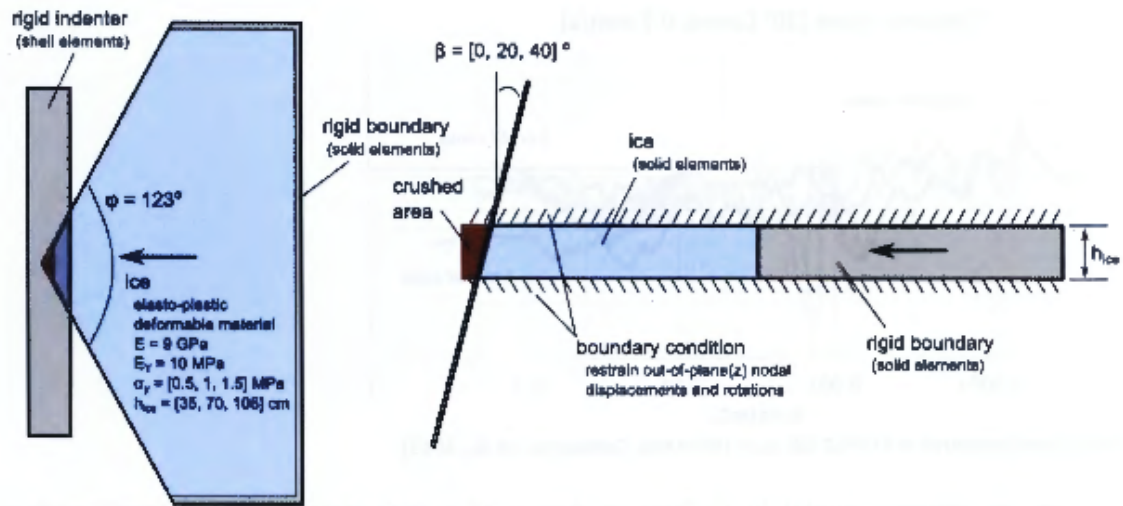
U.S. Department of Defense High Performance Computing Center resources supported all simulations reported here, specifically, the LS-DYNA code installed on the Air Force Research Laboratory (ARL) computing system. The code version used was massively parallel LS-DYNA version mpp-s-Dev, revision 103383, run in single precision. Computing hardware was the ARL SGI IceX 5.62 PFLOPS 3216-core platform *thunder*. Depending on model size, LS-DYNA jobs were completed within 20 min to 30 min of wall-clock time under “debug” queue priority with 16, 18, or 20 processors requested. This rapid turnaround enabled completion of a large number of jobs in reasonable time.

4. Results and Discussion

This section documents the many LS-DYNA ice/structure collision simulations carried out. First, preliminary analyses directly extended from previous ice crushing material model calibration studies are discussed. It was found that ice slab size had to be increased to enable inclusion of flexural fracture effects. Second, ice slab impact studies for impacts on longitudinal stiffeners and (stronger) web frames are documented, with focus on the effects of allowing ice slab fracture and of allowing zero or non-zero ice/structure contact friction. Three ice slab thicknesses are considered in these analyses. Third, a method for allowing LS_DYNA simulation of successive impacts with structural damage accumulation is described and exercised. Fourth and last, several modeling variations (far-field ice slab boundary conditions, more rapid collision loading, and an alternative ice crushing material model) are exercised and discussed.

4.1 Initial Analysis Attempts

Figure 9 shows the ice slab configuration used in the ice crushing parameter calibration effort using a rigid indenter rather than the H3000 FE model (Dolny et al., 2017). Figure 10 shows a specific ice slab FE mesh.



Factors	Description	Symbol	Units	Low	Medium	High
A	material yield strength	σ_y	MPa	0.5	1	1.5
B	ice thickness	h_{ice}	m	0.35	0.7	1.05
C	beta	β	°	0	20	40
fixed	ice wedge angle	Φ	°	123		
fixed	ice density	ρ_{ice}	kg/m ³	900		
fixed	ice modulus of elasticity	E_{ice}	GPa	9.0		
fixed	ice Poisson's ratio	ν_{ice}	--	0.3		
fixed	ice tangent modulus	E_t	MPa	10.0		
Responses	Description	Symbol	Units			
R1	nominal pressure at 1m ²	P_o	MPa			
R2	process P-A exponent	ex	--			

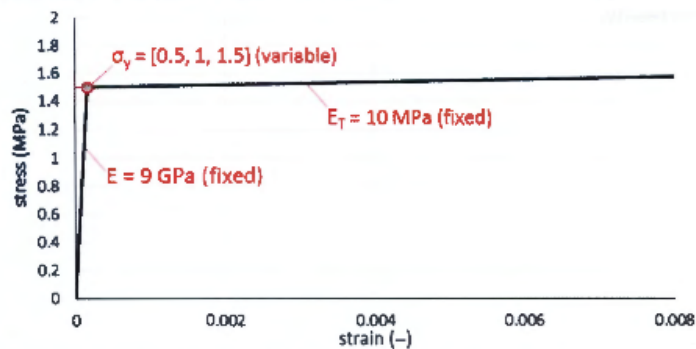


Figure 9. Illustration and Parameters of an Ice Crushing Property Optimization Study using LS-DYNA

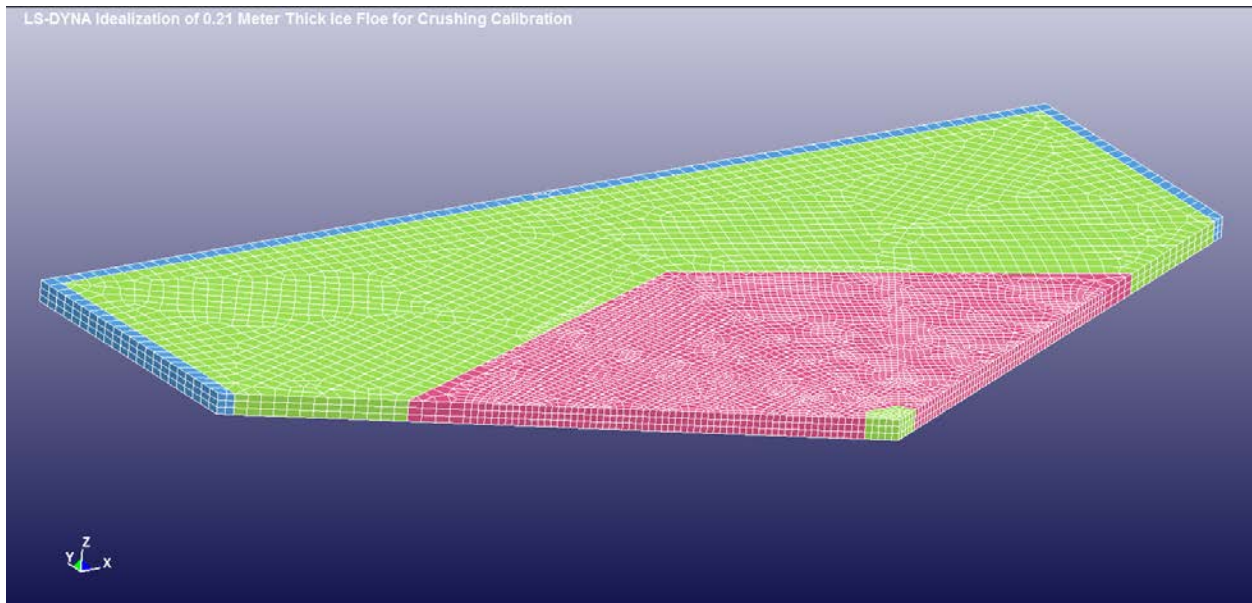


Figure 10. FE Mesh of Small Ice Slab Considered in Crushing Calibration Study

In the interest of literal extension of the crushing phenomena simulations to inclusion of flexure and fracture, initial LS-DYNA runs used these same ice slab FEMs with division into MAT3 and MAT124 ice regions. Analyses were conducted for ice impact on a longitudinal H3000 stiffener for both frictionless and nonzero-friction conditions on the ice/structure interface. The out-of-plane motion constraints shown in the ice slab in Figure 6 were removed to allow slab flexure, and the H3000 structural FEM took the place of the rigid planar indenter.

Unfortunately, the ice slabs used in the crushing material model calibration study were unsuitable for study of flexural fracture. When failure occurred in the MAT124 region, it was confined to the crushing zone/flexure zone boundary and was in the form of mass failure of many elements rather than development of a clean crack. Very little slab flexure occurred before this catastrophic “shattering.” Reducing the size of the crush zone and bringing flexure-failure-enabled ice closer to the structure/ice interface did not change this behavior. Figure 11 shows an example of unsatisfactory LS-DYNA-computed ice slab failure using the crushing calibration model ice FEM.

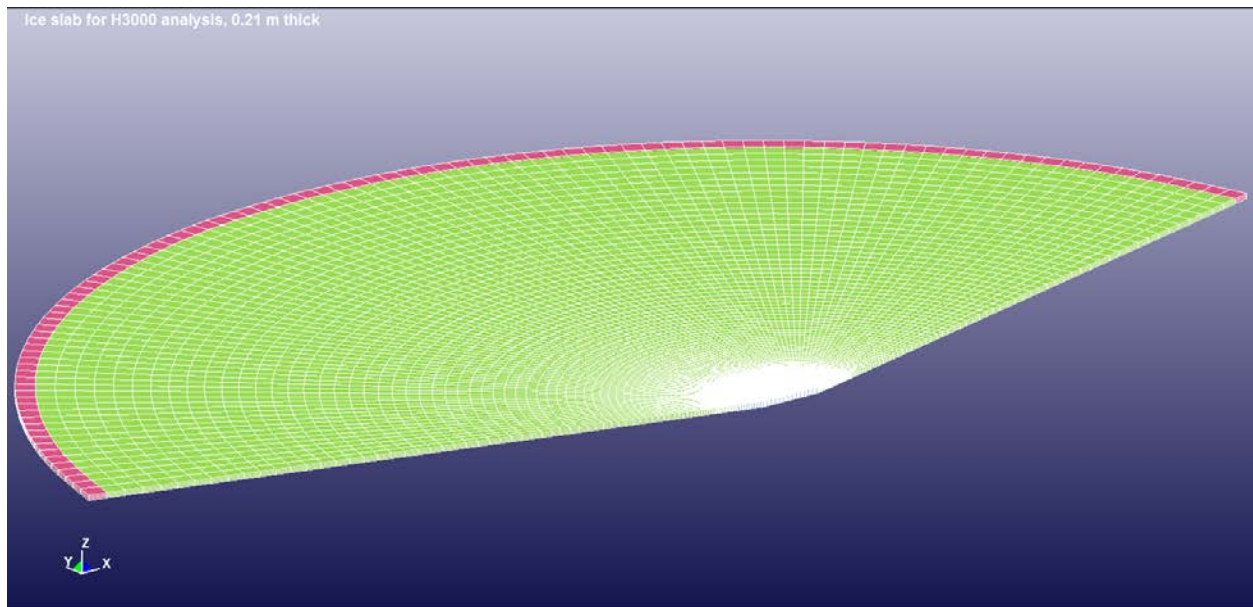
For the two thicknesses (0.14 m and 0.21 m) analyzed in the initial runs, the slab masses were only 8.76 long tons and 13.14 long tons, respectively. The lateral extents of these floes are 5.9-m depth and 11.25-m width⁶. As indicated in Appendix A, these metrics are small compared to “small” ice floe masses and sizes for first-year ice in the Arctic MIZ. Evidently, ice slab lateral extent, particularly depth, needs to be sufficiently large to promote bending and flexure rather than predominantly in-plane response.

⁶ The mass of these slabs does not compute from the cited depth, width, thickness, and assumed ice mass density since a steel “pusher,” labelled as the “rigid boundary” in Figure 7, constituted the outer periphery of the slabs.

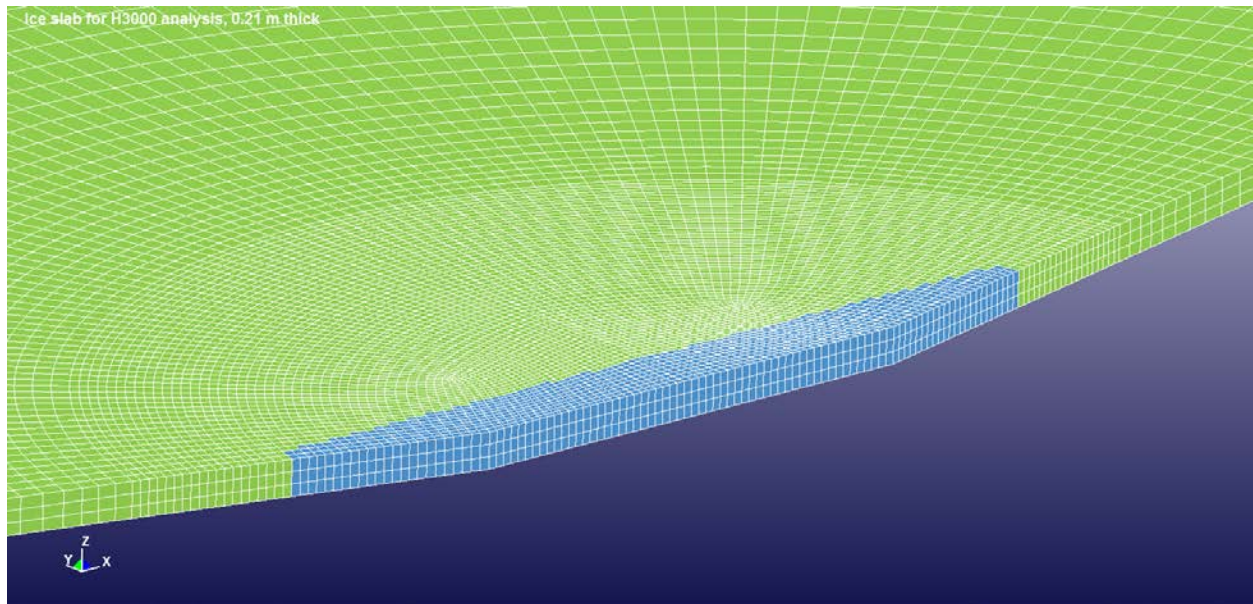


Figure 11. Example of Unsatisfactory LS-DYNA-Computed Ice Slab Failure Using a Crushing Calibration Study Ice FEM

Fortunately, ice slab FEMs of a larger physical extent had been used to good effect in ice edge buckling studies reported by Dolny et al. (2017, section 2.6). These models had been sized to exhibit slab flexure, and a slab with 30-m radius (the “D” dimension in Figure 3) and a 150° edge angle was used (with further mesh refinement) in previous rigid indenter interaction studies (Lesar, 2017). It was natural to use this same slab in the present study concerning interaction with H3000. However, to attain compatibility of ice slab element size with wetted surface shells in the H3000 structural FEM, the ice slab discretization needed further refinement. The new refined mesh, shown in Figure 12, also eliminated wedge-shaped elements in mesh transition zones.



(a) Entire Slab



(b) Local Detail at Crush Zone

Figure 12. FE Mesh of Larger Ice Slab Based on Ice Slab Buckling Studies

4.2 Ice Slab Impact Studies

These studies first considered ice slab impact on an H3000 longitudinal frame between transverse web frames, and later examined impact on an H3000 web frame. In all cases, the structure translated at constant velocity into the ice slab, whose far-field boundary was fully constrained. The buoyancy loading function is active in all analyses. Analyses were conducted

for three ice slab thicknesses for both impact points. For each impact location and ice thickness combination, an LS-DYNA simulation was carried out for four assumptions:

- Frictionless contact, no ice fracture allowed
- Contact with friction, no ice fracture allowed
- Frictionless contact, with ice fracture
- Contact with friction, with ice fracture

Three analysis batches were completed for the longitudinal frame impact scenario:

- Batch A: Structural bulkheads and upper deck not included in the H3000 FEM, stiffness hourglass control
- Batch B: Bulkheads and upper deck included, viscous hourglass control, ice material model in fracture zone made consistent between with-fracture and no-fracture cases
- Batch C: As in batch B, but with ice compressive yield stress in the fracture zone reduced to twice fracture zone tensile yield instead of 10 times higher

Web frame impact analyses used only the assumptions of analysis batch C, which proved to be the best-behaved simulation set.

Thick-shell elements were used for ice slab modeling in all analyses, although parallel analyses with 3D solid elements were carried out for longitudinal frame loading by the thickest ice slab. Intermediate analyses justifying the modeling changes between batch A and batch B were also conducted. Using the web frame impact scenario, a number of additional analysis sets examined effects of three conditions: (1) release of the far-field displacement constraints on the ice slab, (2) faster-velocity loading, and (3) usage of the crushable foam ice crushing material model instead of an elastic-plastic strain-hardening model. Finally, one case of successive impacts by identical slabs at the same impact location was studied for longitudinal frame loading by ice slabs of intermediate thickness.

Over 100 analyses were completed, and documentation of every detailed aspect of each analysis is overwhelming and unnecessary. Consequently, this report will touch only briefly on analysis batches A and B and will most thoroughly address batch C, the additional web frame impact variations listed above, and the one multiple-successive-impact study.

4.2.1 Impact on Longitudinal Stiffener

4.2.1.1 Case H_101

Table 5 lists the times of first ice element deletion, the number of failed ice elements, and the peak ice/structure contact forces reached for the three case H_101 analysis batches. For the frictionless case, there were practically no differences in the peak contact force whether ice fracture occurred or not. The very thin ice slab deflected downward along the hull surface until contact was practically lost. With a 0.10 friction coefficient applied on the contact surface, this downward deflection is retarded and contact is better sustained, allowing considerably higher peak forces that are only slightly relieved when the slab is allowed to fracture.

Table 5. Peak Force and Ice Slab Failure Results for 0.14-m Ice Thickness, Loading on Longitudinal Frame (H_101)

LS-DYNA Run ID	Friction?	Fracture?	Time of First Ice Element Failure ⁺ (s)	Number of Failed Ice Elements (of 23264)	Peak Force (MN)
Batch A	No structural bulkheads or upper deck, stiffness hourglass control				
7458	No	No	N/A	None	0.5799
30785	Yes	No	N/A	None	1.295
36657	No	Yes	0.0847	966	0.5792
37378	Yes	Yes	0.132	1136	0.9721
Batch B	With bulkheads and upper deck, viscous hourglass control, ice material model consistency between fracture/no fracture cases				
16218	No	No	N/A	None	0.5188
16791	Yes	No	N/A	None	1.047
37317	No	Yes	0.0799	893	0.5187
8312	Yes	Yes	0.120	1071	0.8994
Batch C	Compressive ice yield stress in fracture-enabled region 2x tensile yield instead of 10x				
23975	No	No	N/A	None	0.5066
24696	Yes	No	N/A	None	0.8483
25155	No	Yes	0.3363	231	0.5066
25764	Yes	Yes	0.1328	631	0.8378

Note: + "N/A" = Not applicable

Figure 13 provides time histories of ice/structure contact force for all four batch C analyses. The almost complete insensitivity of peak force to allowance of slab fracture and high sensitivity to contact friction is obvious.

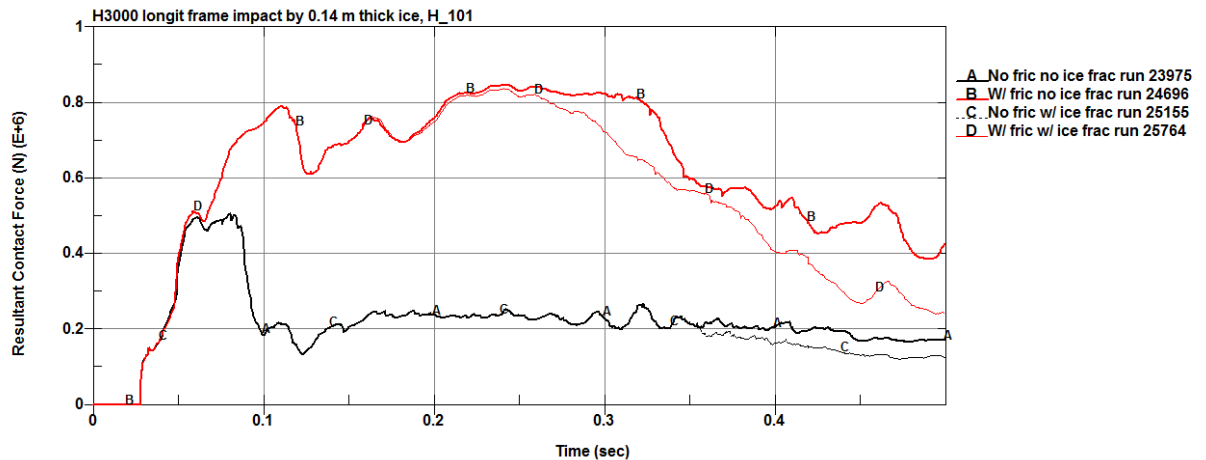
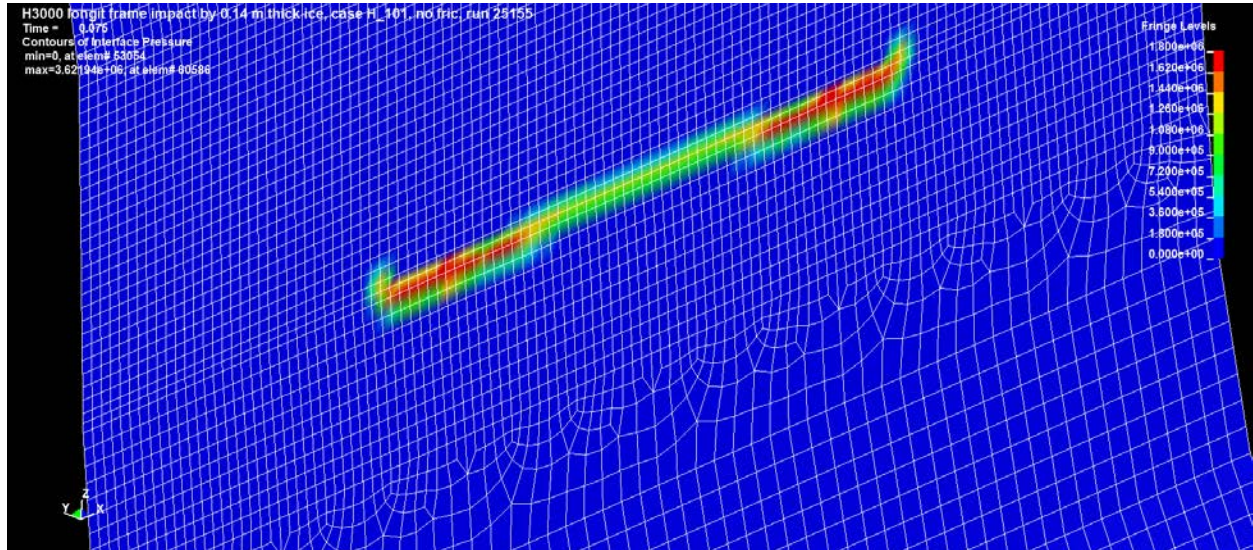
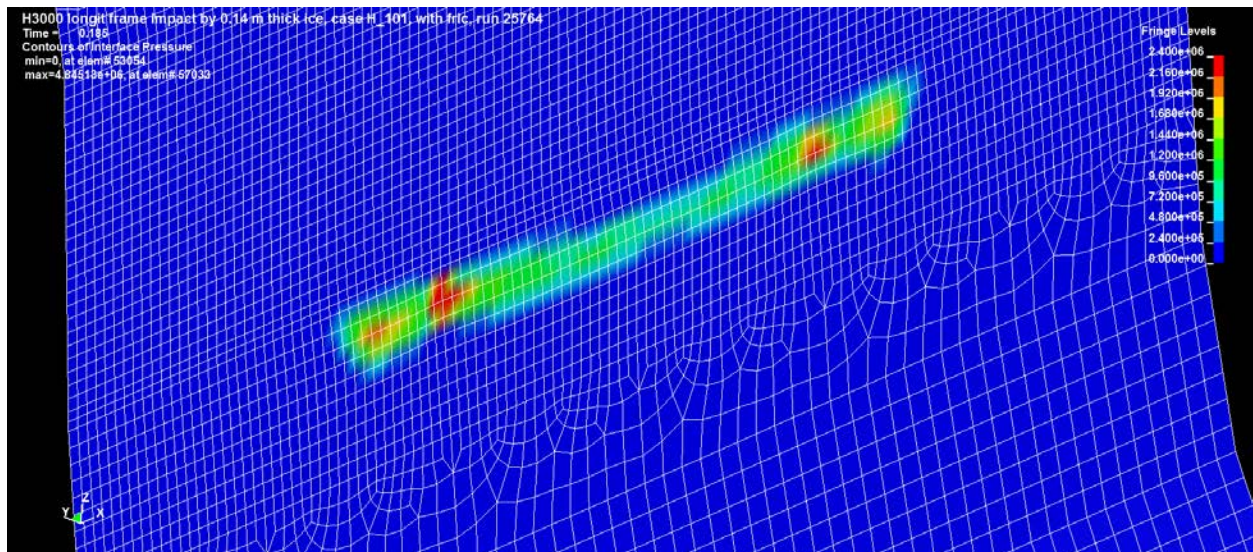
**Figure 13. Ice/Structure Contact Force Time Histories for 0.14-m Ice Thickness, Loading on Longitudinal Frame (H_101)**

Figure 14 contains contour plots of the case H_101 pressure distributions on the hull shell at the times of peak pressures. The uppermost contour limit is specified as about half of the peak

pressure. The first contour is for the frictionless case, and the second is for the case with friction. The nonuniform distribution is the result of pressure localization at the web frames straddling the ice edge. Since contact area changes with time due to ongoing ice slab movement and structural deformation, the times of peak pressure are not necessarily coincident with the times of peak force.



(a) Frictionless Contact

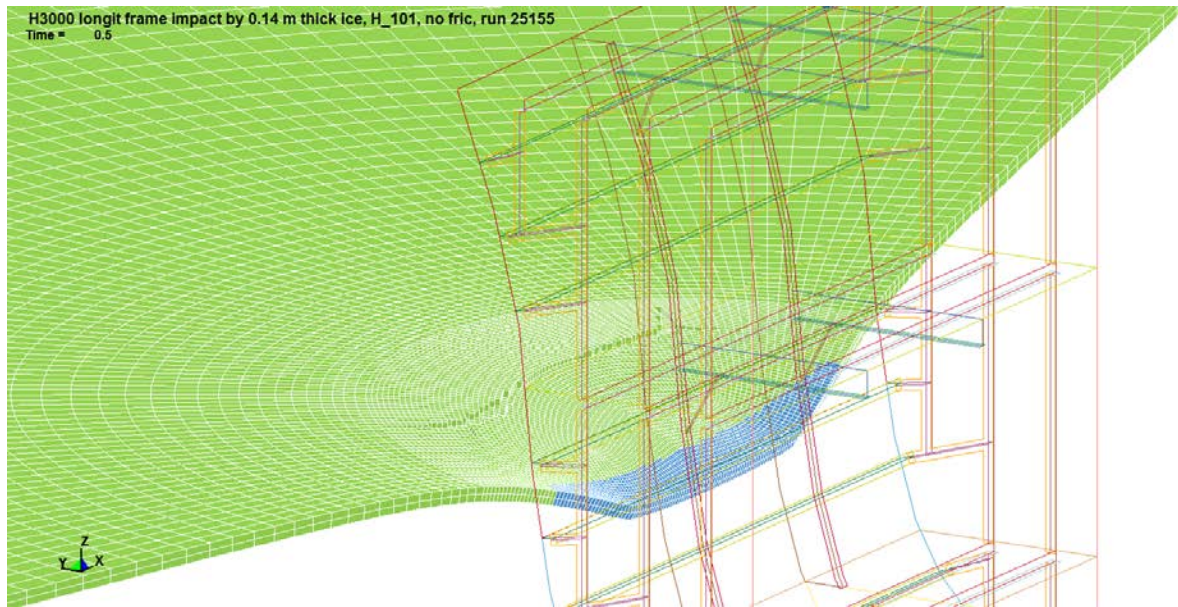


(b) With Contact Surface Friction

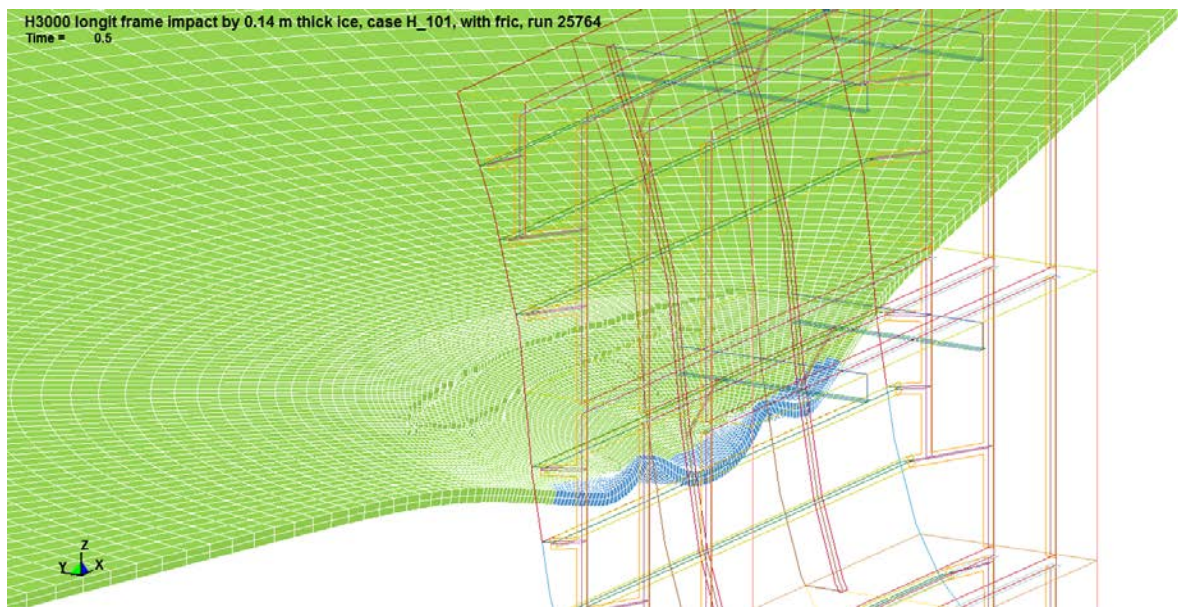
Figure 14. Ice/Structure Contact Pressure Distributions for 0.14-m Ice Thickness, Loading on Longitudinal Frame (H_101)

Figure 15 illustrates the ice slab deflections and crack patterns developed in the final two cases of the batch C runs for case H_101. The first contour is for the frictionless case, and the second is for the case with friction. The partial nature of the circumferential cracks is apparent, with less definite development in the frictionless case. In addition, contact surface friction limits the downward sliding of the ice edge relative to the frictionless assumption, with localized

retardation at the two web frame locations, where contact force (and hence frictional force) is concentrated.



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 15. Ice Slab Deflection and Crack Patterns for 0.14-m Ice Thickness, Loading on Longitudinal Frame (H_101)

Table 6 lists maximum inelastic strains in units of microstrain (strain times 10^6) for the three case H_101 analysis batches. Only the shell plating and the loaded longitudinal frame sustained significant inelastic strains, except for the batch A case with contact friction and ice fracture disallowed. Hourglassing response in one of the deep floors and adjoining lower deck

influenced the strains in the transverse web frame. Hourglassing was reduced in the batch B and C analyses wherein viscous control was used in lieu of stiffness control, and residual structural vibration from time zero motion initiation was better controlled by placing stiff bulkheads and/or decks at FEM extremities. Peak plastic strains generally decrease when superior hourglass control is imposed, and the bulkheads and deck stiffen the structure against vibration triggered by initial motion initiation.

In the frictionless cases, the structure sees virtually no permanent set damage from the 0.14-m-thick slab contact. In the most-technically-acceptable batch C analyses, the occurrence of ice fracture makes very little difference in peak structural strains, which are “small” (order of at most 10^{-3}). Even with greater force on the structure when the contact is not frictionless, the force level exerted by a completely far-field-constrained, 6-long-ton ice slab is too low to impart significant structural damage.

Table 6. Structural Plastic Strain Results[‡] for 0.14-m Ice Thickness, Loading on Longitudinal Frame (H_101)

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Batch A	No structural bulkheads or upper deck, stiffness hourglass control									
7458 (nn)	423.9.	1242	0.0	0.0	215.3.	169.4	0.0	0.0	0.0	0.0
30785 (yn)	80830	99220	6609	6618	17880	14890	70000	70500	13300	18300
36657 (ny)	479.4	968.7	0.0	0.0	220.6	166.8	0.0	0.0	0.0	0.0
37378 (yy)	6719	11000	743.4	1249	3621	3577	0.0	96.0	0.0	155.3
Batch B	With bulkheads and upper deck, viscous hourglass control, ice material model consistency between fracture/no fracture cases									
16218 (nn)	0.0	575.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16791 (yn)	6000	7325	634.3	240.9	3858	2261	0.0	0.0	0.0	0.0
37317 (ny)	0.0	436.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8312 (yy)	3731	7133	634.3	240.9	3856	1990	0.0	0.0	0.0	0.0
Batch C	Compressive ice yield stress in fracture-enabled region 2x tensile yield instead of 10x									
23975 (nn)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24696 (yn)	3641	7286	274.6	137.7	3275	1696	0.0	0.0	0.0	0.0
25155 (ny)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25764 (yy)	3411	7133	274.6	137.7	3275	1696	0.0	0.0	0.0	0.0

Notes:

‡ Maximum inelastic strains in units of microstrain (strain times 10^6)

* Annotations on run ID: (friction (yes/no), fracture (yes/no))

& “Long Web” = Longitudinal Web

+ “Long Flg” = Longitudinal Flange

^ “Tsvse Web” = Transverse Web

% “Tsvse Flg” = Transverse Flange

Peak strains influenced by hourglassing response in nearby structure

Although analysis batches A and B are superseded by the better-behaved batch C simulations, data for batches A and B are included in Table 5 and Table 6 to illustrate that structural load predictions are modestly sensitive, and structural damage predictions are more strongly sensitive to certain modeling assumptions. The sensitivity of structural inelastic strain prediction to effectiveness of hourglass control is evident, as both are mechanisms of (competing) energy dissipation, with hourglassing being a mathematical artifact and inelastic straining being a real physical effect.

4.2.1.2 Case H_102

Table 7 lists the times of first ice element deletion, the number of failed ice elements, and the peak ice/structure contact forces reached for the three case H_102 analysis batches. Forces exerted on the structure are nearly twice as high as for the 0.14-m-thick ice slab. In the most-technically-acceptable batch C analyses, accommodation of ice flexural failure had virtually no effect on peak force when the contact was frictionless. In the nonzero-friction cases, ice slab fracture reduced peak force modestly, though the higher force in the no-fracture case may be an underestimate as it occurred at the end of the timespan of the simulation.

Table 7. Peak Force and Ice Slab Failure Results for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102)

LS-DYNA Run ID	Friction?	Fracture?	Time of First Ice Element Failure* (s)	Number of Failed Ice Elements (of 34896)	Peak Force (MN)
Batch A	No structural bulkheads or upper deck, stiffness hourglass control				
23053	No	No	N/A	None	1.095
43927	Yes	No	N/A	None	1.405
22765	No	Yes	0.0976	4045	0.7941
57233	Yes	Yes	0.2606	1	1.405
Batch B	With bulkheads and upper deck, viscous hourglass control, ice material model consistency between fracture/no fracture cases				
43750	No	No	N/A	None	0.9205
44207	Yes	No	N/A	None	1.970*
6509	No	Yes	0.0944	2911	0.8159
7111	Yes	Yes	0.1317	965	1.960*
Batch C	Compressive ice yield stress in fracture-enabled region 2x tensile yield instead of 10x				
7971	No	No	N/A	None	0.8103
8645	Yes	No	N/A	None	1.891*
9114	No	Yes	0.3561	565	0.8103
14240	Yes	Yes	0.1595	1412	1.776

Notes:

+ "N/A" = Not applicable

* Peak force probably continues to increase after 0.5-s simulation timespan

As with case H_101 analyses, peak contact forces are, at most, modestly sensitive to modeling assumptions between the three analysis batches. Figure 16 provides time histories of ice/structure contact force for all four batch C analyses. Allowance of ice fracture has no effect

on peak load in the frictionless contact case and only modest influence in the variation with nonzero contact friction.

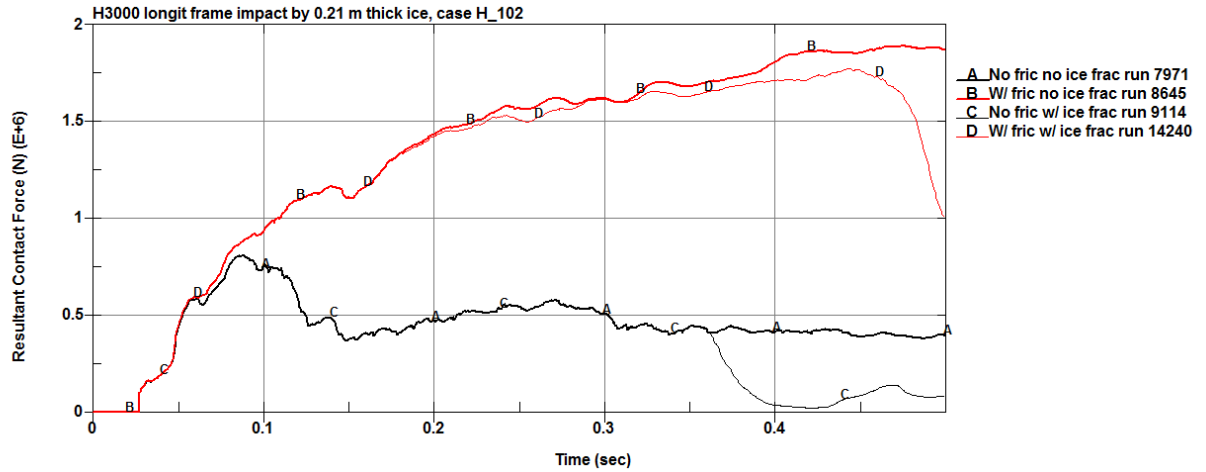
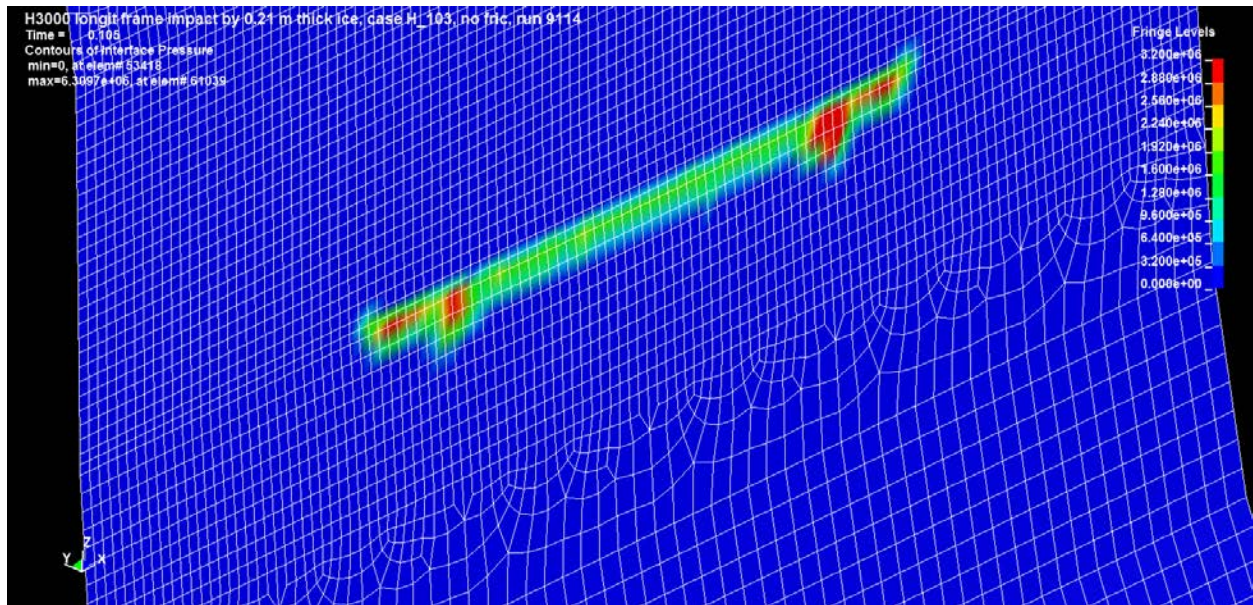
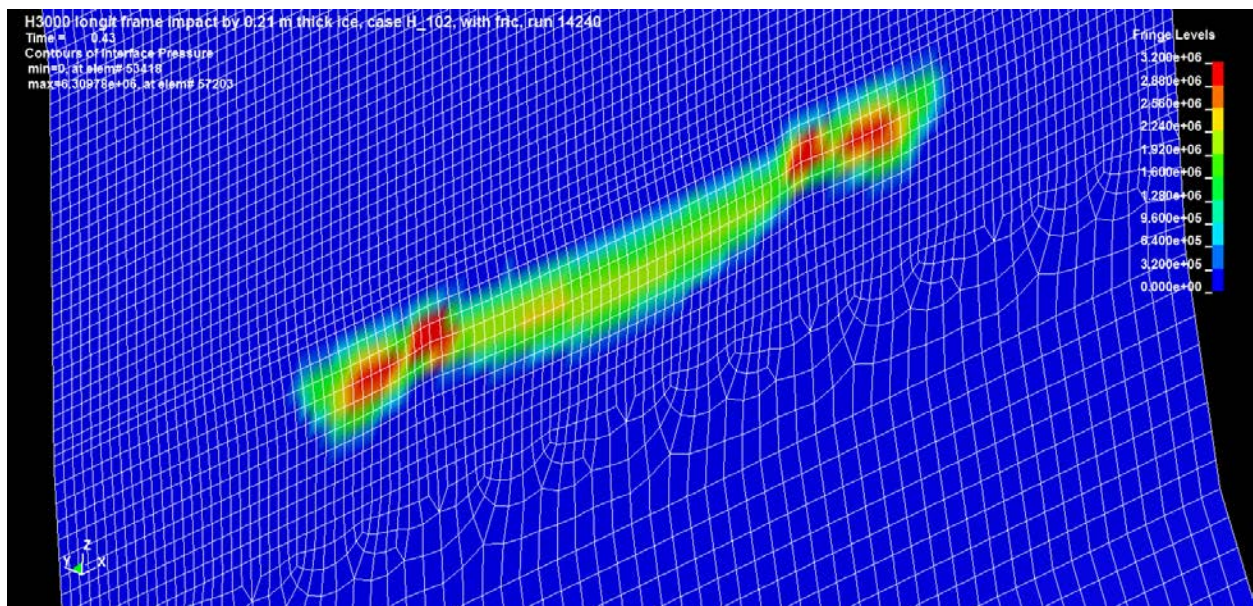


Figure 16. Ice/Structure Contact Force Time Histories for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102)

Figure 17 contains contour plots of the case H_102 pressure distributions on the hull shell at the times of peak pressures. As before, the frictionless case is shown first, followed by the case with contact friction. The uppermost contour limit is specified as about half of the peak pressure. The nonuniform distribution is the result of pressure localization at the web frames straddling the ice edge. Since contact area changes with time due to ongoing ice slab movement and structural deformation, the times of peak pressure are not necessarily coincident with the times of peak force.



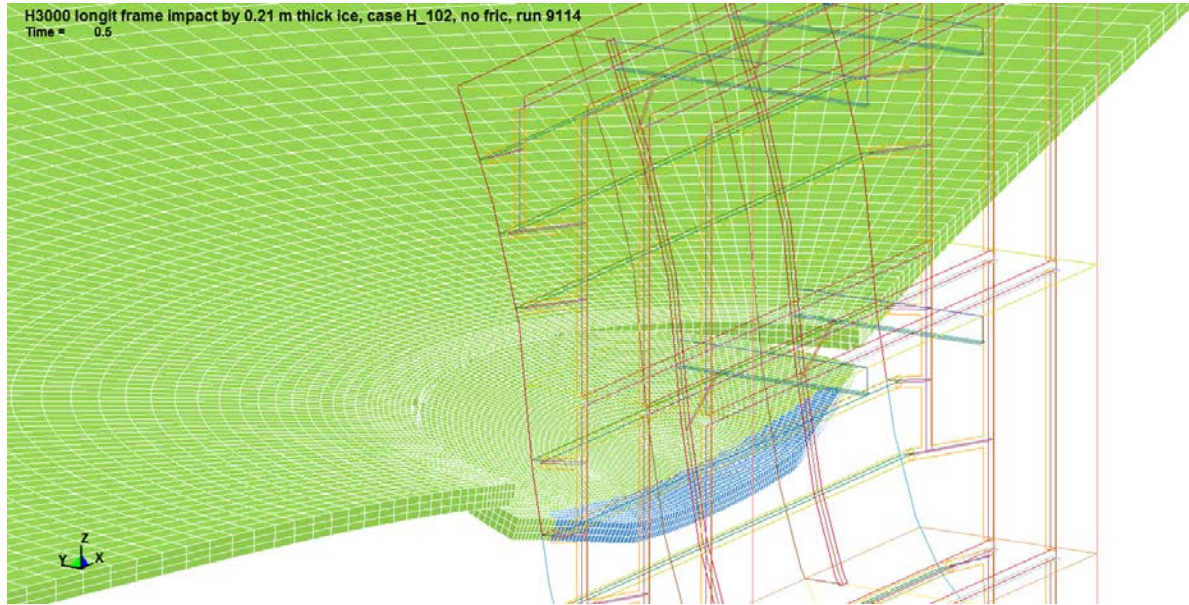
(a) Frictionless Contact



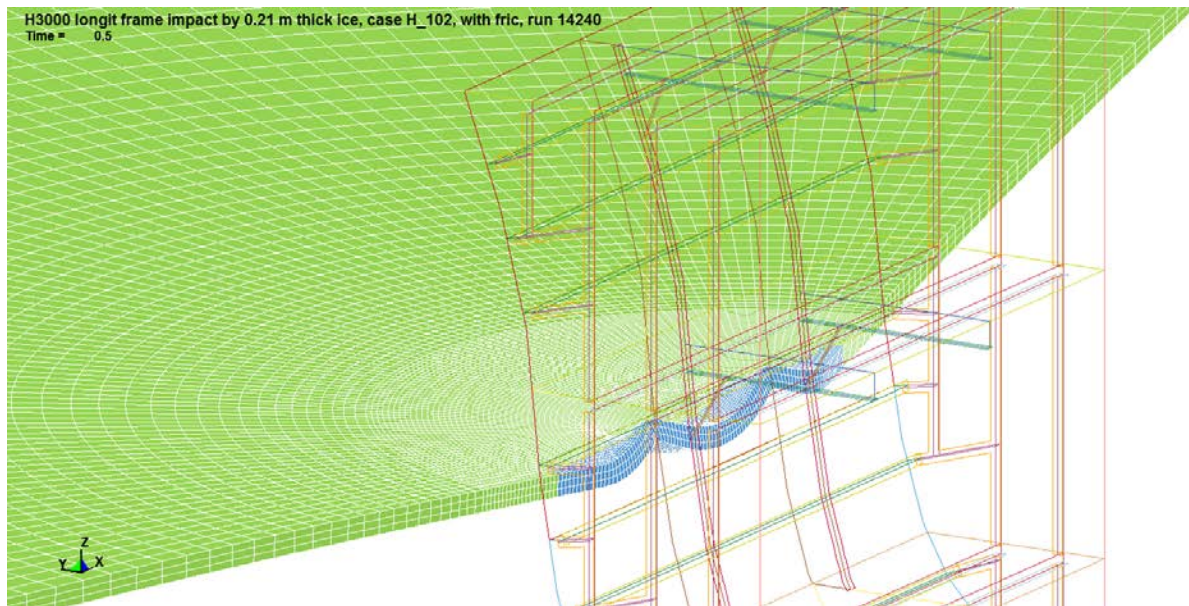
(b) With Contact Surface Friction

Figure 17. Ice/Structure Contact Pressure Distributions for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102)

Figure 18 illustrates the ice slab deflections and crack patterns developed in the final two cases of the batch C runs for H_102. Although fracture of the ice edge feature is well developed and clean in the frictionless contact case, this failure occurred after peak load on the structure had already passed. The crack pattern in the case with contact friction is diffuse failure in the slab behind the (blue-colored) crush zone, principally aligned with the two loaded web frames.



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 18. Ice Slab Deflection and Crack Patterns for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102)

Table 8 lists the maximum inelastic strains in units of microstrain (strain times 10^6) for the three case H_102 analysis batches. As in case H_101, peak plastic strains decreased, sometimes drastically, when hourglassing was better controlled and structural vibration triggered by motion initiation was reduced. As with the lower ice slab thickness, nonzero friction on the contact surface has a large impact on plastic strains in the structure, greatly increasing them over the frictionless contact case.

In the frictionless cases, the structure sees more permanent set damage in the 0.21-m-thick slab contact compared with the 0.14-m-thick slab contact, but peak effective plastic strains are

still relatively low (at most 10^{-1} or 10^5 microstrain). Again, plastic strains increase dramatically with nonzero ice/structure friction. In the most-technically-acceptable batch C analyses, the occurrence of ice fracture reduces peak plastic strains attained, especially in the side shell and the transverse frame webs.

Table 8. Structural Plastic Strain Results[‡] for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102)

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Batch A	No structural bulkheads or upper deck, stiffness hourglass control									
23053 (nn)	4004	8584	24820	19870	21950	12590	6728	6690	2098	2766
43927 (yn)	90280	115200	11450	11460	22480	17600	107600	106800	42910	50450
22765 (ny)	3129	5394	159.2	959.1	2685	1771	3126	3123	0.0	926.3
57233 (yy)	90270	115200	114400	114600	22510	17610	107600	106900	42920	50460
Batch B	With bulkheads and upper deck, viscous hourglass control, ice material model consistency between fracture/no fracture cases									
43750 (nn)	2700	6091	11480	10430	12550	7583	299.1	295.7	0.0	0.0
44207 (yn)	41710	67860	19740	22450	44730	30020	171200	162400	20820	20410
6509 (ny)	2264	4925	773.9	824.3	355.9	2193	0.0	0.0	0.0	0.0
7111 (yy)	41780	68520	18340	20660	40350	26590	134200	143300	20510	19600
Batch C	Compressive ice yield stress in fracture-enabled region 2x tensile yield instead of 10x									
7971 (nn)	1492	3007	316.2	95.81	2464	1306	0.0	0.0	0.0	0.0
8645 (yn)	21640	39380	11120	14030	20270	14130	18070	15590	101.6	655.9
9114 (ny)	1492	3007	316.2	95.81	2464	1306	0.0	0.0	0.0	0.0
14240 (yy)	15510	28820	10470	12390	18750	13530	5409	4999	0.0	154.2

Notes:

[‡] Maximum inelastic strains in units of microstrain (strain times 10^6)

* Annotations on run ID: (friction (yes/no), fracture (yes/no))

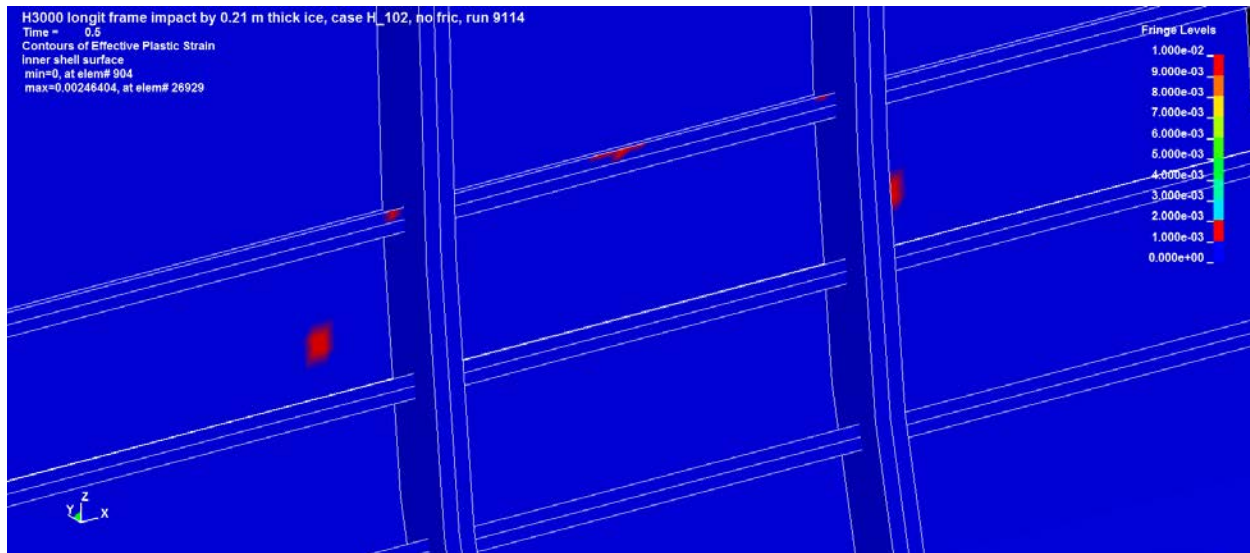
& "Long Web" = Longitudinal Web

+ "Long Flg" = Longitudinal Flange

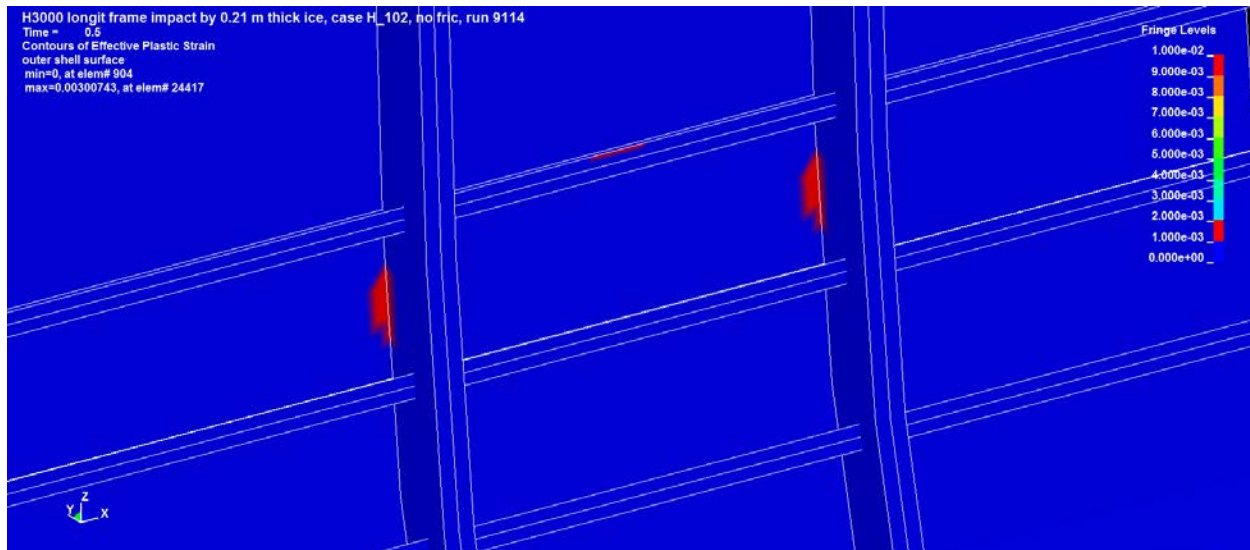
[^] "Tsvse Web" = Transverse Web

[%] "Tsvse Flg" = Transverse Flange

Figure 19 contains plastic strain contours in H3000 structure for the batch C simulations with and without friction, all with ice fracture allowed. The frictionless case appears first, with separate pictures for inner and outer shell surfaces. All strain contours are capped at 1 %. The greater permanent set suffered in the case with nonzero contact friction relative to the frictionless cases is obvious.

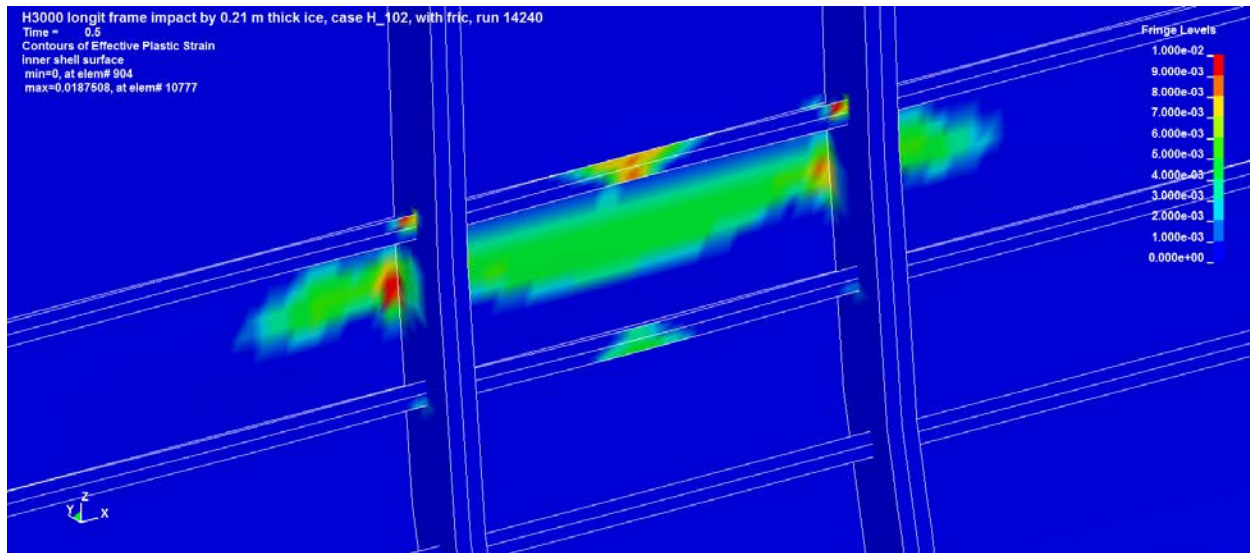


(a) Frictionless Contact, Inner Shell Surfaces

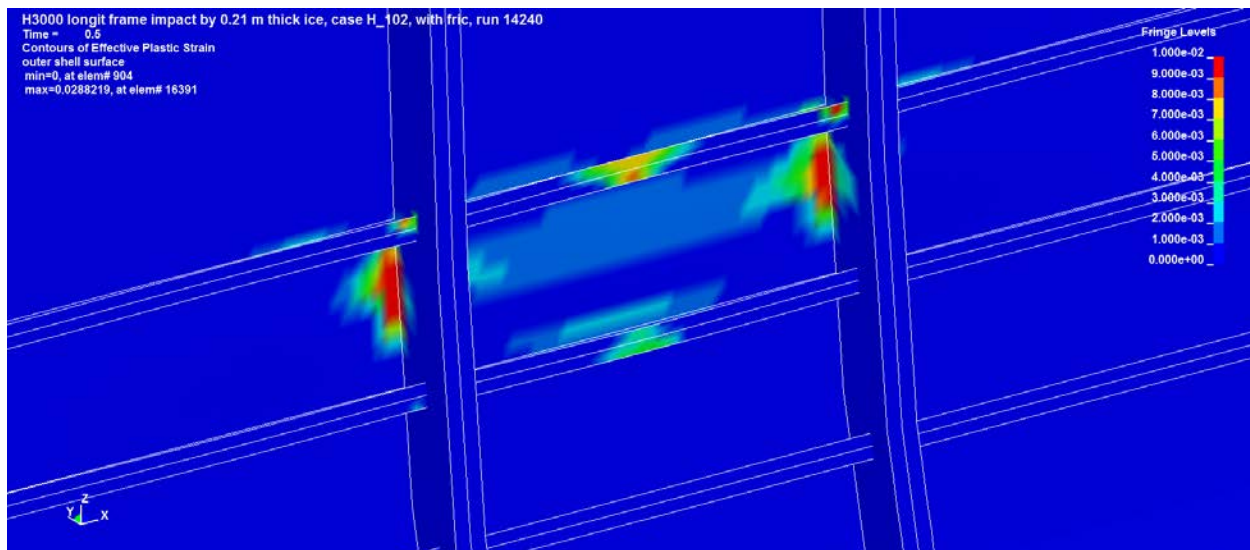


(b) Frictionless Contact, Outer Shell Surfaces

Figure 19. Plastic Strain Contours for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102)



(c) With Contact Surface Friction, Inner Shell Surfaces



(d) With Contact Surface Friction, Outer Shell Surfaces

Figure 19. Plastic Strain Contours for 0.21-m Ice Thickness, Loading on Longitudinal Frame (H_102) (cont'd)

4.2.1.3 Case H_103

Table 9 lists the times of first ice element deletion, the number of failed ice elements, and the peak ice/structure contact forces reached for the three case H_103 analysis batches. Peak forces are, of course, higher than for the 0.21-m-thick slab of case H_102, with, as before, higher forces when contact friction is allowed. In contrast to case H_102, allowance of slab fracture in the frictionless case, even though the failure is extensive, does not reduce peak load significantly. When contact is not frictionless, hardly any fracture occurs in the timespan of the simulation. It appears that with the 0.35-m-thick slab and the shallow inclination angle of the structure, the slab is too thick to sustain flexural deformation sufficient to trigger fracture before the structure has been highly loaded, especially when contact friction is nonzero.

Table 9. Peak Force and Ice Slab Failure Results for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103)

LS-DYNA Run ID	Friction?	Fracture?	Time of First Ice Element Failure* (s)	Number of Failed Ice Elements (of 58160)	Peak Force (MN)
Batch A	No structural bulkheads or upper deck, stiffness hourglass control				
52148	No	No	N/A	None	1.4364
52625	Yes	No	N/A	None	1.5749
42920	No	Yes	0.1374	858	1.5763
52808	Yes	Yes	N/A	None	1.5889
Batch B	With bulkheads and upper deck, viscous hourglass control, ice material model consistency between fracture/no fracture cases				
17635	No	No	N/A	None	2.222
37565	Yes	No	N/A	None	2.172
38090	No	Yes	0.1133	5888	1.581
38548	Yes	Yes	0.2322	53	2.176
Batch C	Compressive ice yield stress in fracture-enabled region 2x tensile yield instead of 10x				
53949	No	No	N/A	None	1.722
54734	Yes	No	N/A	None	2.157
55197	No	Yes	0.1151	3597	1.628
55773	Yes	Yes	0.2432	17	2.164

Note: + "N/A" = Not applicable

As with case H_101 and H_102 analyses, peak contact forces are modestly sensitive to modeling assumptions between the three analysis batches. Figure 20 provides time histories of ice/structure contact force for all four batch C analyses. As with lower ice thicknesses, occurrence of ice fracture has little peak force influence in the frictionless case and none at all when contact friction is nonzero. The differences between the zero- and nonzero-friction cases are less than before, as the thicker ice's greater flexural rigidity retards its ability to slide along the contact surface.

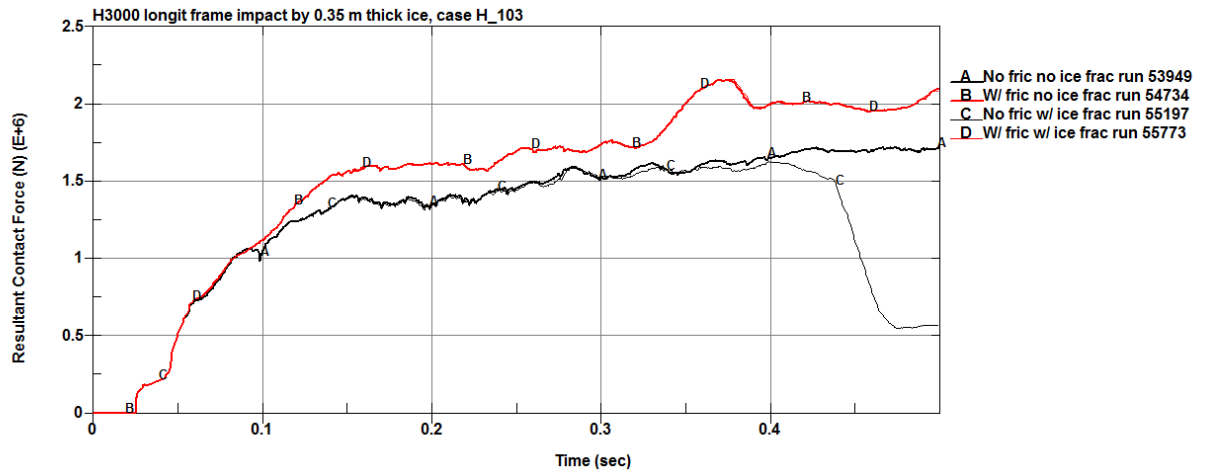
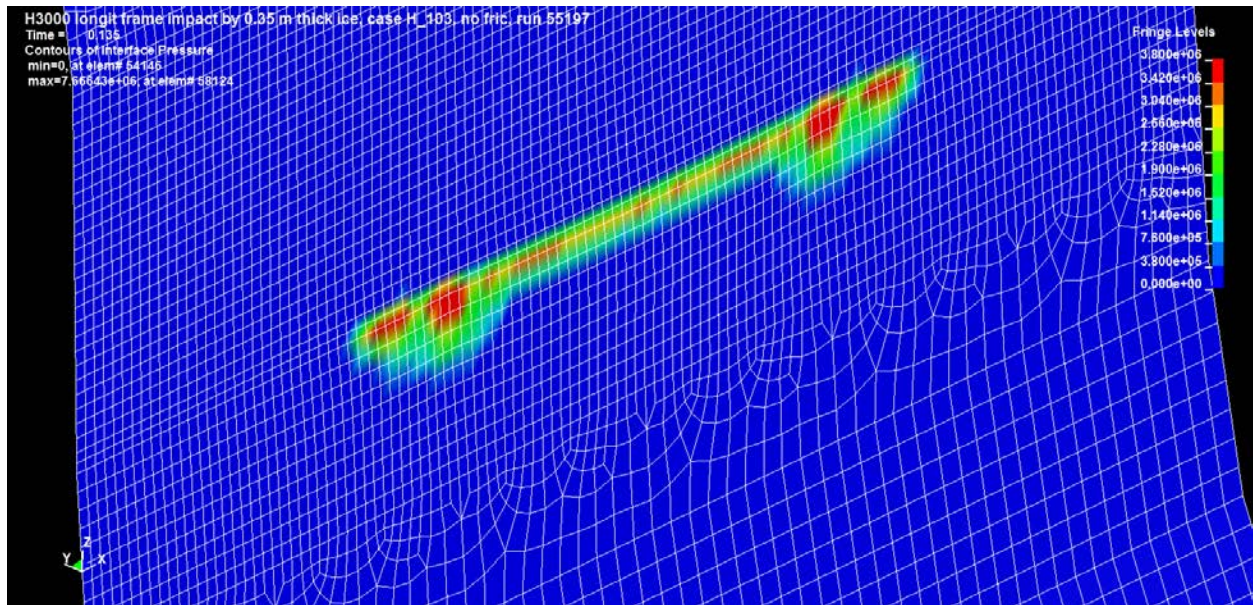
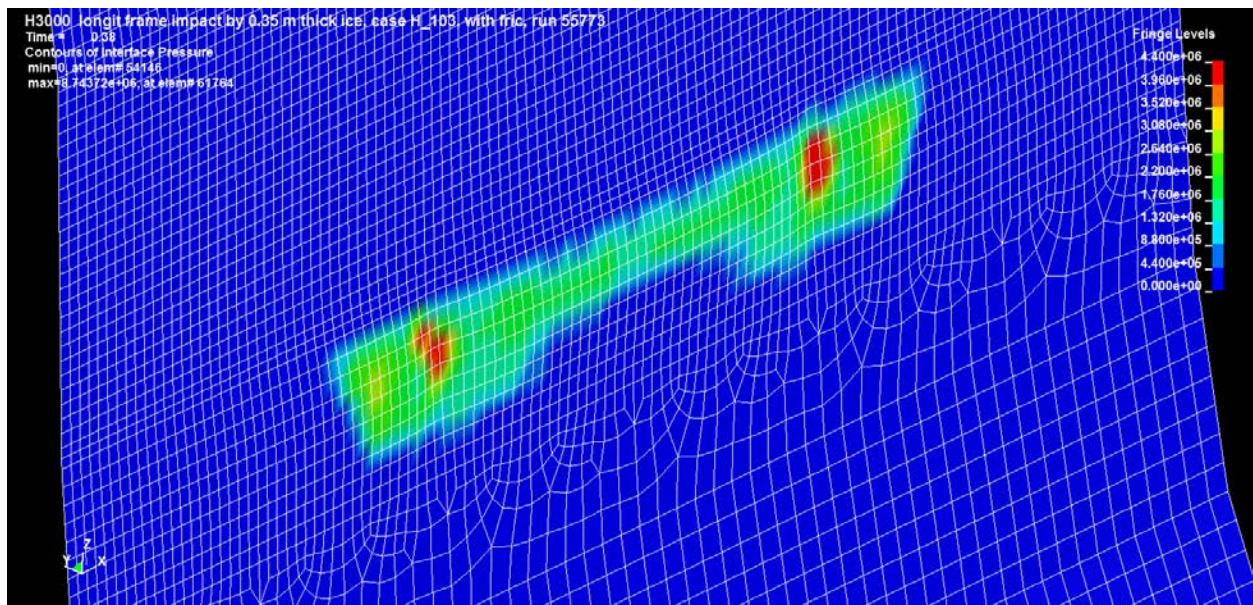


Figure 20. Ice/Structure Contact Force Time Histories for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103)

Figure 21 contains contour plots of the case H_103 pressure distributions on the hull shell at the times of peak pressures, with the frictionless case shown first and the case with friction shown second. The uppermost contour limit is specified as about half of the peak pressure. Again, pressures are strongly nonuniform, and time of peak pressure is not coincident with time of peak force.



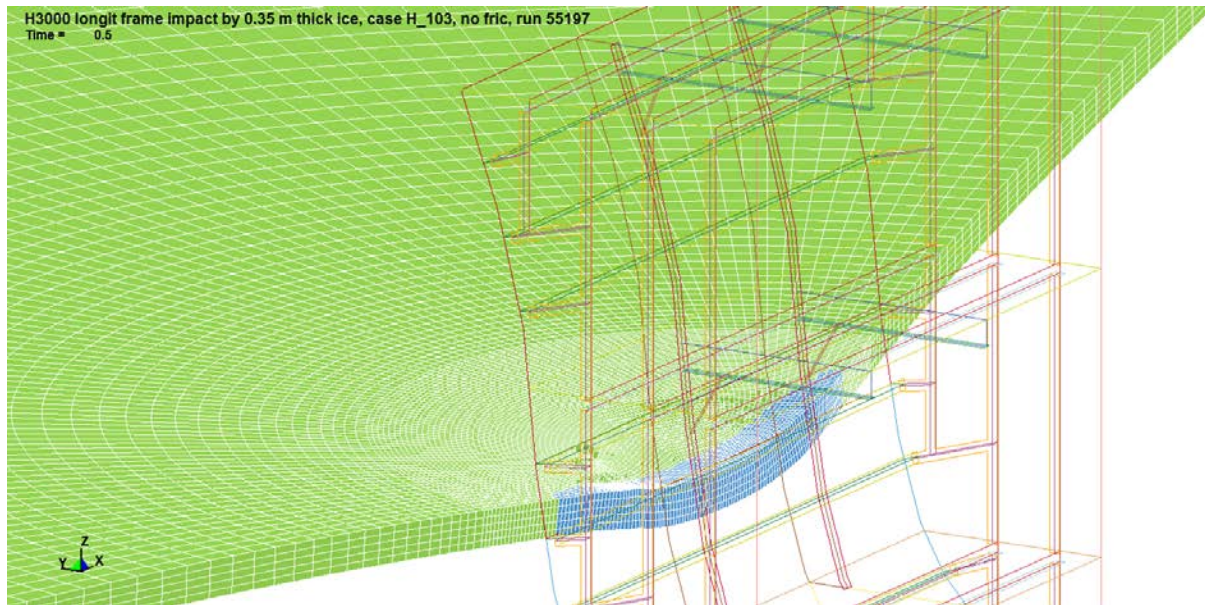
(a) Frictionless Contact Surface



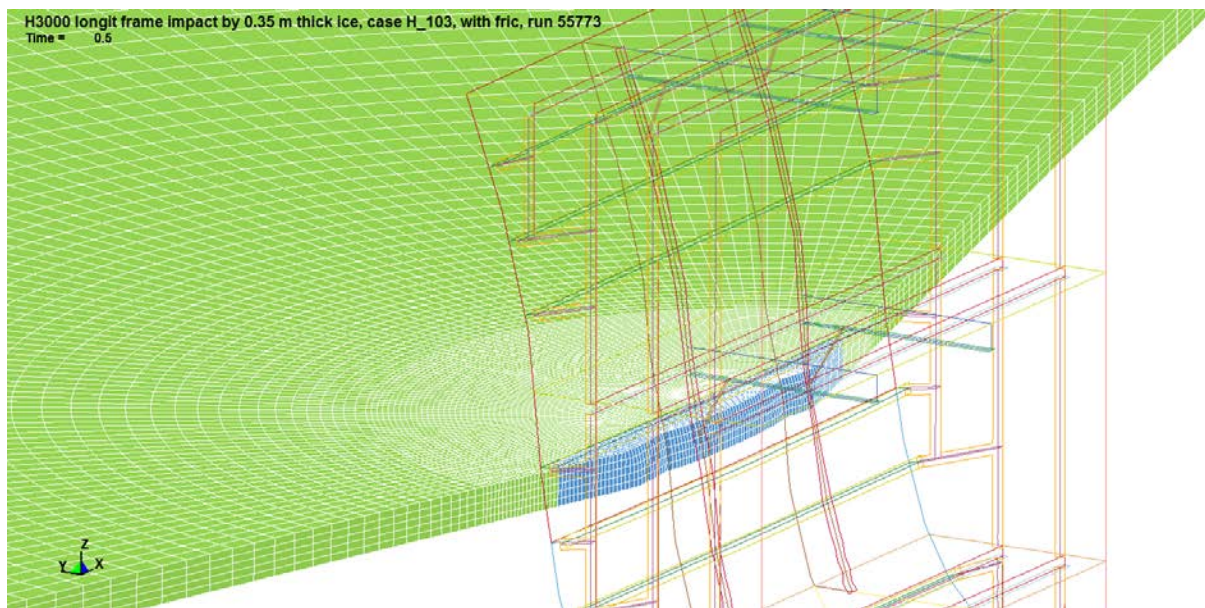
(b) With Contact Surface Friction

Figure 21. Ice/Structure Contact Pressure Distributions for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103)

Figure 22 illustrates the ice slab deflections and crack patterns developed in the final two cases of the batch C runs for H_103. In the frictionless case, ice elements are deleted in diffuse fashion near the crushing-ice-zone boundary, and there is hint of circumferential crack development. Downward sliding of the ice edge along the slanted structural interface is notably less than for the thinner ice slabs. When contact surface friction is nonzero, there is virtually no fracture, and the slab barely deflects out of plane.



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 22. Ice Slab Deflection and Crack Patterns for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103)

Table 10 lists the maximum inelastic strains in units of microstrain (strain times 10^6) for the three case H_103 analysis batches. Peak values are effectively insensitive to whether ice slab fracture is allowed. Interestingly, peak strains are not uniformly higher for the nonzero-contact-friction case versus the frictionless case. This may be attributable to the low level of slab flexure lessening the influence of vertical sliding on the contact interface compared to thinner-slab cases H_101 and H_102.

Table 10. Structural Plastic Strain Results[‡] for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103)

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Batch A	No structural bulkheads or upper deck, stiffness hourglass control									
52148 (nn)	9229	19770	44200	36400	35670	21200	6973	6506	3331	2749
52625 (yn)	68520	95340	16650	18980	26950	18780	73670	73830	77860	92050
42920 (ny)	39650	76230	17620	20380	41920	26570	91320	95630	14890	15810
52808 (yy)	71630	100100	19680	21940	26420	17680	80550	84210	65490	79680
Batch B	With bulkheads and upper deck, viscous hourglass control, ice material model consistency between fracture/no fracture cases									
17635 (nn)	16180	33130	66510	49550	42300	27920	64390	62450	1351	2410
37565 (yn)	20820	46940	44050	47390	44900	39180	184800	183000	22690	21890
38090 (ny)	9231	27460	22500	25680	24510	15970	4028	3623	0.0	0.0
38548 (yy)	21000	46740	44050	47390	44830	39030	184300	183600	22750	21560
Batch C	Compressive ice yield stress in fracture-enabled region 2x tensile yield instead of 10x									
53949 (nn)	7621	20720	65970	57690	42890	25440	3977	3841	0.0	0.0
54734 (yn)	20870	46790	43930	47300	44590	39430	182000	180300	23180	21850
55197 (ny)	7364	20970	64570	53620	43630	26240	3853	3496	0.0	0.0
55773 (yy)	20730	47340	43930	47300	44450	39130	181300	180600	23120	21860

Notes:

‡ Maximum inelastic strains in units of microstrain (strain times 10⁶)

* Annotations on run ID: (friction (yes/no), fracture (yes/no))

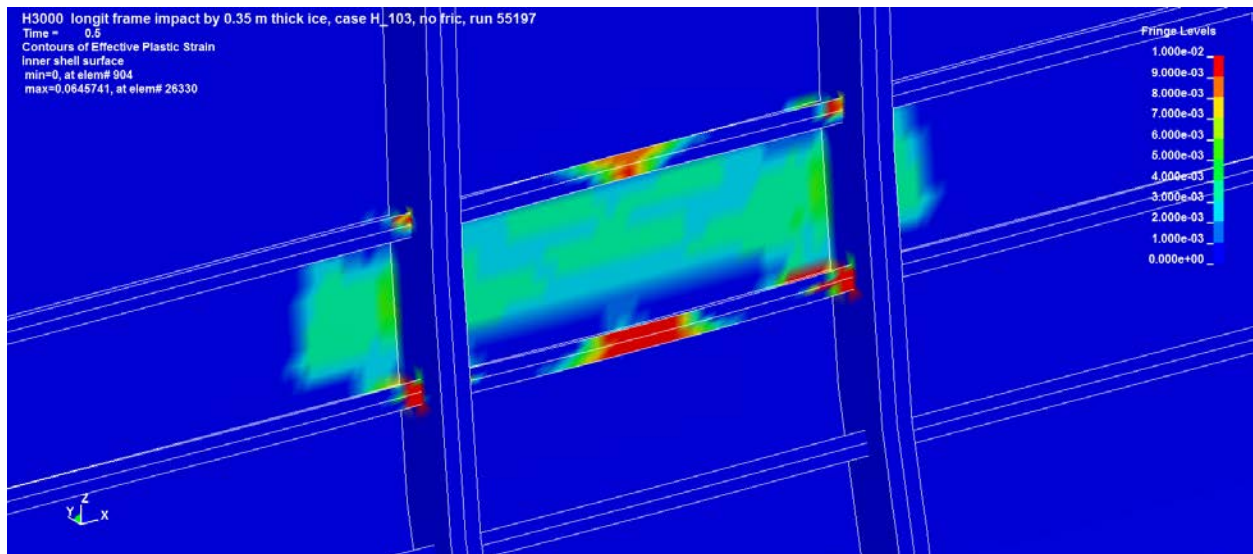
& "Long Web" = Longitudinal Web

+ "Long Flg" = Longitudinal Flange

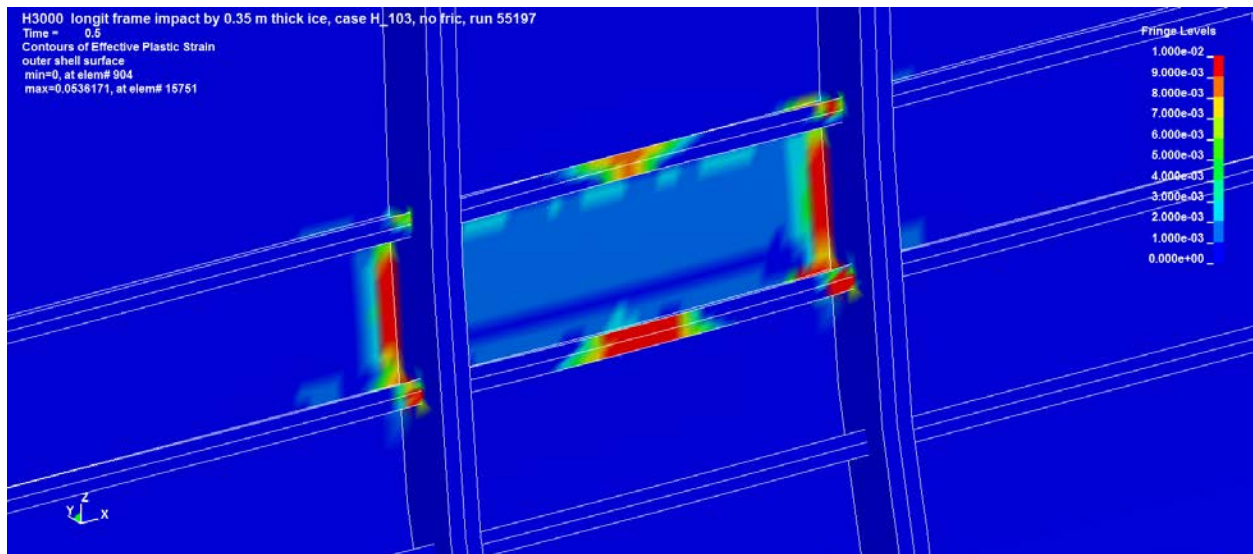
^ "Tsvse Web" = Transverse Web

% "Tsvse Flg" = Transverse Flange

Figure 23 contains plastic strain contours in H3000 structure for the batch C simulations with and without friction, all with ice fracture allowed. The frictionless case appears first, with separate pictures for inner and outer shell surfaces. All strain contours are capped at 1 %. The greater permanent set suffered in the case with nonzero contact friction compared with the frictionless case is obvious. Damage in case H_103 is also visibly greater than in case H_102. In the case of contact with nonzero friction, tripping deformations of the web frames and longitudinal stiffeners is clearly visible.

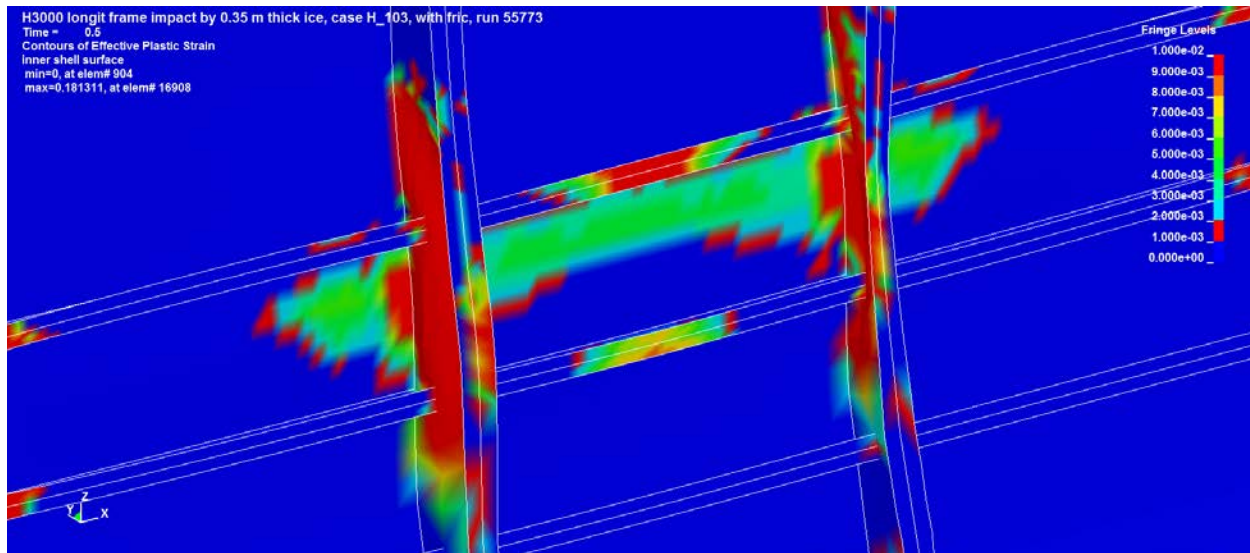


(a) Frictionless Contact, Inner Shell Surfaces

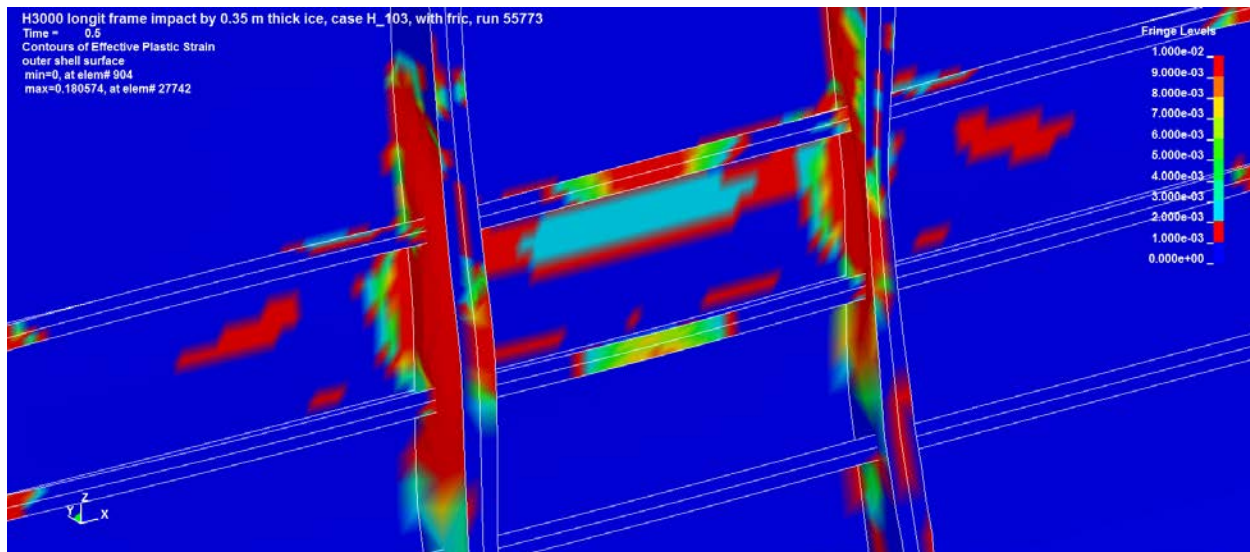


(b) Frictionless Contact, Outer Shell Surfaces

Figure 23. Plastic Strain Contours for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103)



(c) With Contact Surface Friction, Inner Shell Surfaces



(d) With Contact Surface Friction, Outer Shell Surfaces

Figure 23. Plastic Strain Contours for 0.35-m Ice Thickness, Loading on Longitudinal Frame (H_103) (cont'd)

Modeling of the 0.35-m-thick ice slab with LS-DYNA's single integration point 3D solid elements was attempted. In this variation, there was no change to input data except conversion of all thick-shell elements in the ice slab parts to 3D solid elements with a corresponding necessary "section" definition alteration. The eight cases of batches A and B of case H_103 were rerun in this fashion. With ice slab fracture disallowed, peak collision forces were slightly higher with the 3D elements, and peak inelastic strains in the H3000 structure were different but generally similar. However, with ice slab fracture allowed, the behavior of the slabs was completely unsatisfactory in the 3D solid versions; ice failure was comprehensive and premature, with a huge portion of the slab "deleted" before any meaningful load level was attained. This pathology can be blamed on the inadequate number of integration points through the ice slab thickness, which in the thick-shell model is greater than in the 3D solid model by a factor of five. Three-

dimensional solid modeling was not considered worthwhile of exploration for the lower two slab thicknesses, given the low number of through-thickness elements already present, and was not necessary for maintenance of reasonable element aspect ratios.

4.2.1.4 Comparisons as Function of Ice Thickness

An alternative presentation of the above data as a function of ice thickness is useful for recognizing trends. In addition to peak force and element failure data included in previous tables, Table 11 also contains times of peak collision force and times at which peak inelastic strain developed at the highest-strain component and shell surface in the H3000 FEM. Comparison of the data in blocks A and C for frictionless cases shows that ice fracture, when allowed, occurs much later than the contact force peak and has negligible effect for the two lower slab thicknesses. The earlier occurrence of ice fracture in the 0.35-m-thick scenario allows a small decrease in peak load. Comparison of the data in blocks B and D for nonzero-friction cases shows that when ice fracture is allowed, only the responses for the intermediate 0.21-m thickness are impacted, and the decrease in peak load is modest.

Table 11. Peak Force and Ice Slab Failure Results for Three Ice Thicknesses, Loading on Longitudinal Frame

LS-DYNA Run ID	Case ID	Ice Thickness (m)	Time of First Ice Element Failure ⁺ (s)	Number of Failed Ice Elements	Peak Force (MN)	Time of Peak Force (s)	Time of Peak Plastic Strain ⁺ (s)
A	No contact friction, no fracture						
23975	H_101	0.14	N/A	None	0.5066	0.0805	N/A
7971	H_102	0.21	N/A	None	0.8103	0.0855	0.225
53949	H_103	0.35	N/A	None	1.722*	0.5*	0.5*
B	With contact friction, no fracture						
24696	H_101	0.14	N/A	None	0.8483	0.241	0.49
8645	H_102	0.21	N/A	None	1.891*	0.5*	0.5*
54734	H_103	0.35	N/A	None	2.157	0.369 to 0.375	0.5*
C	No contact friction, with fracture						
25155	H_101	0.14	0.3363	231	0.5066	0.0805	N/A
9114	H_102	0.21	0.3561	565	0.8103	0.0855	0.225
55197	H_103	0.35	0.1151	3597	1.628	0.399	0.415
D	With contact friction, with fracture						
25764	H_101	0.14	0.1328	631	0.8378	0.241	0.45
14240	H_102	0.21	0.1595	1412	1.776	0.44	0.45
55773	H_103	0.35	0.2432	17	2.164	0.376	0.5*

Notes:

* Peak value occurs at end of simulation time.

+ "N/A" = Not applicable

4.2.2 Impact on Web Frame

For these load cases, simulations were carried out only for batch C modeling assumptions, as their superiority over batch A and B assumptions was already established.

4.2.2.1 Case H₁₀₆

Table 12 lists the times of first ice element deletion, the number of failed ice elements, and the peak ice/structure contact forces reached for case H₁₀₆. Inclusion of contact surface friction somewhat hastens ice slab fracture, but occurrence of fracture has no impact on peak force.

Table 12. Peak Force and Ice Slab Failure Results for 0.14-m Ice Thickness, Loading on Transverse Web Frame (H₁₀₆)

LS-DYNA Run ID	Friction?	Fracture?	Time of First Ice Element Failure (s)	Number of Failed Ice Elements (of 23264)	Peak Force (MN)
11264	No	No	N/A	None	0.4859
11868	Yes	No	N/A	None	0.7470
12640	No	Yes	0.2951	293	0.4859
13169	Yes	Yes	0.1274	401	0.7470

Figure 24 provides time histories of ice/structure contact force for case H₁₀₆ analyses. As with impact on a longitudinal frame, inclusion of ice slab fracture made practically no difference compared with fracture preclusion.

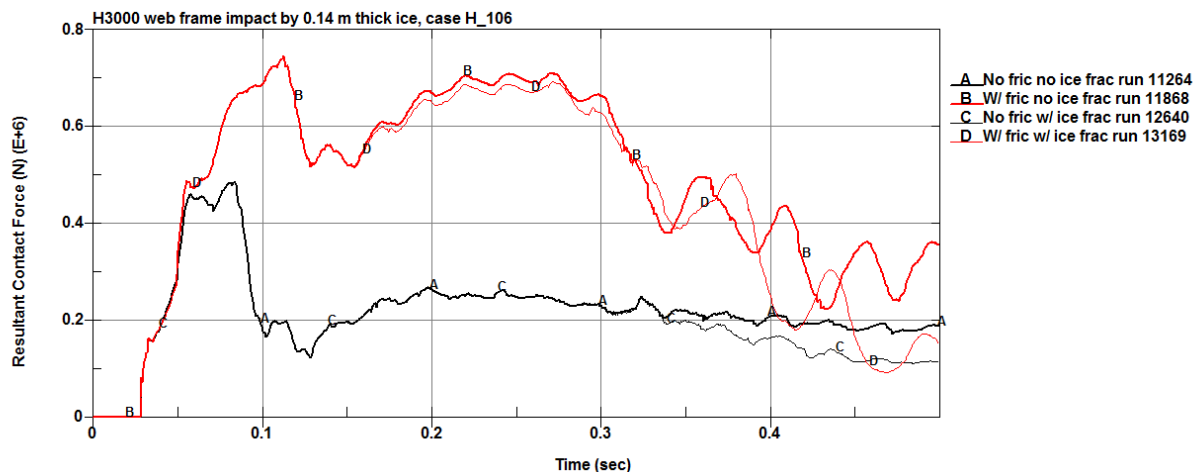
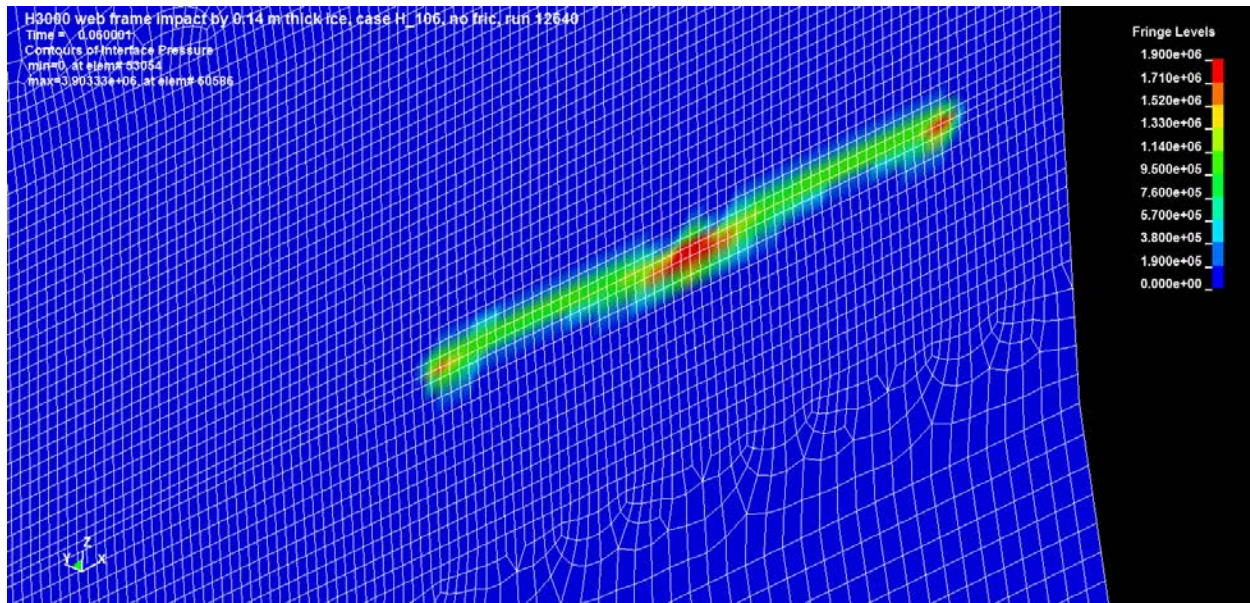
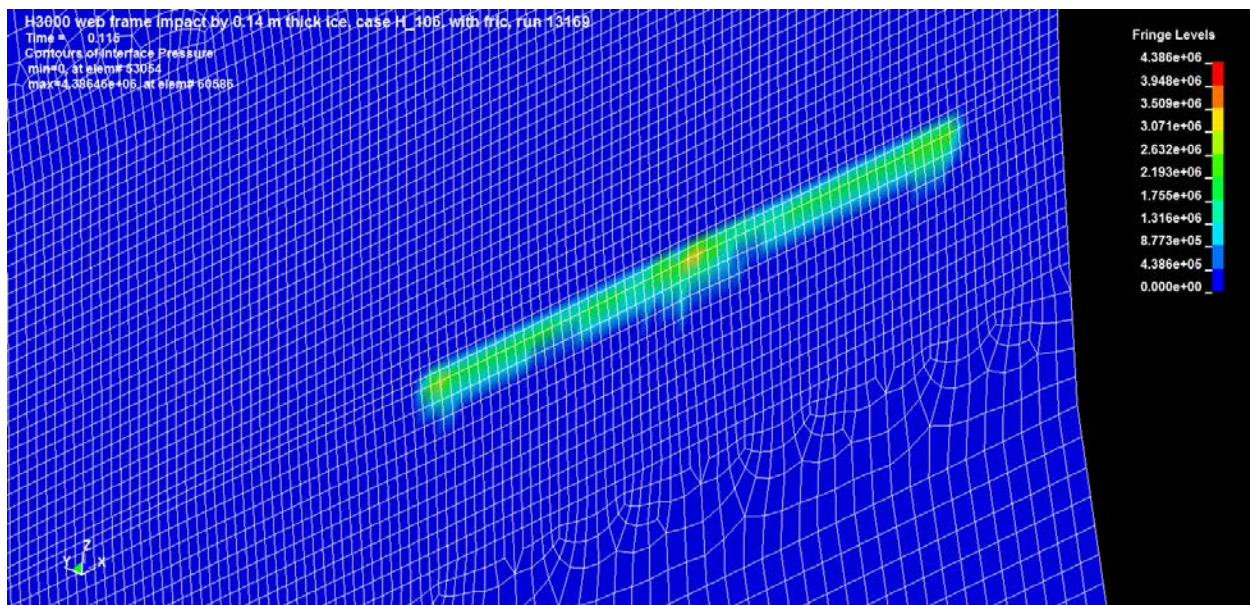


Figure 24. Ice/Structure Contact Force Time Histories for 0.14-m Ice Thickness, Loading on Transverse Web Frame (H₁₀₆)

Figure 25 contains contour plots of the case H₁₀₆ pressure distributions on the hull shell at the times of peak pressures. The uppermost contour limit is specified as about half of the peak pressure. As with longitudinal frame impact, pressures are strongly nonuniform, and time of peak pressure is not coincident with time of peak force. Pressure is concentrated at the location of the one directly loaded web frame, although there are secondary pressure concentrations at the fore and aft edges of the contact area.



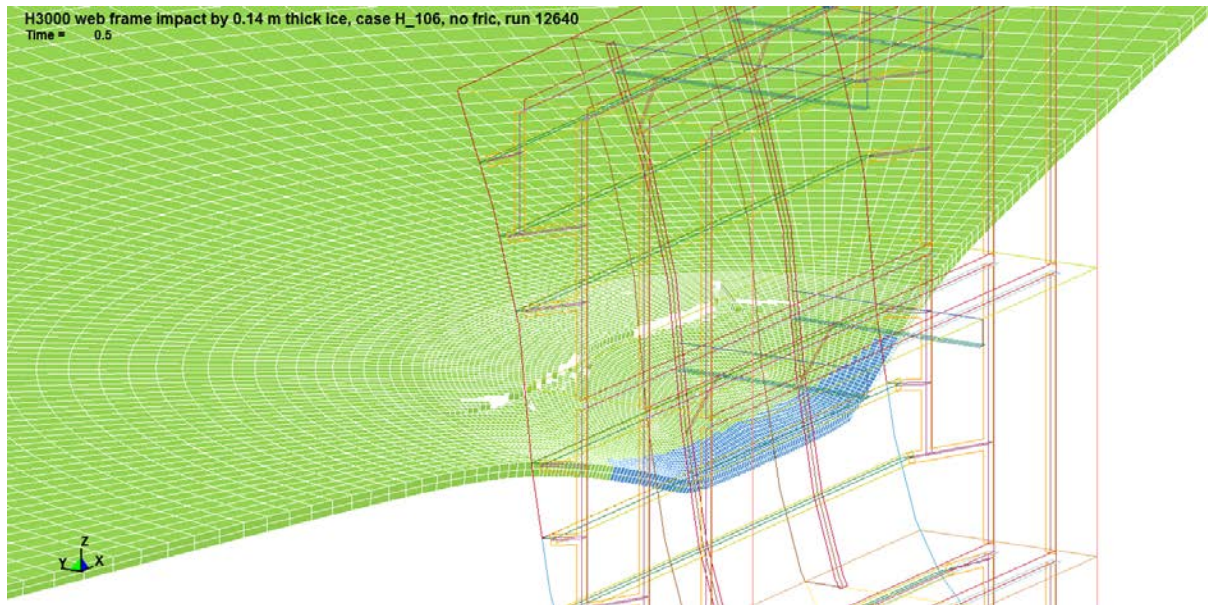
(a) Frictionless Contact



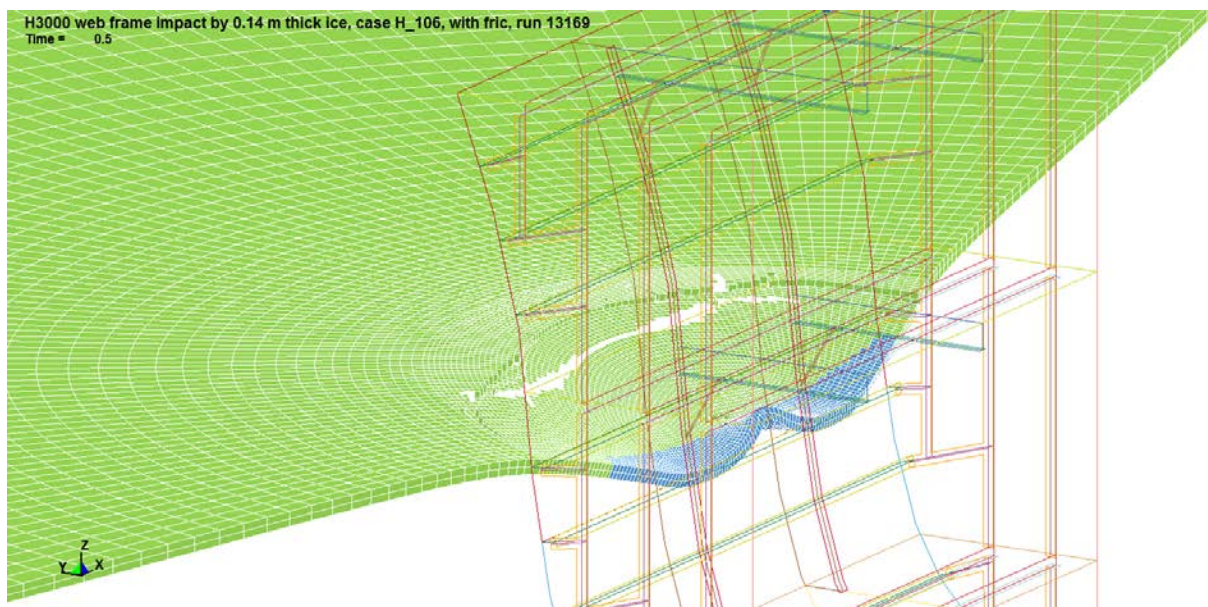
(b) With Contact Surface Friction

Figure 25. Ice/Structure Contact Pressure Distributions for 0.14-m Ice Thickness, Loading on Transverse Web Frame (H₁₀₆)

Figure 26 illustrates the ice slab deflections and crack patterns developed in case H₁₀₆. Slab deflection and crack development trends are very similar to those seen in case H₁₀₁ (see Figure 12). In the nonzero-friction case, as compared to the contact-friction case, the greater frictional grip between slab edge and hull shell is present at the one loaded web frame location.



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 26. Ice Slab Deflection and Crack Patterns for 0.14-m Ice Thickness, Loading on Transverse Web Frame (H_106)

Table 13 lists maximum inelastic strains in units of microstrain (strain times 10^6) for the case H_106 analyses.

Table 13. Structural Plastic Strain Results for 0.14-m Ice Thickness, Loading on Transverse Web Frame (H_106)

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
11264 (nn)	0.0	0.0	0.0	0.0	2339	1361	0.0	0.0	0.0	0.0
11868 (yn)	2695	4842	4282	3190	10060	7428	237.7	370.6	0.0	0.0
12640 (ny)	0.0	0.0	0.0	0.0	2339	1361	0.0	0.0	0.0	0.0
13169 (yy)	2313	4231	4282	3190	10060	7428	237.7	370.6	0.0	0.0

Notes:

‡ Maximum inelastic strains in units of microstrain (strain times 10⁶)

* Annotations on run ID: (friction (yes/no), fracture (yes/no))

& “Long Web” = Longitudinal Web

+ “Long Flg” = Longitudinal Flange

^ “Tsvse Web” = Transverse Web

% “Tsvse Flg” = Transverse Flange

4.2.1.1 Case H_107

Table 14 lists the times of first ice element deletion, the number of failed ice elements, and the peak ice/structure contact forces reached for case H_107.

Table 14. Peak Force and Ice Slab Failure Results for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107)

LS-DYNA Run ID	Friction?	Fracture?	Time of First Ice Element Failure ⁺ (s)	Number of Failed Ice Elements (of 34896)	Peak Force (MN)
47889	No	No	N/A	None	0.7600
48443	Yes	No	N/A	None	1.927*
49001	No	Yes	0.2658	657	0.7600
49515	Yes	Yes	0.1531	2717	1.500

Notes:

+ “N/A” = Not applicable

* Peak force probably continues to increase after 0.5-s simulation timespan.

Figure 27 provides time histories of ice/structure contact force for case H_107 analyses. As with longitudinal frame impact, allowance of ice fracture has no effect in the frictionless contact case. However, for nonzero contact friction, structural loading is relieved when the ice breaks behind the crush zone.

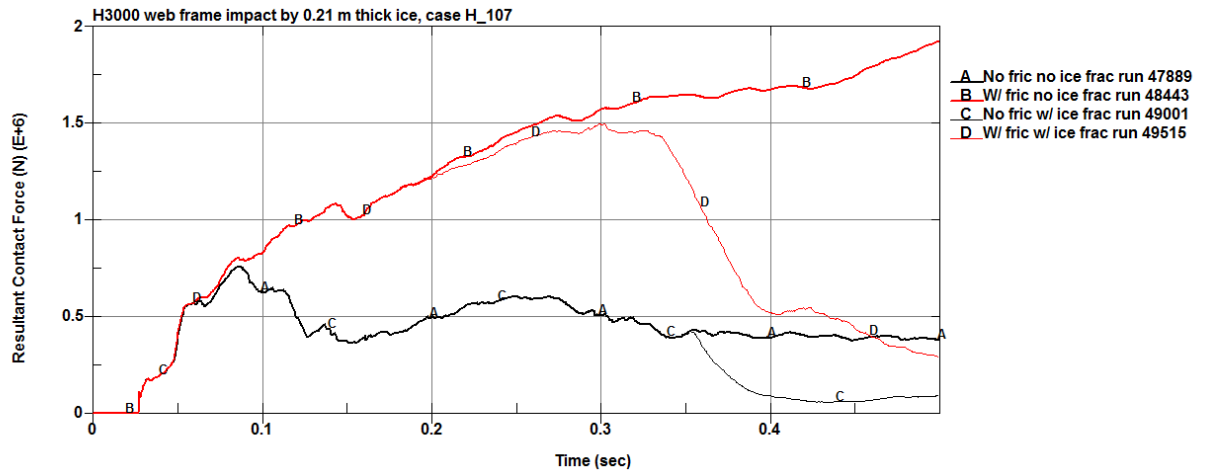
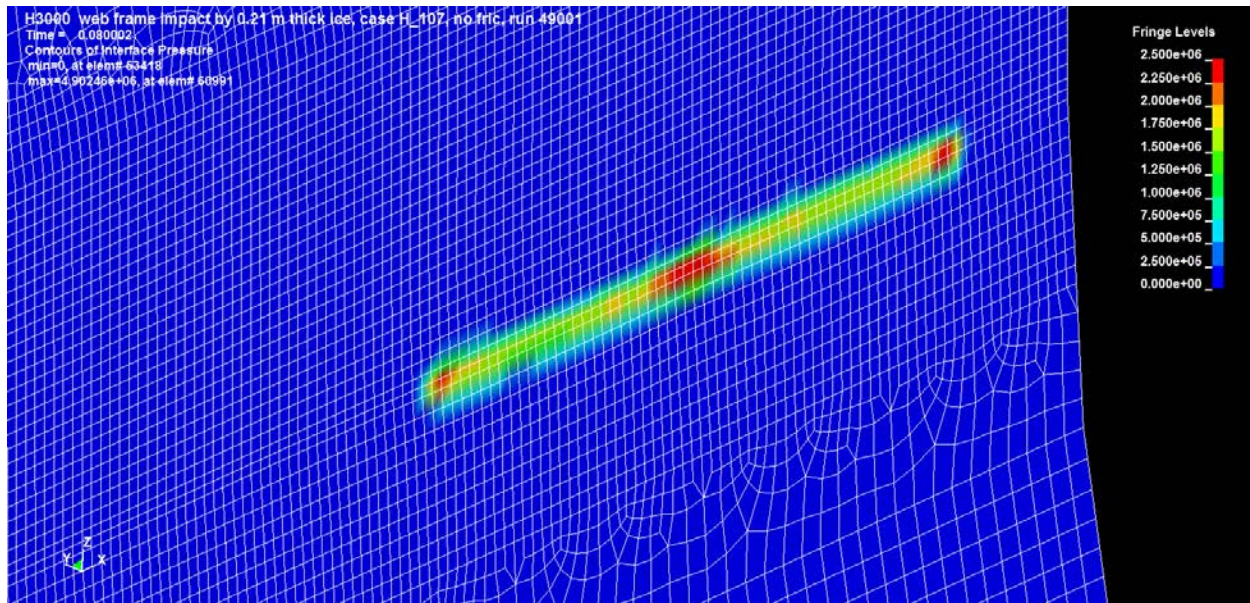
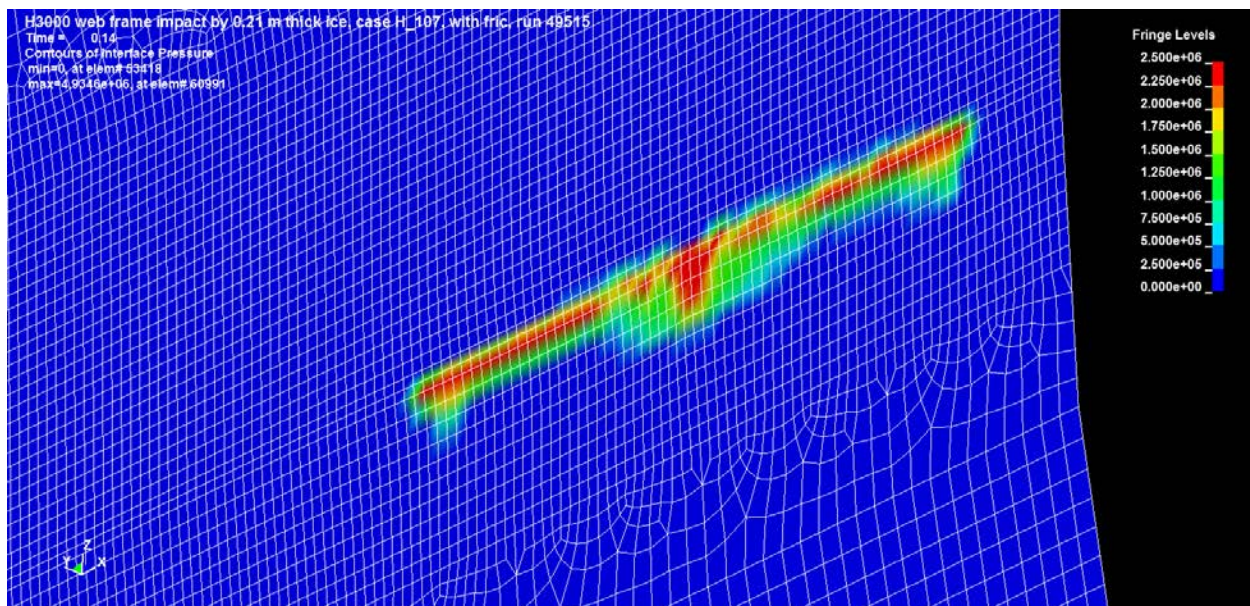


Figure 27. Ice/Structure Contact Force Time Histories for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107)

Figure 28 contains contour plots of the case H_107 pressure distributions on the hull shell at the times of peak pressures. The uppermost contour limit is specified as about half of the peak pressure. As with longitudinal frame impact, pressures are strongly nonuniform, and time of peak pressure is not coincident with time of peak force. Pressure is concentrated at the location of the one directly loaded web frame, although there are secondary pressure concentrations at the fore and aft edges of the contact area. In the case with contact friction, high pressure is more evenly distributed than in the frictionless case.



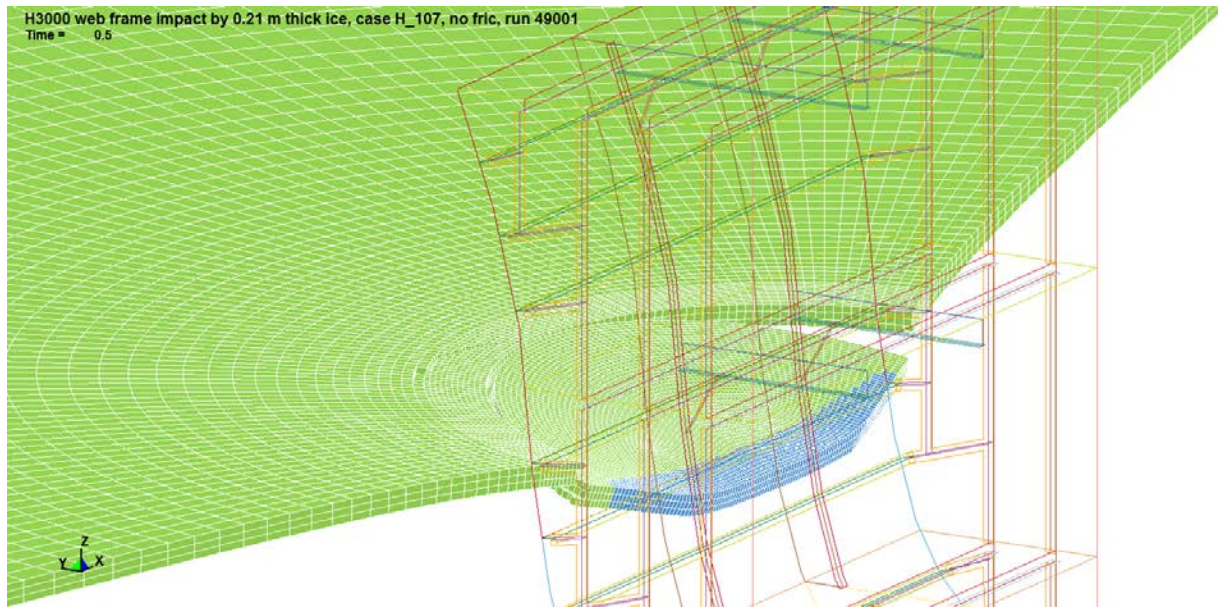
(a) Frictionless Contact



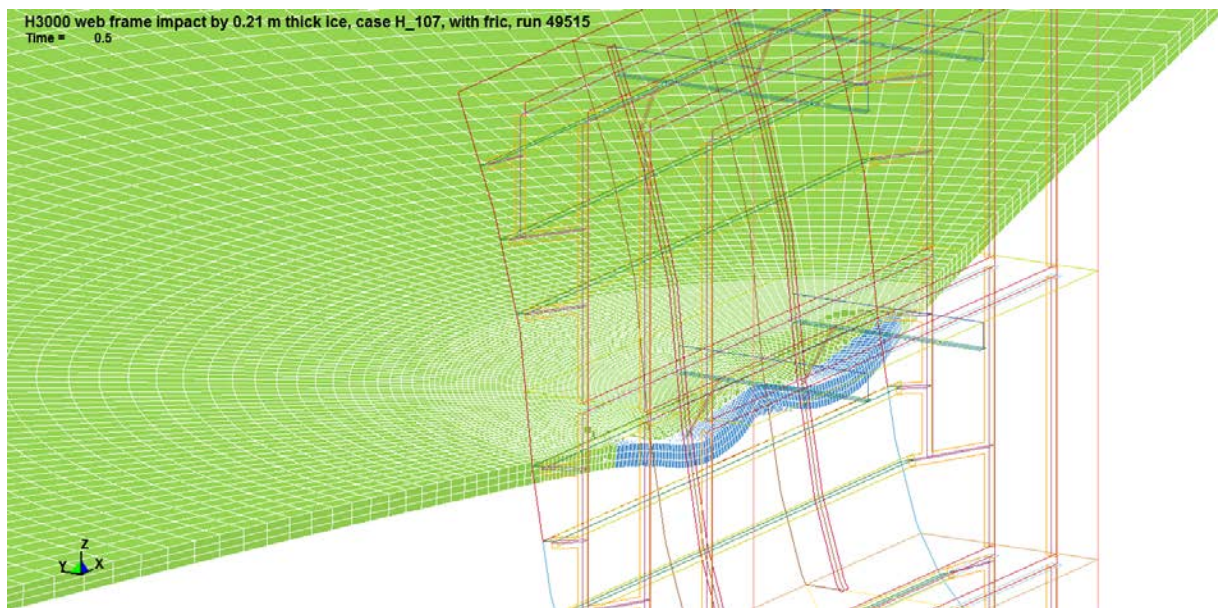
(b) With Contact Surface Friction

Figure 28. Ice/Structure Contact Pressure Distributions for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107)

Figure 29 illustrates the ice slab deflections and crack patterns developed in case H_107 analyses. Slab deflection and crack development trends are very similar to those seen in case H_102 (see Figure 18), though the loading on one web frame is an obvious difference with respect to case H_102.



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 29. Ice Slab Deflection and Crack Patterns for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107)

Table 15 lists the maximum inelastic strains in units of microstrain (strain times 10^6) for case the H_107 analyses.

Table 15. Structural Plastic Strain Results[‡] for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107)

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
47889 (nn)	1697	2668	5605	4603	11840	8163	602.2	785.0	0.0	0.0
48443 (yn)	45900	65820	50590	56790	56440	39000	115400	104600	20660	21470
49001 (ny)	1697	2668	5605	4603	11560	8163	602.2	785.0	0.0	0.0
49515 (yy)	10690	22750	15010	15480	28630	20420	3888	4483	0.0	0.0

Notes:

‡ Maximum inelastic strains in units of microstrain (strain times 10^6)

* Annotations on run ID: (friction (yes/no), fracture (yes/no))

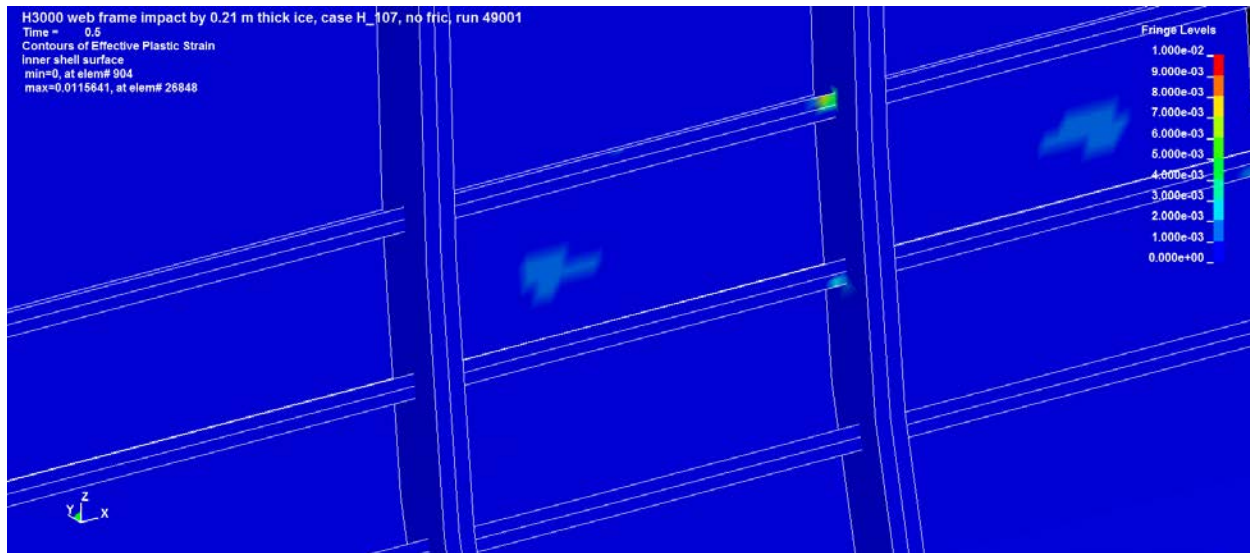
& “Long Web” = Longitudinal Web

+ “Long Flg” = Longitudinal Flange

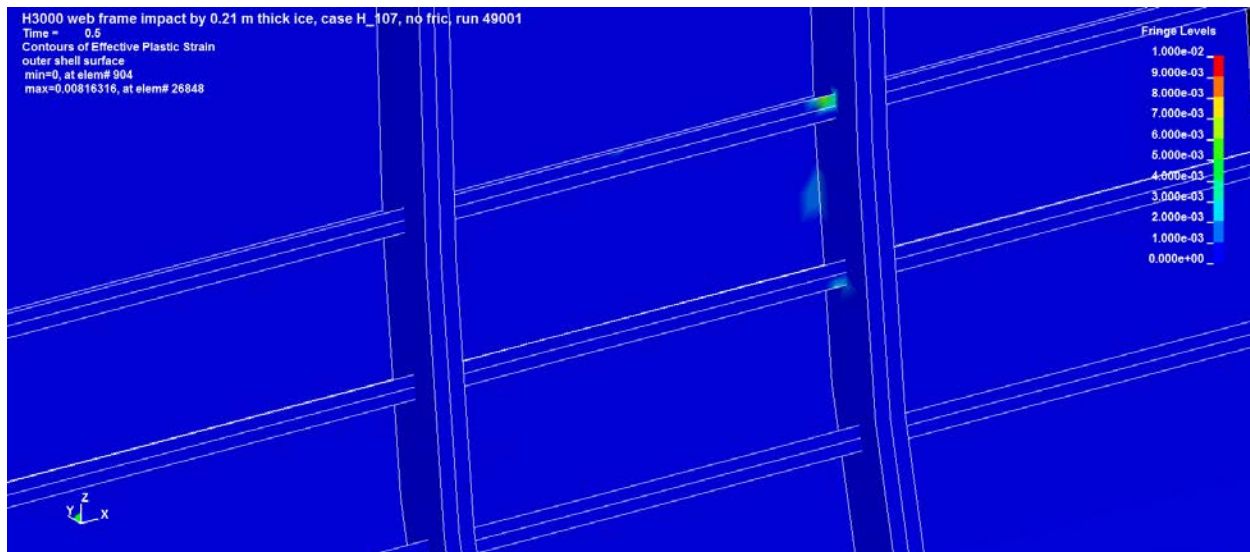
^ “Tsvse Web” = Transverse Web

% “Tsvse Flg” = Transverse Flange

Figure 30 contains plastic strain contours in H3000 structure for the fracture-enabled simulations with and without friction, the last two listed in Table 15. The frictionless case appears first, with separate pictures for inner and outer shell surfaces. All strain contours are capped at 1 %. The greater permanent set suffered in the case with nonzero contact friction compared with the frictionless case is obvious.

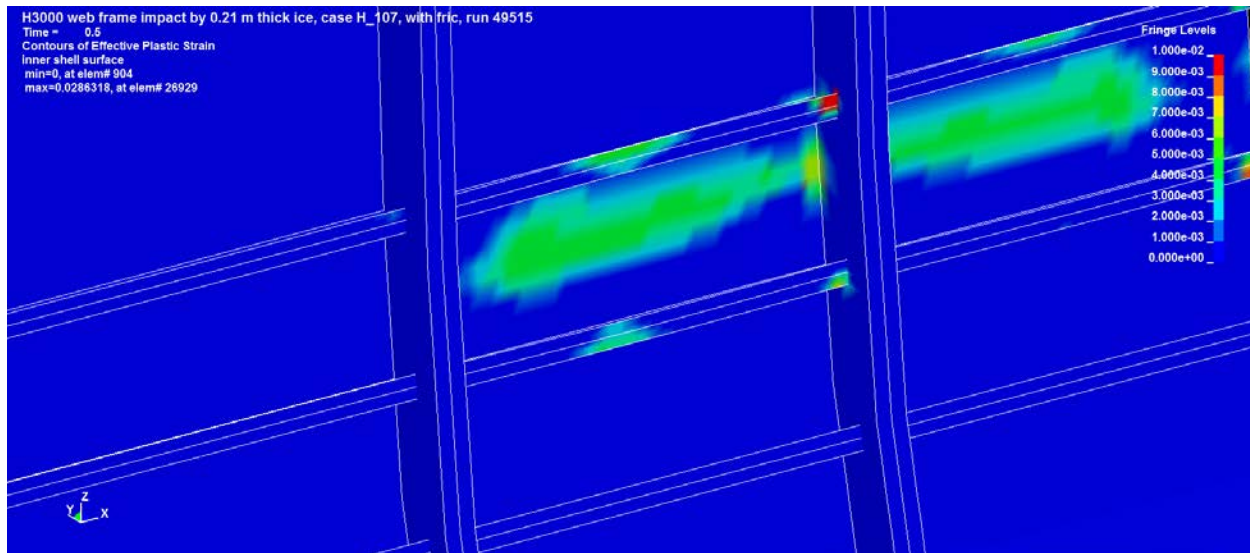


(a) Frictionless Contact, Inner Shell Surfaces

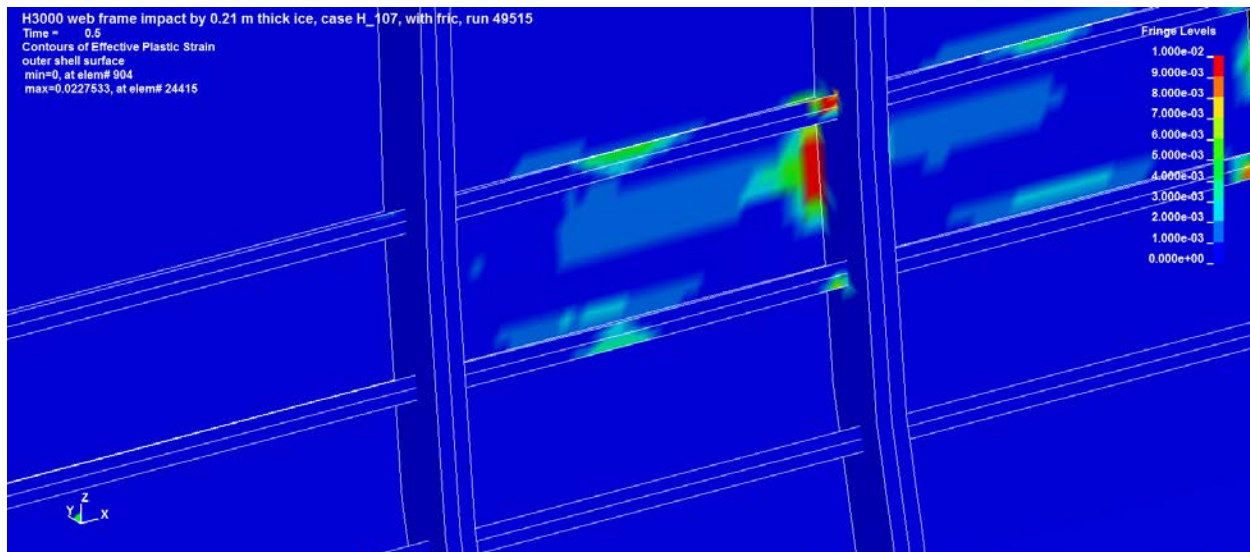


(b) Frictionless Contact, Outer Shell Surfaces

Figure 30. Plastic Strain Contours for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107)



(c) With Contact Surface Friction, Inner Shell Surfaces



(d) With Contact Surface Friction, Outer Shell Surfaces

Figure 30. Plastic Strain Contours for 0.21-m Ice Thickness, Loading on Transverse Web Frame (H_107) (cont'd)

4.2.1.2 Case H_108

Table 16 lists the times of first ice element deletion, the number of failed ice elements, and the peak ice/structure contact forces reached for case H_108.

Table 16. Peak Force and Ice Slab Failure Results for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H_108)

LS-DYNA Run ID	Friction?	Fracture?	Time of First Ice Element Failure ⁺ (s)	Number of Failed Ice Elements (of 58160)	Peak Force (MN)
17333	No	No	N/A	None	1.770
17851	Yes	No	N/A	None	2.836*
9366	No	Yes	0.1388	3471	1.588
9972	Yes	Yes	0.2141	120	2.787*

Notes:

+ "N/A" = Not applicable

* Peak force probably continues to increase after 0.4-s simulation timespan

Figure 31 provides time histories of ice/structure contact force for case H_108 analyses. Behaviors are very similar to those seen with longitudinal frame impact by ice of the same thickness.

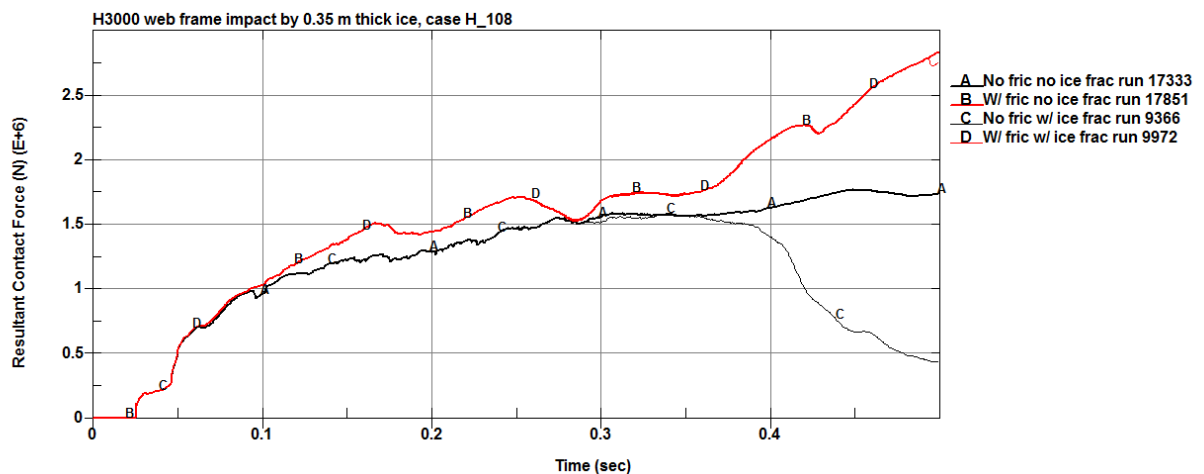
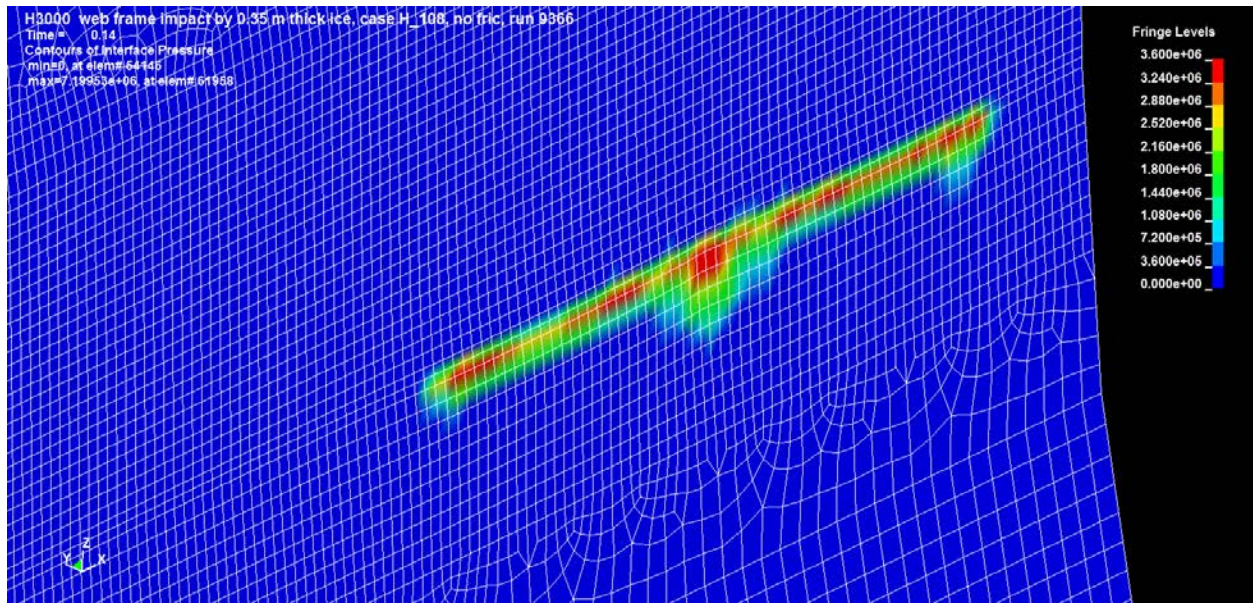
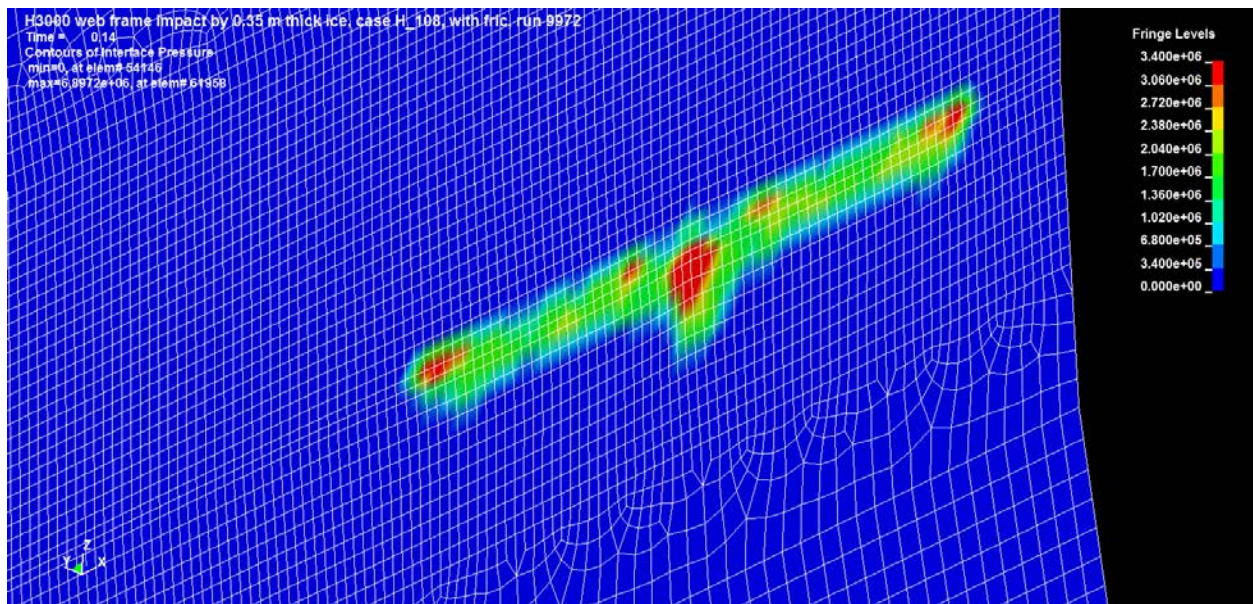
**Figure 31. Ice/Structure Contact Force Time Histories for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H_108)**

Figure 32 contains contour plots of the case H_108 pressure distributions on the hull shell at the times of peak pressures. The uppermost contour limit is specified as about half of the peak pressure. As with longitudinal frame impact, pressures are strongly nonuniform, and time of peak pressure is not coincident with time of peak force. Pressure is concentrated at the location of the one directly loaded web frame, although there are secondary pressure concentrations at the fore and aft edges of the contact area. In the case without contact friction, high pressure is more evenly distributed than when nonzero friction is presumed.



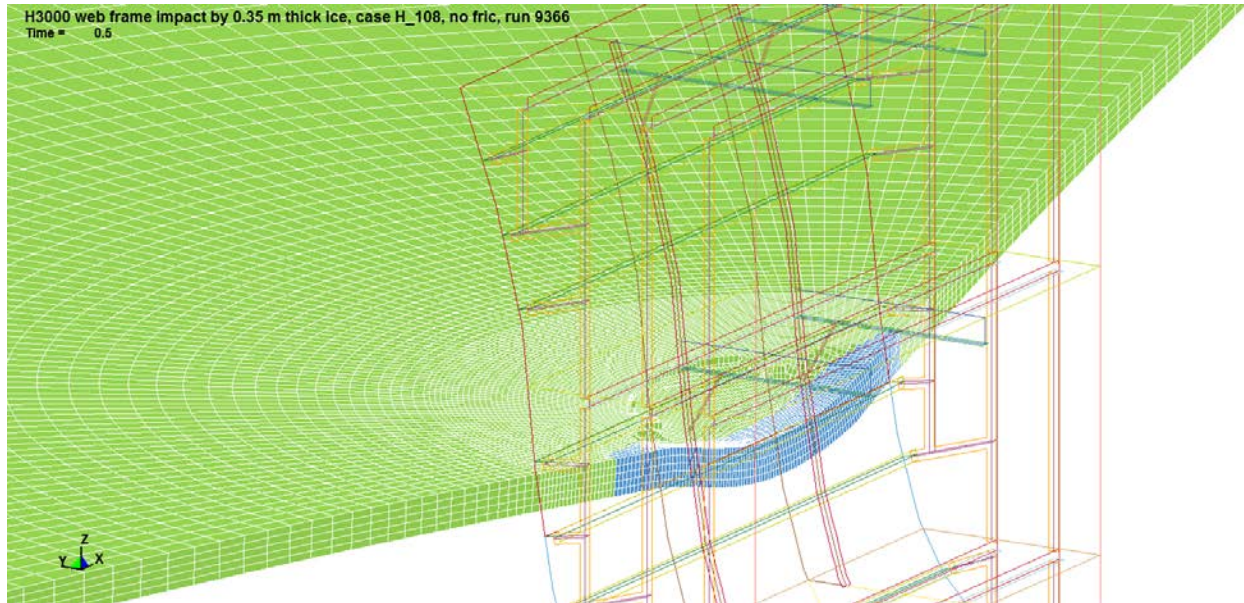
(a) Frictionless Contact



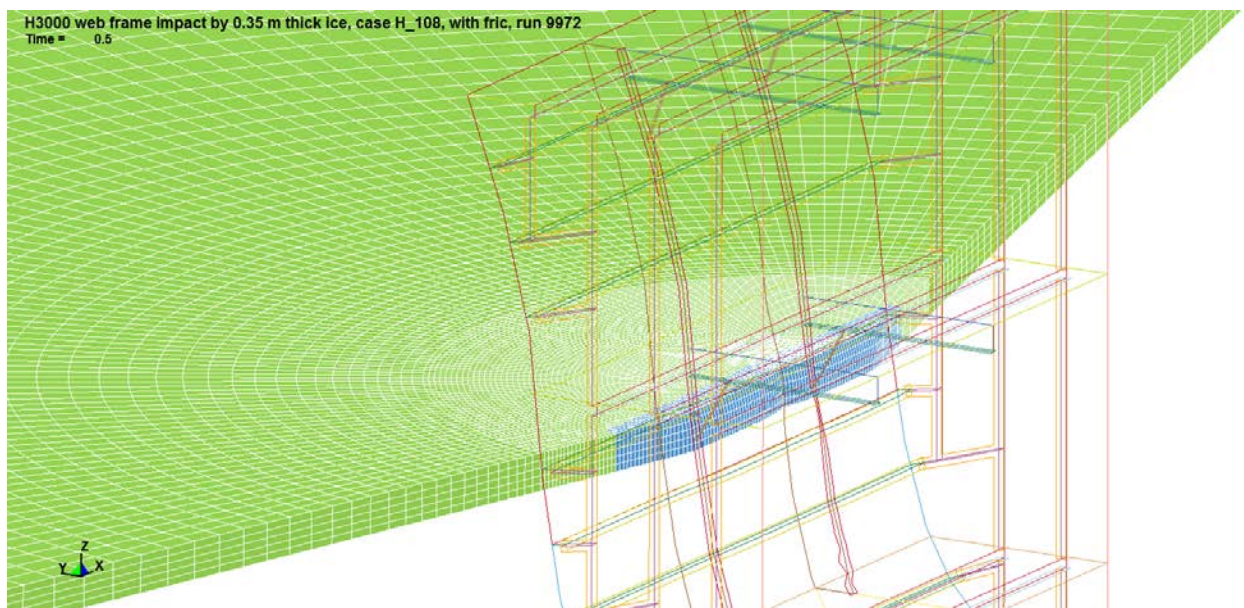
(b) With Contact Surface Friction

Figure 32. Ice/Structure Contact Pressure Distributions for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H_108)

Figure 33 illustrates the ice slab deflections and crack patterns developed in case H_108 analyses. Behaviors are somewhat similar to case H_103 (see Figure 16), though fracture is more definitive in the frictionless case. As in H_103, with friction acting on the ice/structure interface, the slab barely moves downward.



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 33. Ice Slab Deflection and Crack Patterns for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H_108)

Table 17 lists the maximum inelastic strains in units of microstrain (strain times 10^6) for the case H_108 analyses.

Table 17. Structural Plastic Strain Results[‡] for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H_108)

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
17333 (nn)	15470	33670	80870	87310	92080	72110	146200	113800	4260	4593
17851 (yn)	25220	50810	151900	158000	149800	92210	243700	253200	33890	18870
9366 (ny)	14470	34270	50430	52280	75420	48600	16170	15860	0.0	616.9
9972 (yy)	25170	50510	151400	157500	146400	91410	242100	250200	33130	18240

Notes:

‡ Maximum inelastic strains in units of microstrain (strain times 10^6)

* Annotations on run ID: (friction (yes/no), fracture (yes/no))

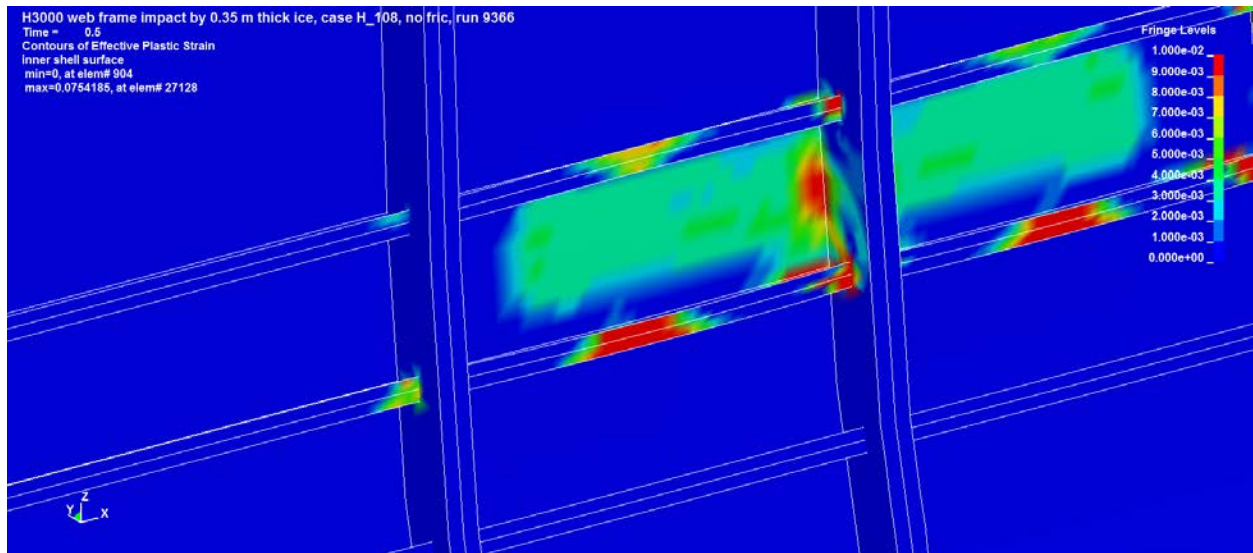
& “Long Web” = Longitudinal Web

+ “Long Flg” = Longitudinal Flange

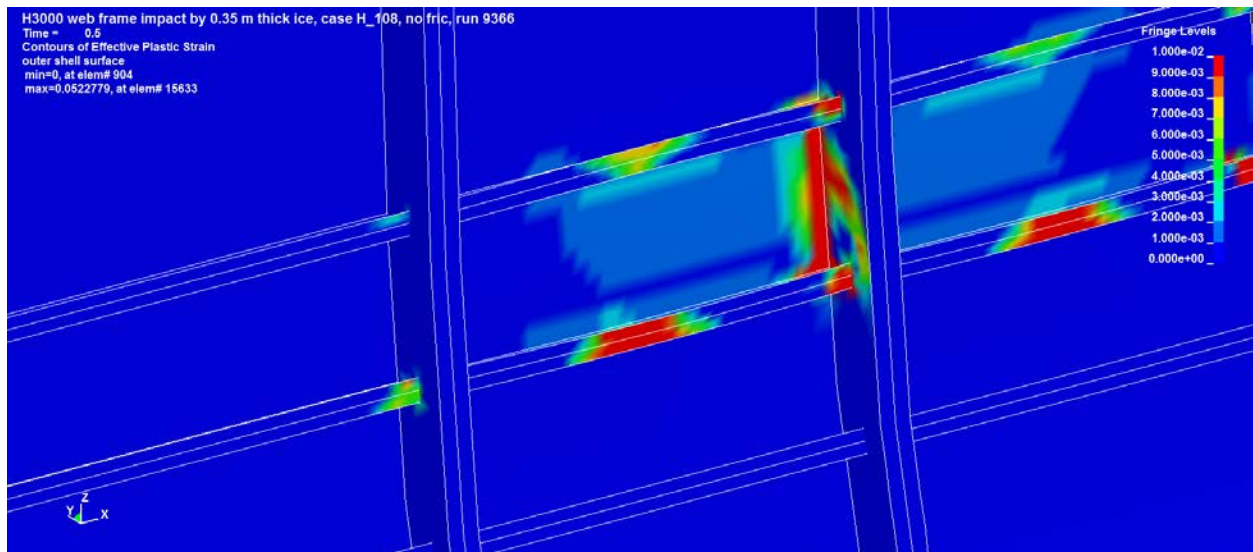
^ “Tsvse Web” = Transverse Web

% “Tsvse Flg” = Transverse Flange

Figure 34 contains plastic strain contours in H3000 structure for the fracture-enabled simulations with and without friction, the last two listed in Table 17. The frictionless case appears first, with separate pictures for inner and outer shell surfaces. All strain contours are capped at 1 %. The greater permanent set suffered in cases with nonzero contact friction compared to frictionless cases is obvious, as well as the greater damage suffered with case H_108 ice thickness in comparison to lower case H_107 ice thickness. As in case H_103, web frame tripping distortion is apparent.

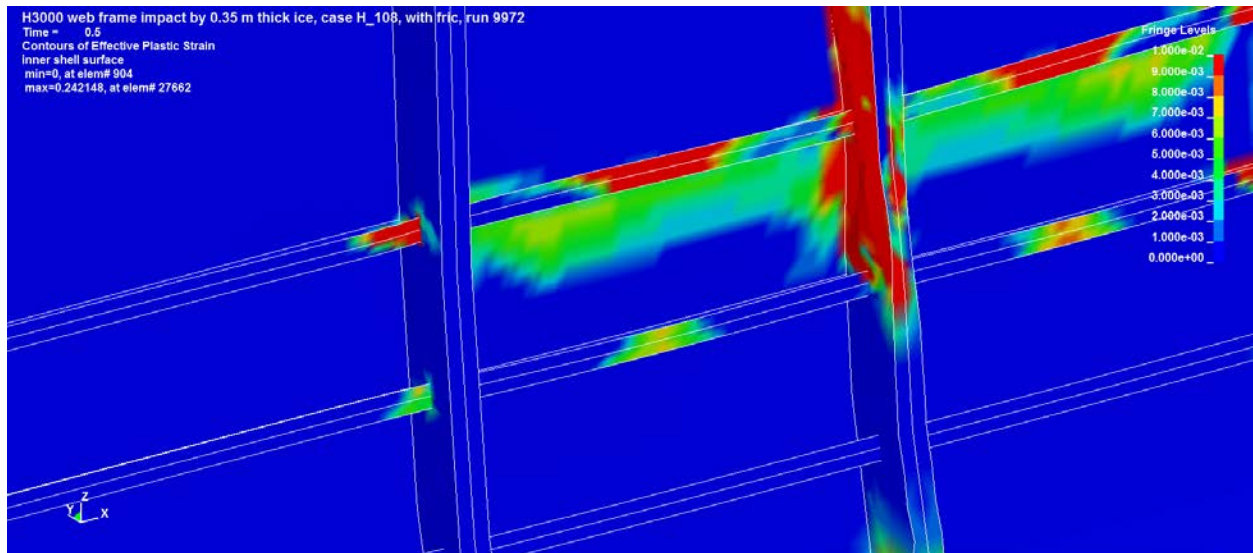


(a) Frictionless Contact, Inner Shell Surfaces

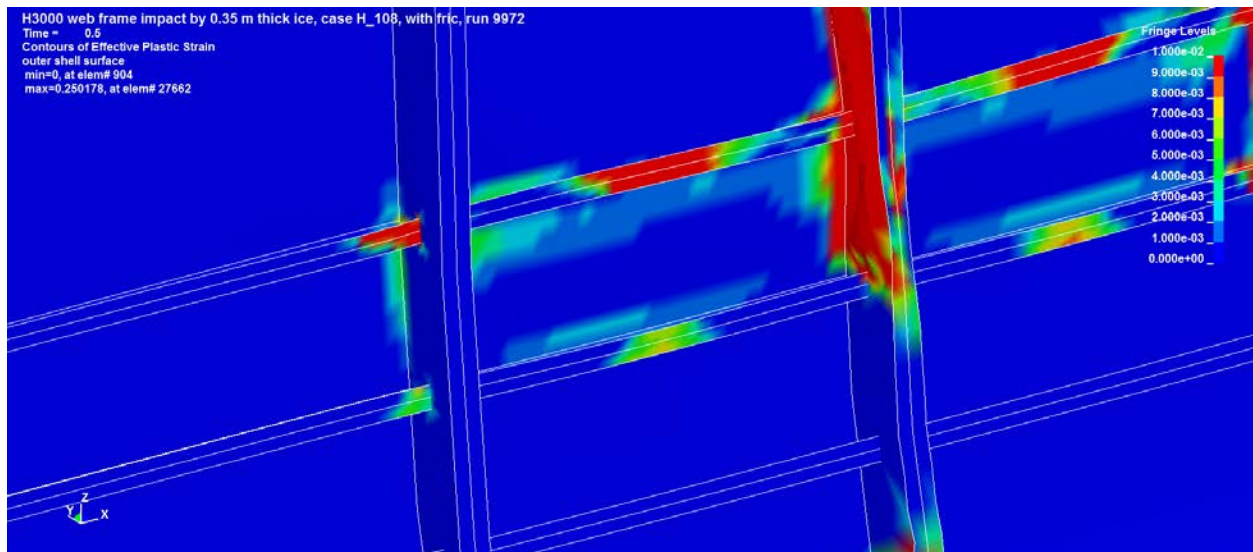


(b) Frictionless Contact, Outer Shell Surfaces

Figure 34. Plastic Strain Contours for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H_108)



(c) With Contact Surface Friction, Inner Shell Surfaces



(d) With Contact Surface Friction, Outer Shell Surfaces

Figure 34. Plastic Strain Contours for 0.35-m Ice Thickness, Loading on Transverse Web Frame (H₁₀₈) (cont'd)

4.2.1.8 Comparisons as Function of Ice Thickness

Presentation of the above data as a function of ice thickness is useful for recognizing trends. Table 18 contains peak force and element failure data included in previous tables, but it also contains times of peak collision force and times at which peak inelastic strain developed at the highest-strain component and shell surface in the H3000 FEM. Comparing the data in blocks A and C for frictionless cases shows that when ice fracture is allowed, it occurs much later than the contact force peak and has negligible effect for the two lower slab thicknesses. The earlier occurrence of ice fracture in the 0.35-m-thick scenario allows a small decrease in peak load. Comparison of the data in blocks B and D for nonzero-friction cases shows that when ice fracture is allowed, only the responses for the intermediate 0.21-m thickness are impacted, and

the decrease in peak load is modest. These behaviors are essentially the same as those observed for impact on a longitudinal frame, as tabulated in Table 11.

Table 18. Peak Force and Ice Slab Failure Results for Three Ice Thickness, Loading on Transverse Web Frame

LS-DYNA Run ID	Case ID	Ice Thickness (m)	Time of First Ice Element Failure (s)	Number of Failed Ice Elements	Peak Force (MN)	Time of Peak Force (s)	Time of Peak Plastic Strain (s)
A	No contact friction, no fracture						
11264	H_106	0.14	N/A	None	0.4859	0.0805	0.085
47889	H_107	0.21	N/A	None	0.7600	0.087	0.48
17333	H_108	0.35	N/A	None	1.770*	0.5*	0.5*
B	With contact friction, no fracture						
11868	H_106	0.14	N/A	None	0.7470	0.112	0.115
48443	H_107	0.21	N/A	None	1.927*	0.5*	0.5*
17851	H_108	0.35	N/A	None	2.836*	0.5*	0.5*
C	No contact friction, with fracture						
12640	H_106	0.14	0.2951	293	0.4859	0.0805	0.085
49001	H_107	0.21	0.2658	657	0.7600	0.087	0.355
9366	H_108	0.35	0.1388	3471	1.588	0.34	0.5*
D	With contact friction, with fracture						
13169	H_106	0.14	0.1274	401	0.7470	0.113	0.115
49515	H_107	0.21	0.1531	2717	1.500	0.299	0.49
9972	H_108	0.35	0.2141	120	2.787*	0.5*	0.495

Note: * Peak force and plastic strain probably continue to increase after 0.5-s simulation timespan.

4.3 Analysis of Multiple Impacts

This section documents a single-point evaluation of whether multiple impacts by thinner, lighter slabs are as damaging as a single impact by a thicker, heavier slab. This hypothetical situation is motivated by a ship's higher likelihood, when operating in the MIZ, of repeated encounters with smaller ice floes than with larger floes. Due to cumulative damage by smaller floes, the operational risk might need to be bounded on analysis of repeated encounters by smaller-but-more-likely hazards, rather than by a single, larger-but-rarer hazard.

An LS-DYNA modeling technique for addressing multiple ice slab impacts was developed, using the H_102 collision scenario for longitudinal stiffener impact by 0.21-m-thick ice. This intermediate thickness is appropriate, as thinner ice tended to be relatively nondamaging, and thicker ice impact is closer to being a single-overload event. The ice/structure contact is frictionless, and flexural fracture is allowed in the ice slabs.

Analysis of repeated successive loadings is straightforward in the FEM when the structure is constrained by the same boundary conditions throughout all events, and time-dependent force and/or pressure functions adequately describe the loading. However, the present problem is more challenging. The structure is a moving body, and the entity responsible for the loading is, in itself, a discretized “structure” governed by nonlinear constitutive laws. In simulation of a single ice slab impact, the presence of the slab in the problem is required only until the slab “fails,” after which it might be presumed to depart the scene (although in reality, its remains may recontact, but that is a random complication). We are not concerned with the realism of real-life randomness but instead seek insight as to the damage potential of highly idealized, successive impacts compared with a single, heavier impact.

The element, boundary constraint, and contact surface “birth” and “death” functions in LS-DYNA can be exploited to accomplish simulation of repeated impacts on the same structure in a single LS-DYNA run, without resorting to multiple modified restarts. One piece of information required is the relative timespan required for structure/impactor interaction, after which the continued presence of the impactor is no longer needed (i.e., it has “failed”). The structural portion of the LS-DYNA model and its boundary conditions and motion history are prescribed in the usual way. Instead of a single ice slab, multiple ice slabs are defined; they need not be identical, although they are in the three-slab case analyzed here.

Figure 35 shows a three-slab LS-DYNA model at time zero. The H3000 structure is positioned with respect to ice slab number 1 in the usual way, and its constant-velocity movement toward the ice bodies is as before. The two additional slabs are positioned “behind” slab number 1. These have the same boundary conditions and buoyancy/gravity functions applied, but although they overlap slab number 1 and each other in space, they are unconnected and do not interact. Unique contact pairs are defined between the structure and each of the three slabs. All ice elements are “active” at time zero, but boundary conditions and structure/ice contact surfaces are active only during the timespans denoted in Table 19. In the case analyzed here, structure/ice interaction takes place in the span of 0.5 s. When 0.5 s has elapsed, slab 1 has contacted and fractured, and LS-DYNA is then instructed to delete all remaining elements in that slab. Deletion of boundary constraints and the contact surface on slab 1 is also commanded at a “death” time of 0.5 s. After activation of its boundary conditions and contact surface at $t = 0.5$ s, slab 2 is now ready for interaction with H3000, which continues to move at constant velocity, though it has been permanently deformed during the slab 1 collision. The slab 2 collision, producing additional structural deformation, takes place during the 0.5-s-to-1.0-s interval, after which “failed” slab 2 and its constraints and contact surface are deleted. A similar process takes place with respect to slab 3 during the 1.0-s-to-1.5-s interval. In this way, permanent set strain accumulation progresses in the structure, and incremental damages during each independent collision can be determined.

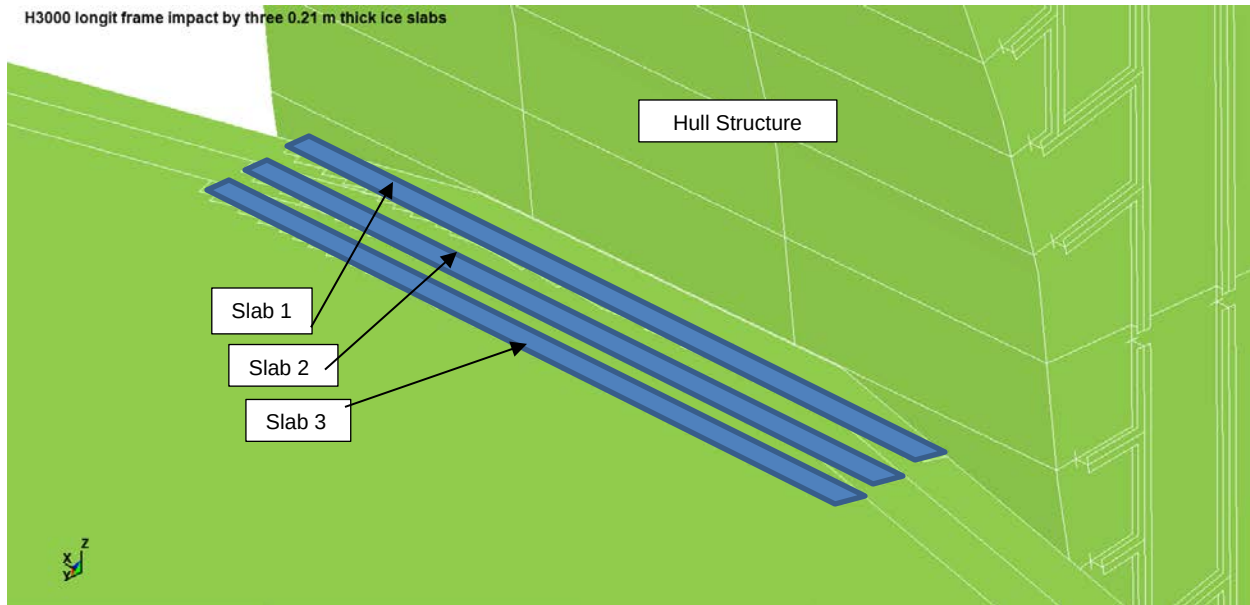


Figure 35. LS-DYNA Modeling of Successive Structure/Ice Impacts

Table 19. Lifetimes of Ice Slab Entities in Multiple-Collision LS-DYNA Simulation

Entity		Elements (s)	Constraints (s)	Contact Surface (s)
Slab 1	Birth	0.0	0.0	0.0
	Death	0.5	0.5	0.5
Slab 2	Birth	0.0	0.5	0.5
	Death	1.0	1.0	1.0
Slab 3	Birth	0.0	1.0	1.0
	Death	1.5	1.5	1.5

Energy loss mechanisms are a concern in the multiple-impact analysis, as the timespan of simulation is more than three times longer than in the single-impact analysis. In single-impact simulations, the initial, transient vibration of the structure as it is accelerated from rest prior to impact was largely suppressed by equipping the structural model with stiff truncation boundaries. Nevertheless, exertion of additional extraneous vibration control in the longer-time-range multiple-impact simulation via LS-DYNA's structural damping modeling options was attempted. Of these, *DAMPING_FREQUENCY_RANGE_DEFORM appeared to be the most worthwhile, as unlike the popular Rayleigh damping options (one-term mass-dependent or two-term alpha and beta damping), rigid body motions are not damped. LS-DYNA developer LSTC devised this proprietary damping model to impose a nearly frequency-independent damping coefficient over a range of user-chosen frequencies.

Like the stiffness-proportional damping variation of Rayleigh damping, *DAMPING_FREQUENCY_RANGE_DEFORM exacted a critical time-integration-step penalty. A damping coefficient of 0.05 and low and high frequency bounds of 10 Hz and 1000 Hz, respectively, provided the most tolerable result among several trials. With this set of damping specifications, the critical time step decreased from 2.40 μ s to 1.57 μ s. Unfortunately,

imposition of these structural damping parameters greatly decreased the inelastic material response in the H3000 structure from undamped calculations, rendering imposition of structural damping in these models not likely worth the benefit⁷.

Hourglassing response is another energy-related concern in the multiple-impact simulation over a longer time range. As discussed in section 4.2, an isolated portion of the H3000 FEM in a relatively unimportant location suffered visible hourglassing. In the multiple-impact case, the energy dissipated by hourglassing viscous control grew to comparable level to the kinetic energy in the structure. Given that the structural model was wholly composed of hourglassing-prone single-integration point H-L shell elements, the performance of selective/reduced (S/R) integration H-L shells in eliminating hourglassing was examined.

Figure 36 presents internal, kinetic, and (dissipated) hourglass energies for the multiple-impact simulations for the two element types. As expected, usage of S/R integration shells reduced hourglass energy to identically zero, though the required LS-DYNA execution wall-clock time was over a factor of three greater than with single-point integration shells. Since internal energy reported by LS-DYNA includes energy dissipated in plastic deformation, the “steady” internal energy level during time intervals after and between impacts is higher for the S/R integration shell option. This is reasonable, as that energy would otherwise have been dissipated in hourglassing. Interestingly, the kinetic energy histories show distinct frequencies of oscillation; about 34.4 Hz for single-point H-L shells, and about 38.9 Hz for the S/R integration H-L shells. These are almost surely the fundamental vibration modal frequencies of the structure, as constrained by the assumed boundary conditions.

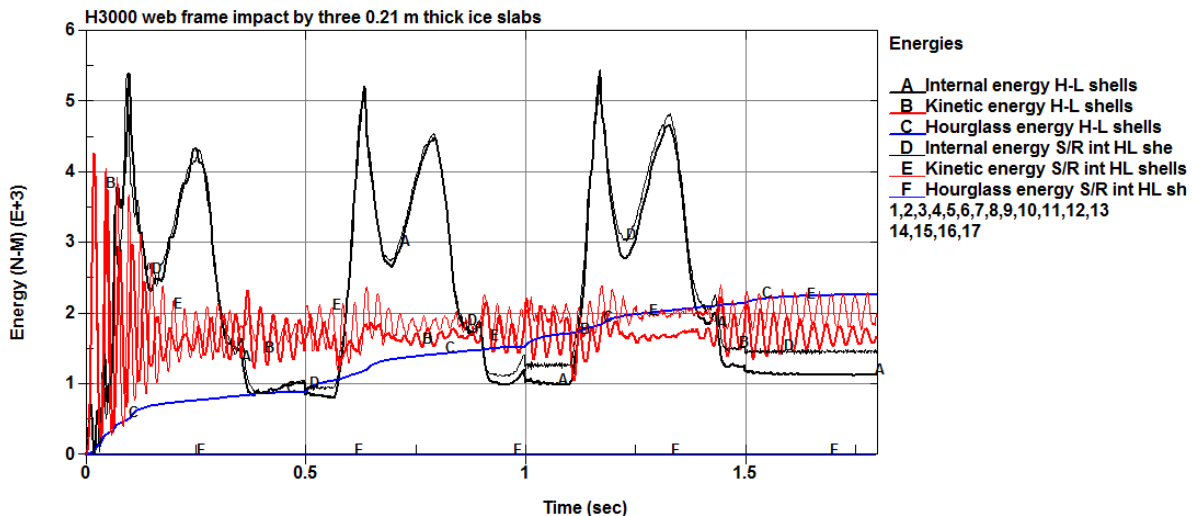


Figure 36. Energy Time Histories in Multiple Ice Slab Collision Simulation

Figure 37 contains the time history of ice/structure contact force magnitude for the three successive collisions. The first increase, peak, and decrease is the same as for the single collision analyzed previously. The second and third force history segments are strikingly similar to the first, with nearly identical peak force levels. Collision force histories are virtually the same for the two shell element types considered.

⁷ Better-focused application of damping to a narrower frequency range, along with adjustments to the damping coefficient, may be of benefit but this issue was judged overly distracting at the present time.

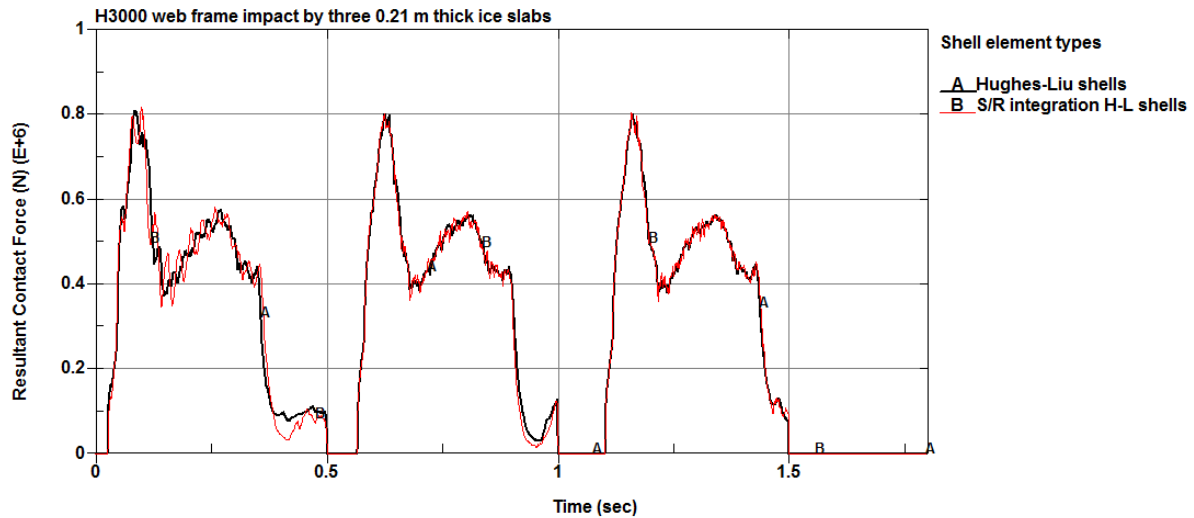


Figure 37. Contact Force Time Histories in Multiple Ice Slab Collision Simulation

Figure 38 illustrates the crack pattern developed in all three slabs in the multiple-impact simulation. This figure shows a top view of essentially the same crack pattern shown for frictionless case H_102 in the first panel of Figure 15. The crack is located near but not at the radius of transition from a uniform to a gradually increasing element radial length.

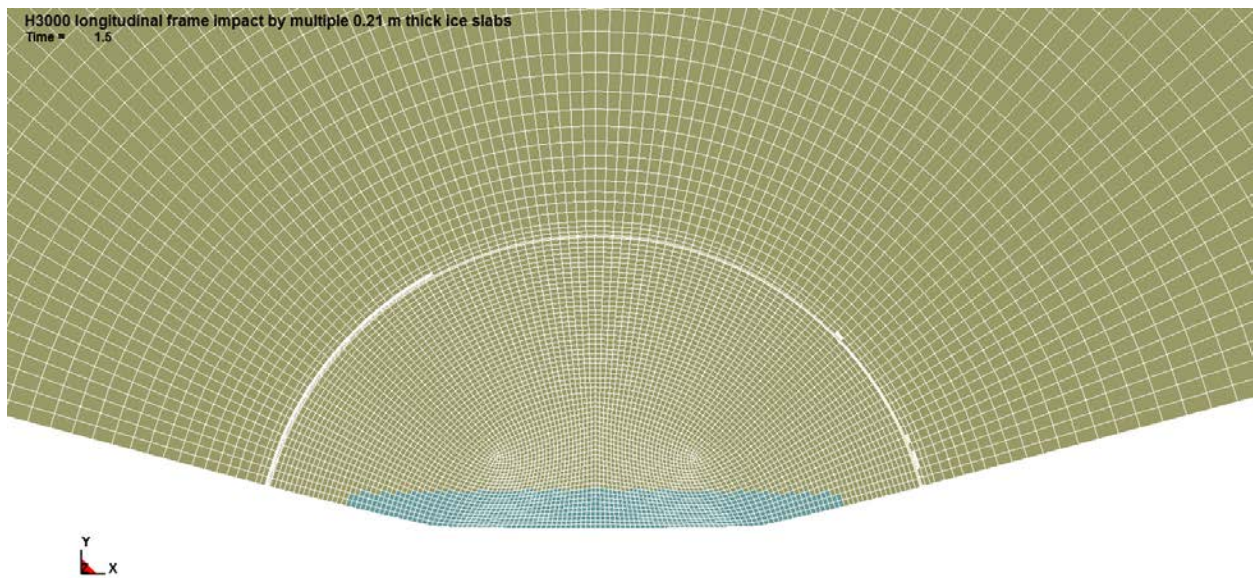


Figure 38. Typical Ice Slab Fracture Pattern for the Three Successively Hit Ice Slabs

Differences between the outcomes of the three collisions are only evident in the inelastic structural strain increments incurred in each collision. Table 20 lists increments of peak inelastic strain in units of microstrain (strain times 10^6) in H3000 components incurred in each of the three collisions⁸, and Table 21 lists fractions of the total accumulated plastic strain in each collision. These data are taken from the simulations using single-point integration and S/R integration H-L shells. The two shell element types produce somewhat different permanent set developments. For the single-point integration shells, the majority of damage takes place during the first two collisions, and in five of six structural components, the majority occurs during the first collision. Only the hull shell continues to suffer significant damage in the second and third impacts. For the S/R integration shells, the majority of damage is even more strongly weighted to the first collision, but the stiffeners suffer greater incremental damage during the latter two collisions than when single-point integration shells were used. Nevertheless, the “totals” data in Table 20 indicate similar ultimate permanent set levels for the two element types, and the need for significant additional analysis expense for the S/R integration shells is arguable.

Although it is unwise to generalize too strongly from one example, this exercise indicates that, short of tearing and rupture, non-ice-strengthened hull structure may be able to tolerate multiple ice collisions reasonably well, as long as the ice pieces are not overly massive.

Table 20. Increments of Inelastic Strain[‡] in H3000 for Three Successive Collisions with Identical Ice Slabs

Collision Number	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Run 5182, single-point integration Hughes/Liu shells										
First	1498	3003	354.2	118.4	2467	1304	0.0	0.0	0.0	0.0
Second	119	348	272.6	218.2	676	230	0.0	0.0	0.0	0.0
Third	344	494	51.5	5.9	18	0.0	0.0	0.0	0.0	0.0
TOTAL	1961	3845	678.3	342.5	3161	1534	0.0	0.0	0.0	0.0
Run 36202, S/R integration Hughes-Liu shells										
First	1677	3287	367.0	201.4	2603	1404	208.6	173.2	0.0	0.0
Second	133	258	36.7	51.1	327	60	208.4	96.4	0.0	0.0
Third	67	72	87.5	37.7	406	333	179.2	104.7	0.0	0.0
TOTAL	1877	3617	491.2	290.2	3336	1797	596.2	374.3	0.0	0.0

Notes:

[‡] Increments of peak inelastic strain in units of microstrain (strain times 10^6)

[&] “Long Web” = Longitudinal Web

⁺ “Long Flg” = Longitudinal Flange

[^] “Tsvse Web” = Transverse Web

[%] “Tsvse Flg” = Transverse Flange

⁸ The strains reached after the first impact are very close to but not identical to those listed in Table 8, run 9114. The cause for the small differences is unknown.

Table 21. Percentages of H3000 Inelastic Strain Accumulation between Three Successive Identical Ice Slab Impacts

Collision Number	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
Run 5182, single-point integration Hughes/Liu shells										
First	0.76	0.78	0.52	0.35	0.78	0.85	N/A	N/A	N/A	N/A
Second	0.06	0.09	0.40	0.64	0.21	0.15	N/A	N/A	N/A	N/A
Third	0.18	0.13	0.08	0.02	0.01	0.00	N/A	N/A	N/A	N/A
Run 36202, S/R integration Hughes-Liu shells										
First	0.89	0.91	0.75	0.69	0.78	0.78	0.35	0.46	N/A	N/A
Second	0.07	0.07	0.07	0.18	0.10	0.03	0.35	0.26	N/A	N/A
Third	0.04	0.02	0.18	0.13	0.12	0.19	0.30	0.28	N/A	N/A

Notes:

& "Long Web" = Longitudinal Web

+ "Long Flg" = Longitudinal Flange

^ "Tsvse Web" = Transverse Web

% "Tsvse Flg" = Transverse Flange

Another aspect of the multiple-collision study results is comparison of the total permanent set damage incurred with respect to the permanent set resulting from a single collision with a slab of the next highest thickness and mass considered in this effort. Table 22 compares the peak inelastic strain values in units of microstrain (strain times 10^6) attained in the triple-impact simulation for 0.21-m ice using single-point integration H-L shells (see totals for run 5182, Table 20) with those attained in a single impact with 0.35-m ice (see run 55197, Table 10). It is readily apparent that the single collision with the thicker and heavier slab is greatly more damaging than three successive collisions with the thinner and lighter slab.

Table 22. Comparison of Inelastic Strains[‡] Attained in Three 0.21-m Ice Collisions and One 0.35-m Ice Collision

Slab Thickness (# of impacts)	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
0.21 m (3x)	1961	3845	678.3	342.5	3161	1534	0.0	0.0	0.0	0.0
0.35 m (1x)	7364	20970	64570	53620	43630	26240	3853	3496	0.0	0.0

Notes:

[‡] Maximum inelastic strains in units of microstrain (strain times 10^6)

& "Long Web" = Longitudinal Web

+ "Long Flg" = Longitudinal Flange

^ "Tsvse Web" = Transverse Web

% "Tsvse Flg" = Transverse Flange

4.4 Miscellaneous Modeling Variations

The sensitivity to three structure/ice collision modeling assumptions was explored, using the web frame impact scenarios discussed above (H_106, H_107, H_108) as a baseline.

4.4.1 *Effect of Far-Field Ice Boundary Constraint*

In the predecessor LS-DYNA study of thin ice mechanics (Dolny, 2017, section 2.6), the far edges of the ice slabs were totally constrained against displacement, effectively attaining the conservative bounding condition of infinitely extended ice. All of the simulations reported in sections 4.2 and 4.3 retained these constraints. Even though the local nature of the available H3000 structural FEM precludes consideration of full ship and finite ice floe collision interaction with free-body-collision momentum transfer, the impact of relaxing displacement constraints on the far-field ice slab boundary is of interest. This consideration was evaluated in reruns of the six frictionless and with-friction web frame impact analyses for all three ice thicknesses, with ice fracture enabled, and with no modeling change other than removal of far-field ice slab displacement constraint.

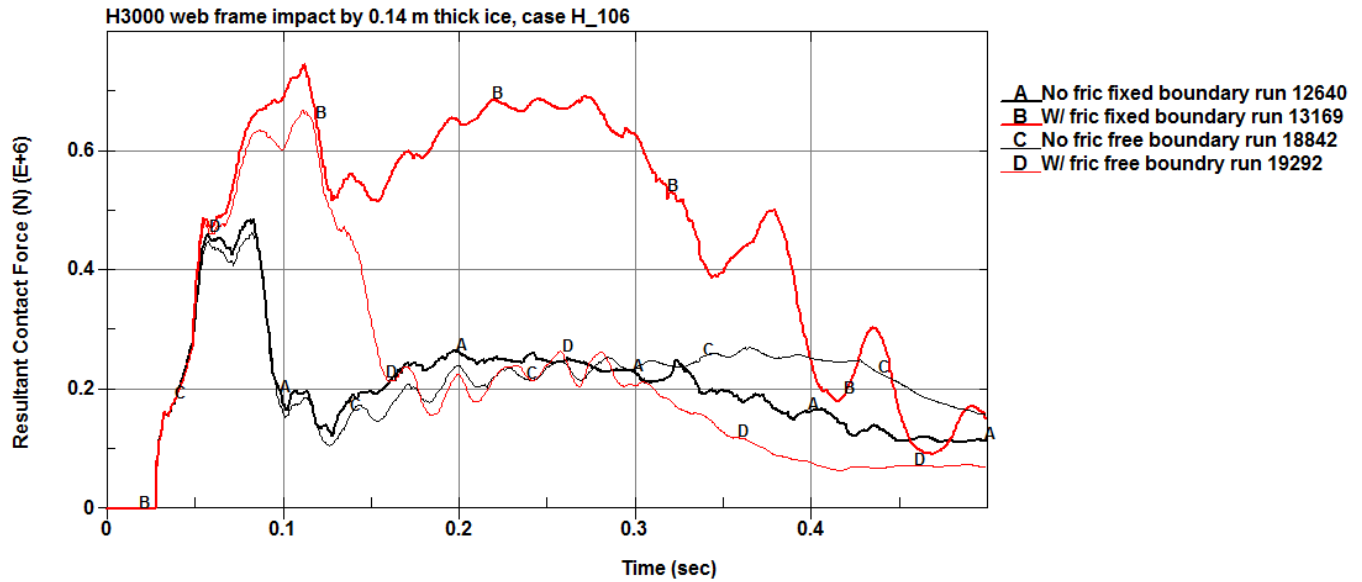
Table 23, blocks A and B, provides data on ice failure, peak collision force, and times of peak force and peak plastic strain attainment in the structure. Parallel results previously reported for the constrained ice slab are also included in blocks C and D. Removing the ice slab displacement constraint practically eliminates ice fracture, reducing the relevant ice mechanics to crushing behavior only. Peak collision forces decrease with constraint removal, increasingly so as ice thickness increases. Contact friction remains as a major effect on contact forces.

Table 23. Peak Force and Ice Slab Failure Results for Two Bounding Ice Slab Constraint Assumptions, Loading on Transverse Web Frame

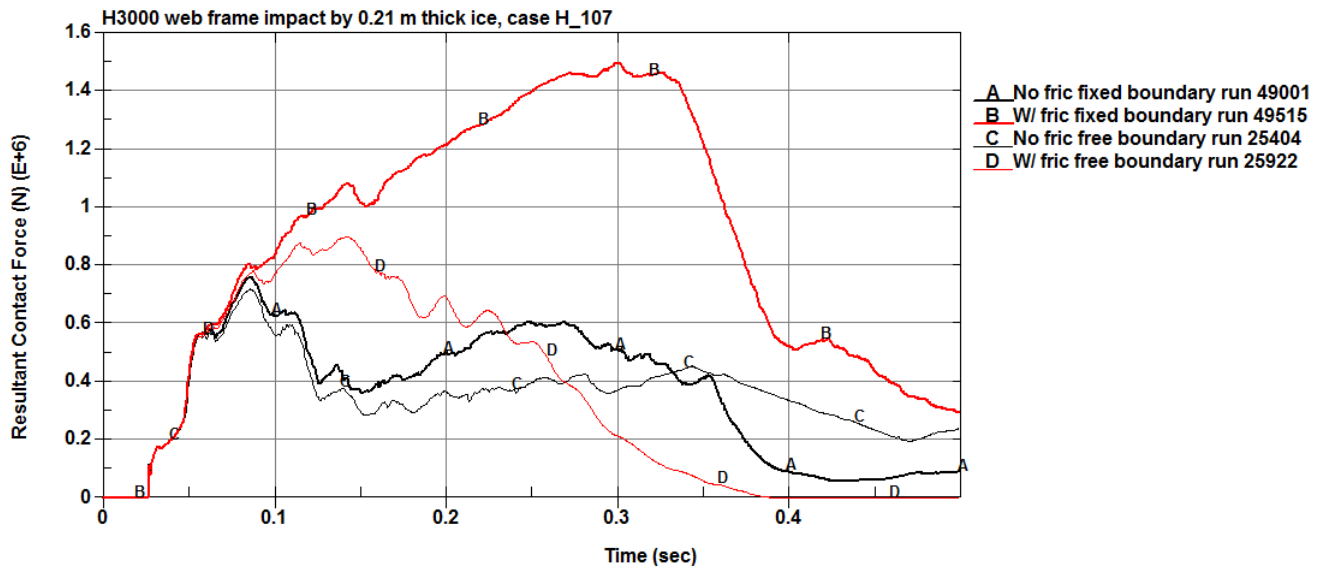
LS-DYNA Run ID	Case ID	Ice Thickness (m)	Time of First Ice Element Failure (s)	Number of Failed Ice Elements	Peak Force (MN)	Time of Peak Force (s)	Time of Peak Plastic Strain (s)
A	NO FARFIELD DISPLACEMENT CONSTRAINT, No contact friction, with fracture						
18842	H_106	0.14	N/A	None	0.4635	0.0825	0.085
25404	H_107	0.21	N/A	None	0.7192	0.0865	0.35
9650	H_108	0.35	N/A	None	1.075	0.141	0.5*
B	NO FARFIELD DISPLACEMENT CONSTRAINT, With contact friction, with fracture						
19292	H_106	0.14	N/A	None	0.6696	0.112	0.12
25922	H_107	0.21	0.1819	4	0.9008	0.142	0.405
37870	H_108	0.35	N/A	None	1.304	0.198	0.455
C	WITH FARFIELD DISPLACEMENT CONSTRAINT, No contact friction, with fracture						
12640	H_106	0.14	0.2951	293	0.4859	0.0805	0.085
49001	H_107	0.21	0.2658	657	0.7600	0.087	0.355
9366	H_108	0.35	0.1388	3471	1.588	0.34	0.5*
D	WITH FARFIELD DISPLACEMENT CONSTRAINT, With contact friction, with fracture						
13169	H_106	0.14	0.1274	401	0.7470	0.113	0.115
49515	H_107	0.21	0.1531	2717	1.500	0.299	0.49
9972	H_108	0.35	0.2141	120	2.787*	0.5*	0.495

Note: * Peak force and plastic strain probably continue to increase after 0.4-s simulation timespan.

Figure 39 presents time histories of contact forces for the cases listed in Table 23. For the lower two slab thicknesses with frictionless contact, peak forces are not greatly changed between the two far-field ice slab boundary conditions. For the thickest slab, it is apparent that rebound has occurred when the remote slab boundary is unconstrained. The cases with contact friction exhibit differing behaviors. Although rebound and unloading occur for the less-constrained 0.14-m-thick slab, peak force reduction is minor. For the two thicker slabs, rebound allows dramatic loading reductions, providing less opportunity for friction to enforce structure/ice engagement with buildup of contact force.

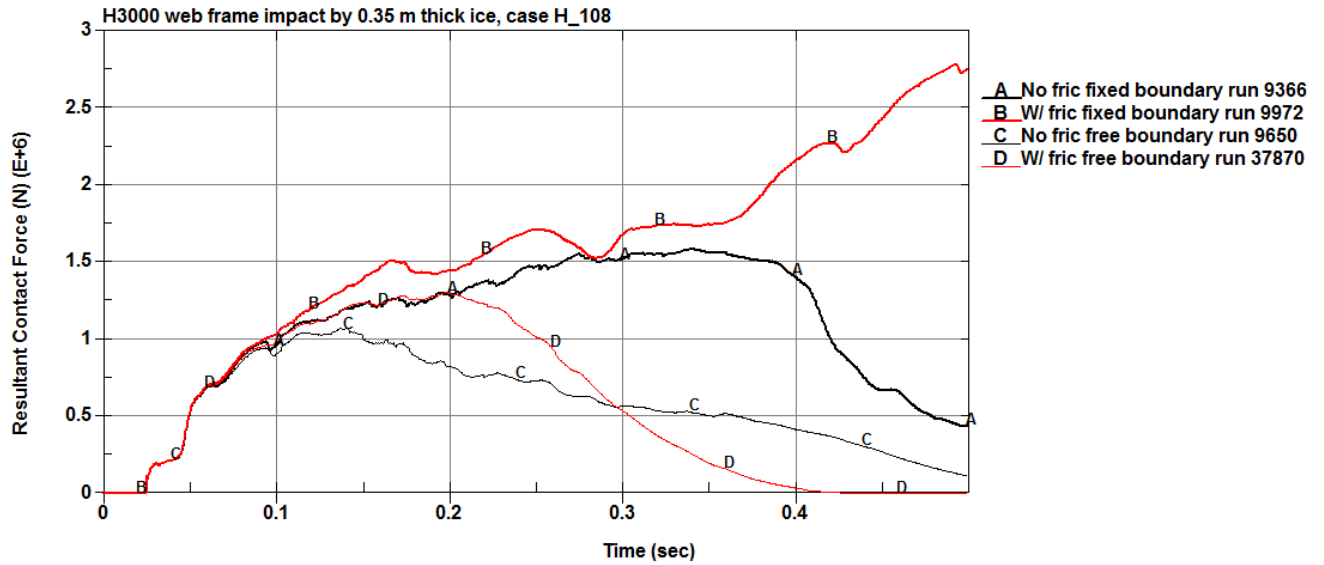


(a) 0.14-m Ice Thickness



(b) 0.21-m Ice Thickness

Figure 39. Contact Force Time Histories for Constrained and Unconstrained Far-Field Ice Boundary, Loading on Transverse Web Frame



(c) 0.35-m Ice Thickness

Figure 39. Contact Force Time Histories for Constrained and Unconstrained Far-Field Ice Boundary, Loading on Transverse Web Frame (cont'd)

The impact of ice slab boundary constraint on peak inelastic strains reached in the H3000 structure is indicated in the data (in units of microstrain (strain times 10^6)) in Table 24. The LS-DYNA runs in each block of the table appear in the order of increasing ice slab thickness. The effect on strains is dramatic; reductions between a factor of two and an order of magnitude are achieved when ice slab constraints are relaxed.

From the behaviors of contact forces and structural responses discussed above for constrained and less-constrained ice slabs, it is clear that the degree of constraint of the ice slab is an important collision mechanics factor.

Table 24. Peak Inelastic Strain Results[‡] for Two Bounding Ice Slab Constraint Assumptions, Loading on Transverse Web Frame

LS-DYNA Run ID*	Hull Shell	Hull Shell	Long Web ^{&}	Long Web ^{&}	Long Flg ⁺	Long Flg ⁺	Tsvse Web [^]	Tsvse Web [^]	Tsvse Flg [%]	Tsvse Flg [%]
Surface	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
A	NO FARFIELD DISPLACEMENT CONSTRAINT, No contact friction, with fracture									
18842	0.0	0.0	0.0	0.0	1582	690.5	0.0	0.0	0.0	0.0
25404	1210	2290	4357	3382	9147	6754	288.6	446.0	0.0	0.0
9650	4052	10080	176500	187300	297100	199100	5233	5777	0.0	0.0
B	NO FARFIELD DISPLACEMENT CONSTRAINT, With contact friction, with fracture									
19292	396.3	515.0	2636	1675	7488	5269	0.0	0.0	0.0	0.0
25922	1588	3731	9928	8389	18520	12510	1318	1878	0.0	0.0
37870	3276	15890	39630	41440	43700	29410	8898	9733	0.0	0.0
C	WITH FARFIELD DISPLACEMENT CONSTRAINT, No contact friction, with fracture									
12640	0.0	0.0	0.0	0.0	2339	1361	0.0	0.0	0.0	0.0
49001	1697	2668	5605	4603	11560	8163	602.2	785.0	0.0	0.0
9366	14470	34270	50430	52280	75420	48600	16170	15860	0.0	616.9
D	WITH FARFIELD DISPLACEMENT CONSTRAINT, With contact friction, with fracture									
13169	2313	4231	4282	3190	10060	7428	237.7	370.6	0.0	0.0
49515	10690	22750	15010	15480	28630	20420	3888	4483	0.0	0.0
9972	25170	50510	151400	157500	146400	91410	242100	250200	33130	18240

Notes:

‡ Maximum inelastic strains in units of microstrain (strain times 10⁶)

& “Long Web” = Longitudinal Web

+ “Long Flg” = Longitudinal Flange

^ “Tsvse Web” = Transverse Web

% “Tsvse Flg” = Transverse Flange

4.4.2 Effect of Faster Loading

In all analyses of report sections 4.2 and 4.3, the H3000 FEM was driven into the ice slab at a translational velocity of 0.58824 m/s (slightly over 1 kn) for a 5-s time period. The predecessor ice crushing calibration analysis series (Dolny et al., 2017) assumed this approach velocity, but it is rather “slow” even in the context of “cautious” ship speed during ice zone navigation. A repeat of the analysis set for web frame impact with a constrained far-field ice slab boundary was carried out with approach speed increased to 2.06 m/s (~ 4 kn) over a 4-s timespan. Although simulations were carried out with and without fracture, discussion is chiefly restricted to the cases allowing ice fracture.

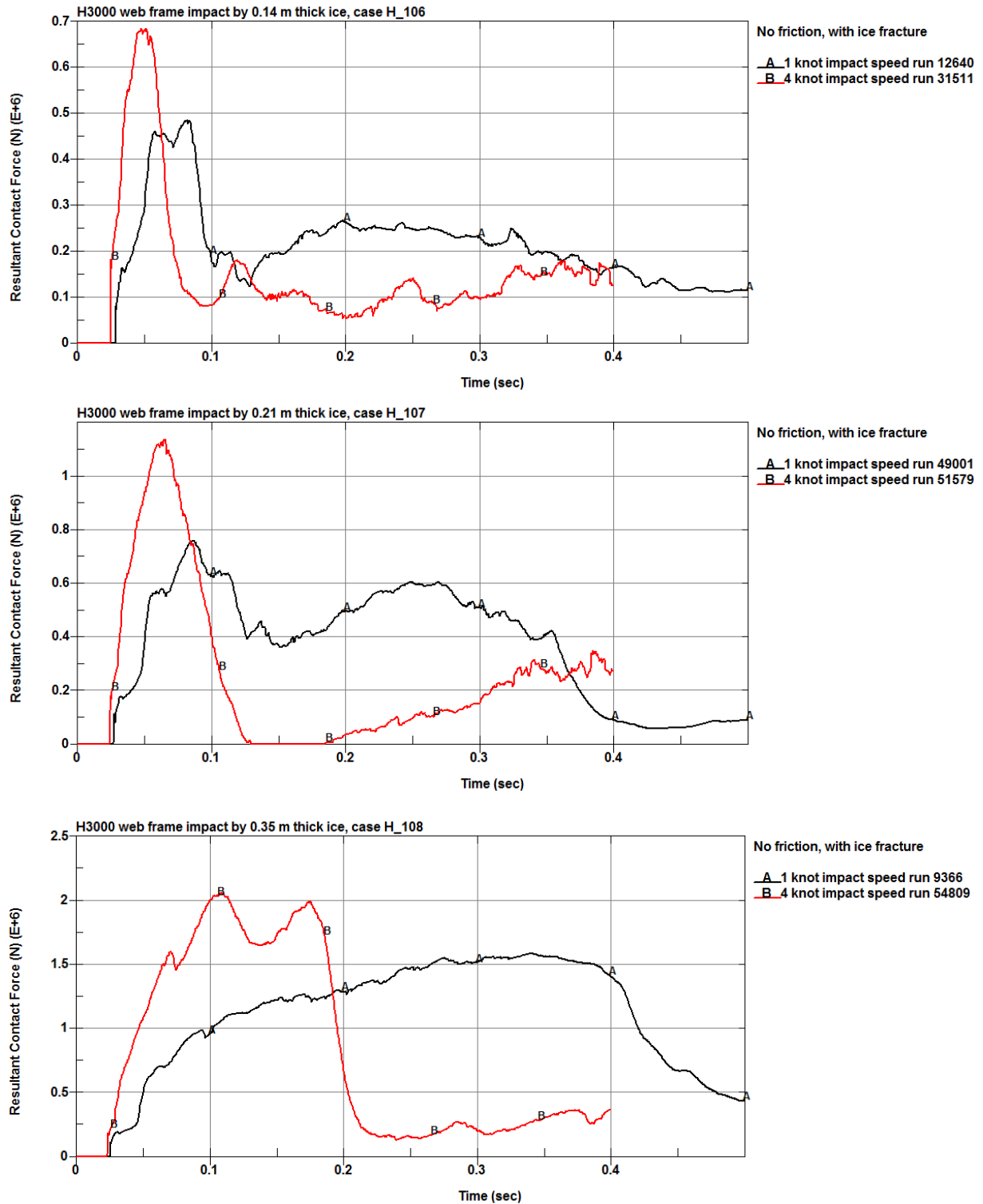
Table 25 compares peak forces and ice fracture data for the higher-speed impact with data for the baseline slow-speed impact. In all cases, peak force is higher when loading is more rapid, especially with frictionless contact. Ice fracture is faster and more decisive and complete when the relative velocity between ice and structure is higher.

Table 25. Peak Force and Ice Slab Failure Results for Baseline and Increased Approach Speed, Loading on Transverse Web Frame

LS-DYNA Run ID	Case ID	Ice Thickness (m)	Time of First Ice Element Failure (s)	Number of Failed Ice Elements	Peak Force (MN)	Time of Peak Force (s)	Time of Peak Plastic Strain (s)
A	BASELINE APPROACH SPEED (1 kn), no contact friction, with fracture						
12640	H_106	0.14	0.2951	293	0.4859	0.0805	0.085
49001	H_107	0.21	0.2658	657	0.7600	0.087	0.355
9366	H_108	0.35	0.1388	3471	1.588	0.34	0.500*
B	BASELINE APPROACH SPEED (1 kn), with contact friction, with fracture						
13169	H_106	0.14	0.1274	401	0.7470	0.113	0.115
49515	H_107	0.21	0.1531	2717	1.500	0.299	0.490
9972	H_108	0.35	0.2141	120	2.787*	0.500*	0.495
C	INCREASED APPROACH SPEED (4 kn), no contact friction, with fracture						
31511	H_106	0.14	0.0749	1161	0.6860	Near 0.05	0.244
51579	H_107	0.21	0.0726	2046	1.138	0.0648	0.260
54809	H_108	0.35	0.0785	6814	2.061	0.107	0.332
D	INCREASED APPROACH SPEED (4 kn), with contact friction, with fracture						
50940	H_106	0.14	0.0714	1107	1.003	0.0624	0.196
44805	H_107	0.21	0.0828	4092	1.660	0.114	0.320
55644	H_108	0.35	0.1540	6867	3.221	0.235	0.400*

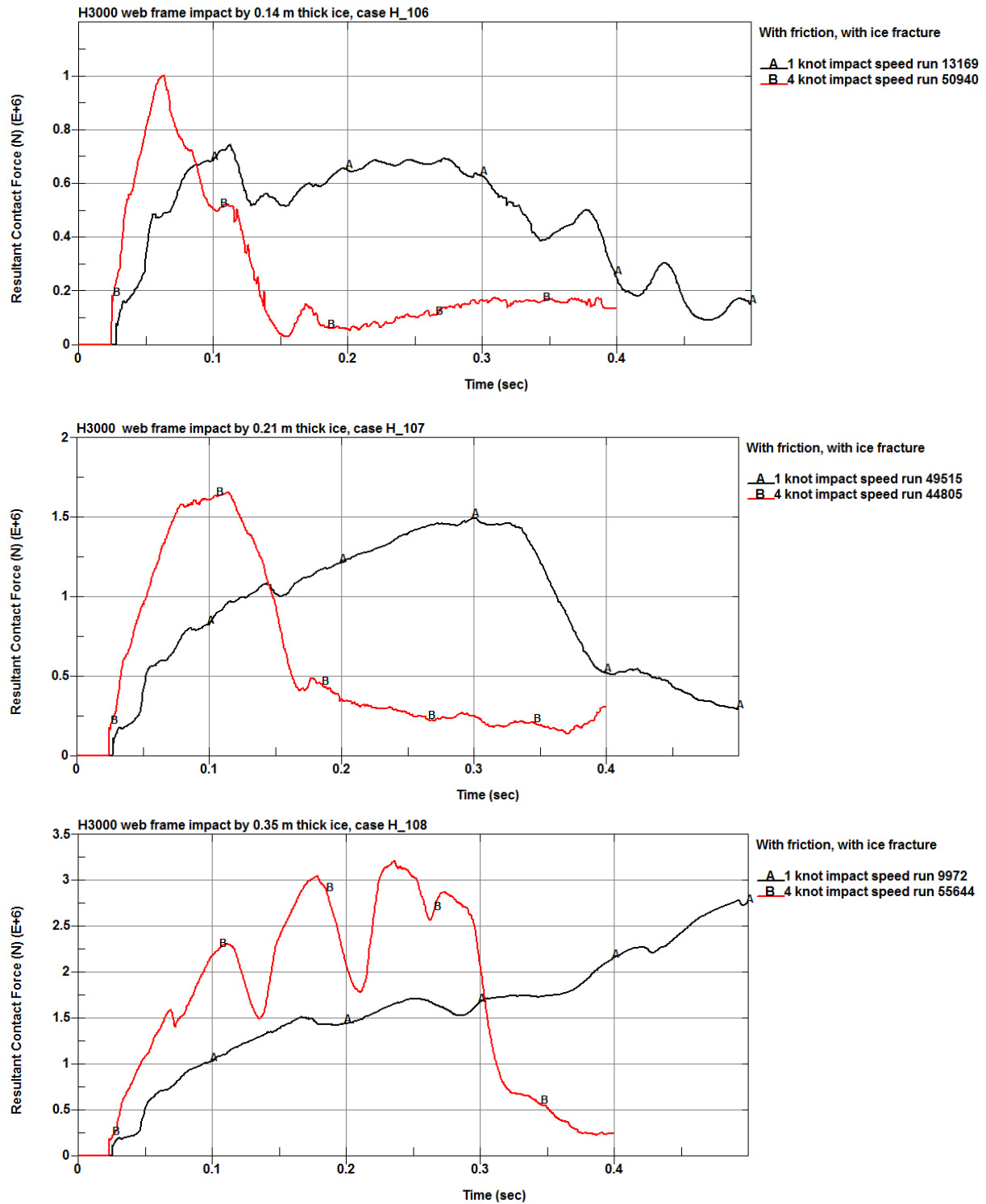
Note: * Peak force and plastic strain probably continue to increase after 0.4-s or 0.5-s simulation timespans.

Figure 40 presents time histories of contact forces for the cases listed in Table 25. Zero-friction scenarios appear first, followed by the cases with contact surface friction. The contact force history demonstrates low-frequency oscillation in the final faster-rate scenario pictured for the case of 0.35-m-thick ice and nonzero contact friction. This intriguing behavior, not seen in any other simulation discussed thus far, may be due to excitation of structural vibration.



(a) Frictionless Contact

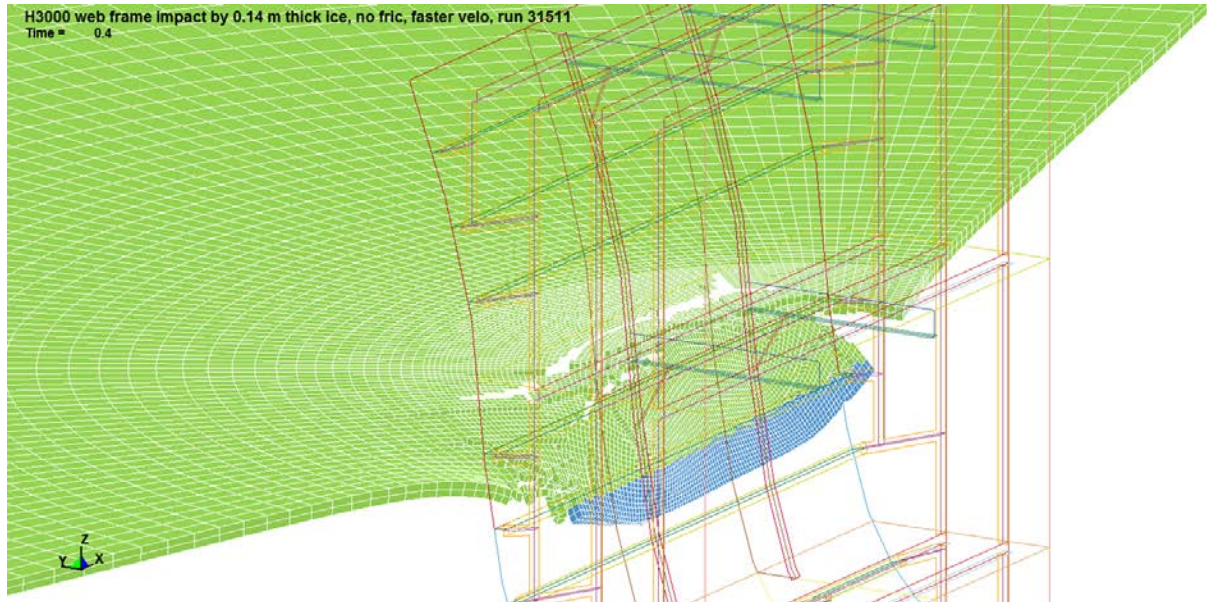
Figure 40. Contact Force Time Histories for Baseline and Increased Approach Speed, Loading on Transverse Web Frame



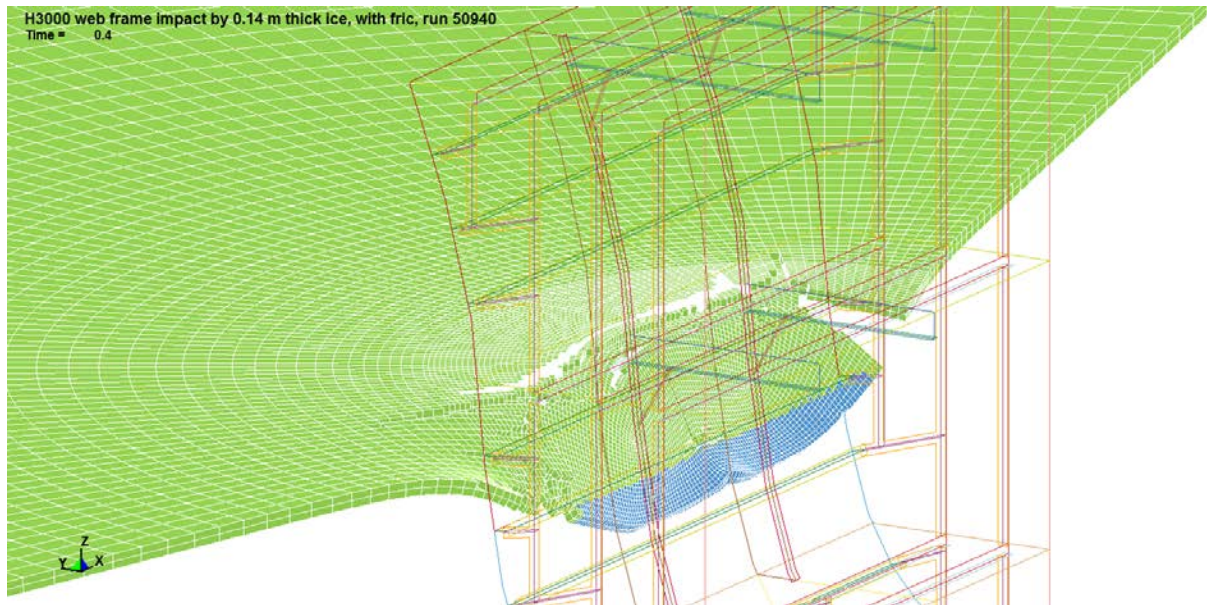
(b) With Contact Surface Friction

Figure 40. Contact Force Time Histories for Baseline and Increased Approach Speed, Loading on Transverse Web Frame (cont'd)

Ice slab crack patterns occurring in the six faster loading cases appear in Figure 41, Figure 42, and Figure 43. These may be compared to those appearing in Figure 26, Figure 29, and Figure 33, respectively. Crack patterns for the intermediate-thickness cases are shown at times shortly after peak load rather than at simulation end time.

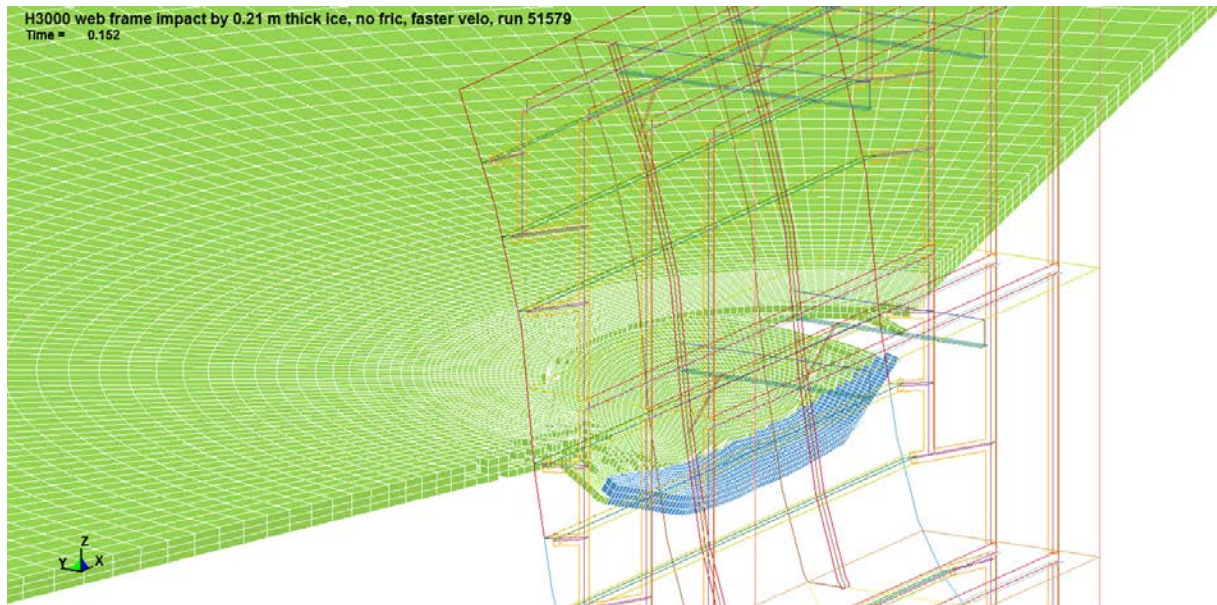


(a) Frictionless Contact

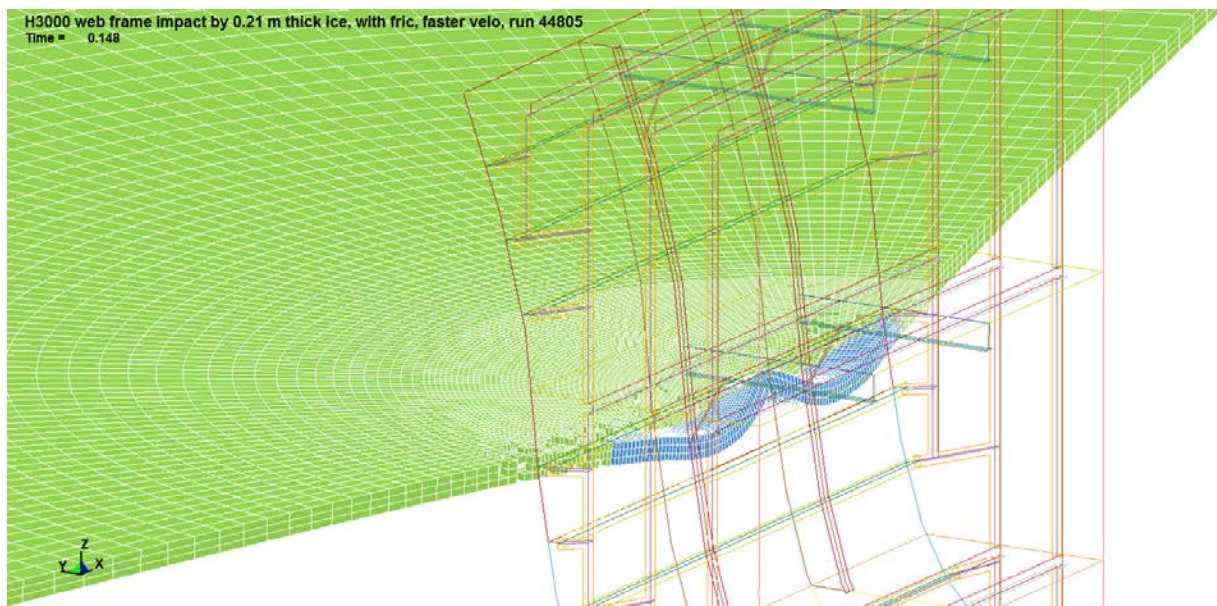


(b) With Contact Surface Friction

Figure 41. Ice Slab Fracture Patterns for Faster Web Frame Impact, 0.14-m Thickness

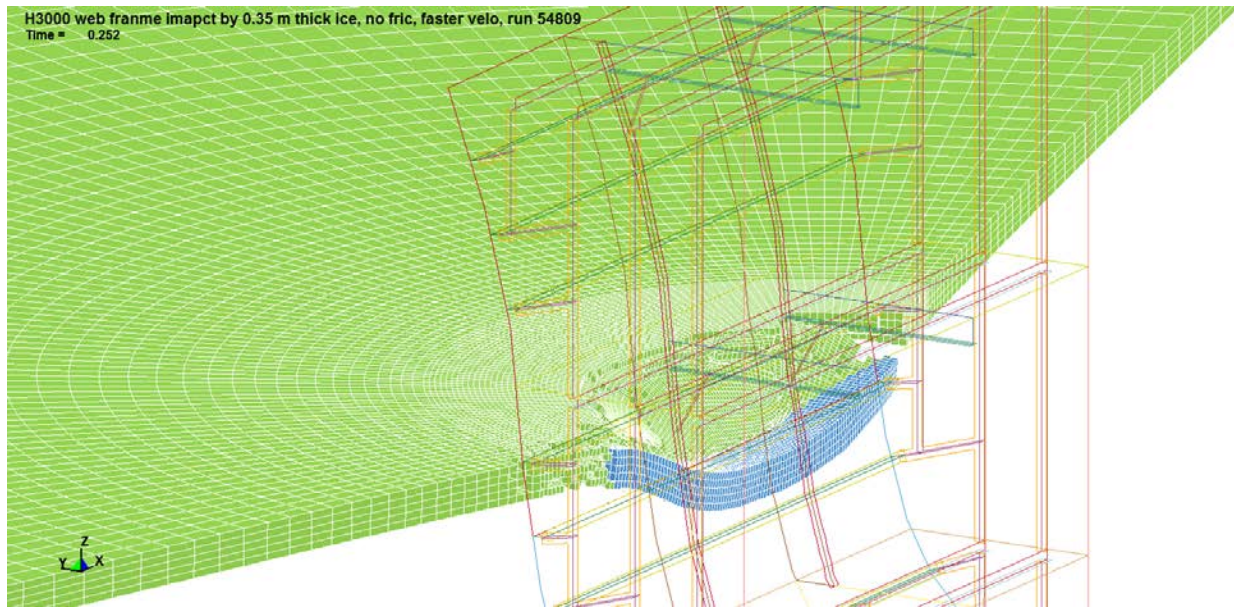


(a) Frictionless Contact

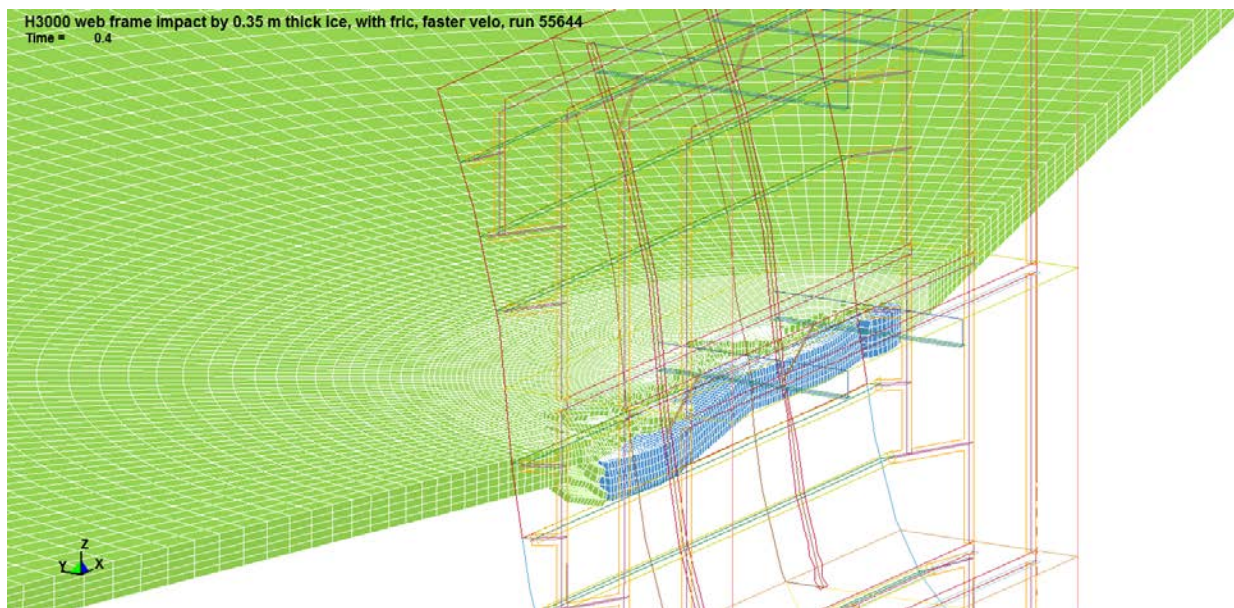


(b) With Contact Surface Friction

Figure 42. Ice Slab Fracture Patterns for Faster Web Frame Impact, 0.21-m Thickness



(a) Frictionless Contact



(b) With Contact Surface Friction

Figure 43. Ice Slab Fracture Patterns for Faster Web Frame Impact, 0.35-m Thickness

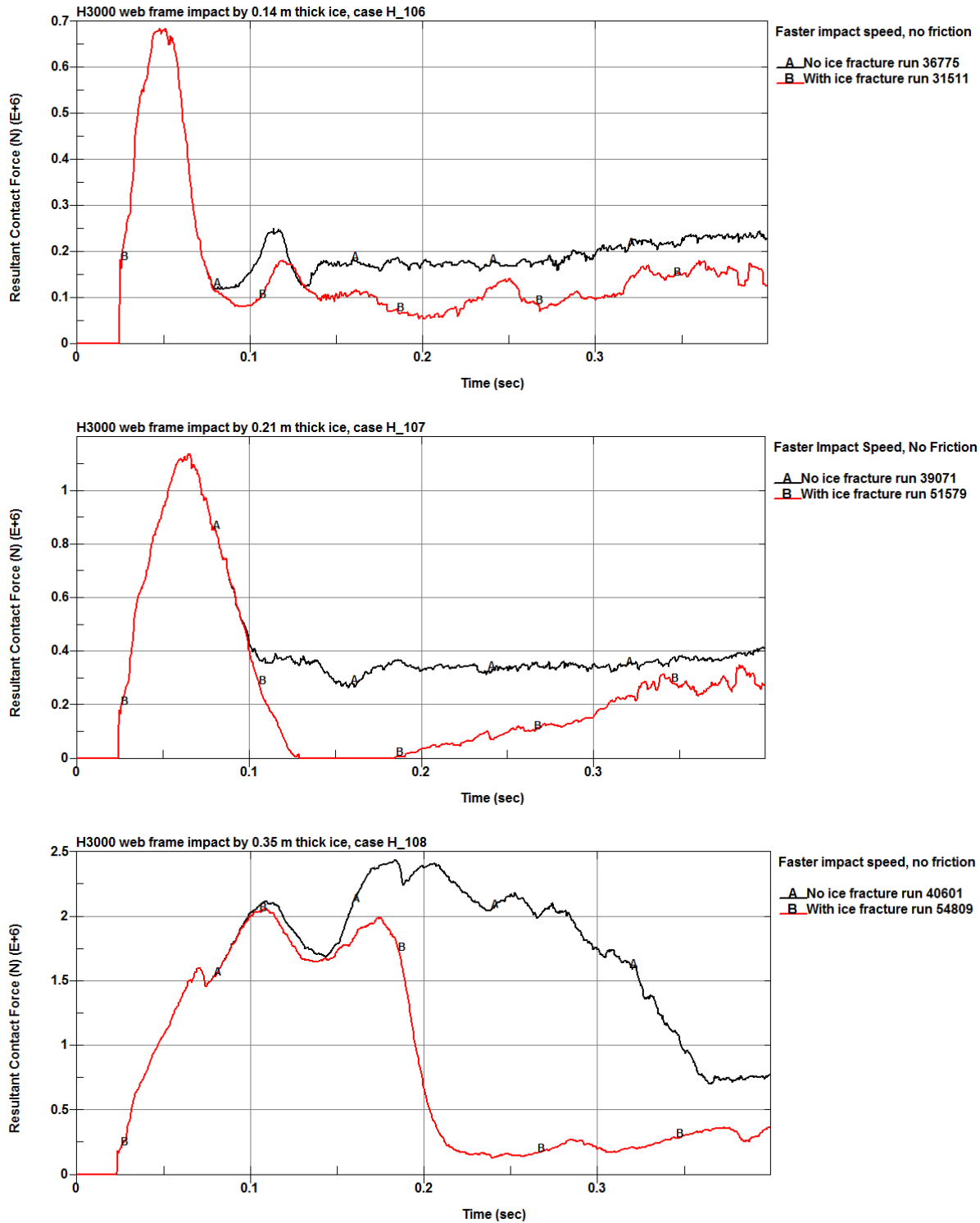
However, as with slower loading, ice fracture does not consistently limit peak loads, a point evident in Table 26, although the difference for the largest ice thickness between slower and faster loading cases is more substantial.

Table 26. Comparison of Peak Loads for No-Fracture and With-Fracture Analyses at Increased Approach Speed, Loading on Transverse Web Frame

LS-DYNA Run ID	Case ID	Ice Thickness (m)	Time of First Ice Element Failure (s)	Number of Failed Ice Elements	Peak Force (MN)	Time of Peak Force (s)	Time of Peak Plastic Strain (s)
A	INCREASED APPROACH SPEED (4 kn), no contact friction, no fracture						
36775	H_106	0.14	N/A	None	0.6860	Near 0.05	0.192
39071	H_107	0.21	N/A	None	1.138	0.0648	0.200
40601	H_108	0.35	N/A	None	2.439	0.184	0.392
B	INCREASED APPROACH SPEED (4 kn), with contact friction, no fracture						
37462	H_106	0.14	N/A	None	1.003	0.0624	0.196
39819	H_107	0.21	N/A	None	1.824	0.176	0.388
41250	H_108	0.35	N/A	None	4.635	0.343	0.400*
C	INCREASED APPROACH SPEED (4 kn), no contact friction, with fracture						
31511	H_106	0.14	0.0749	1161	0.6860	Near 0.05	0.244
51579	H_107	0.21	0.0726	2046	1.138	0.0648	0.260
54809	H_108	0.35	0.0785	6814	2.061	0.107	0.332
D	INCREASED APPROACH SPEED (4 kn), with contact friction, with fracture						
50940	H_106	0.14	0.0714	1107	1.003	0.0624	0.196
44805	H_107	0.21	0.0828	4092	1.660	0.114	0.320
55644	H_108	0.35	0.1540	6867	3.221	0.235	0.400*

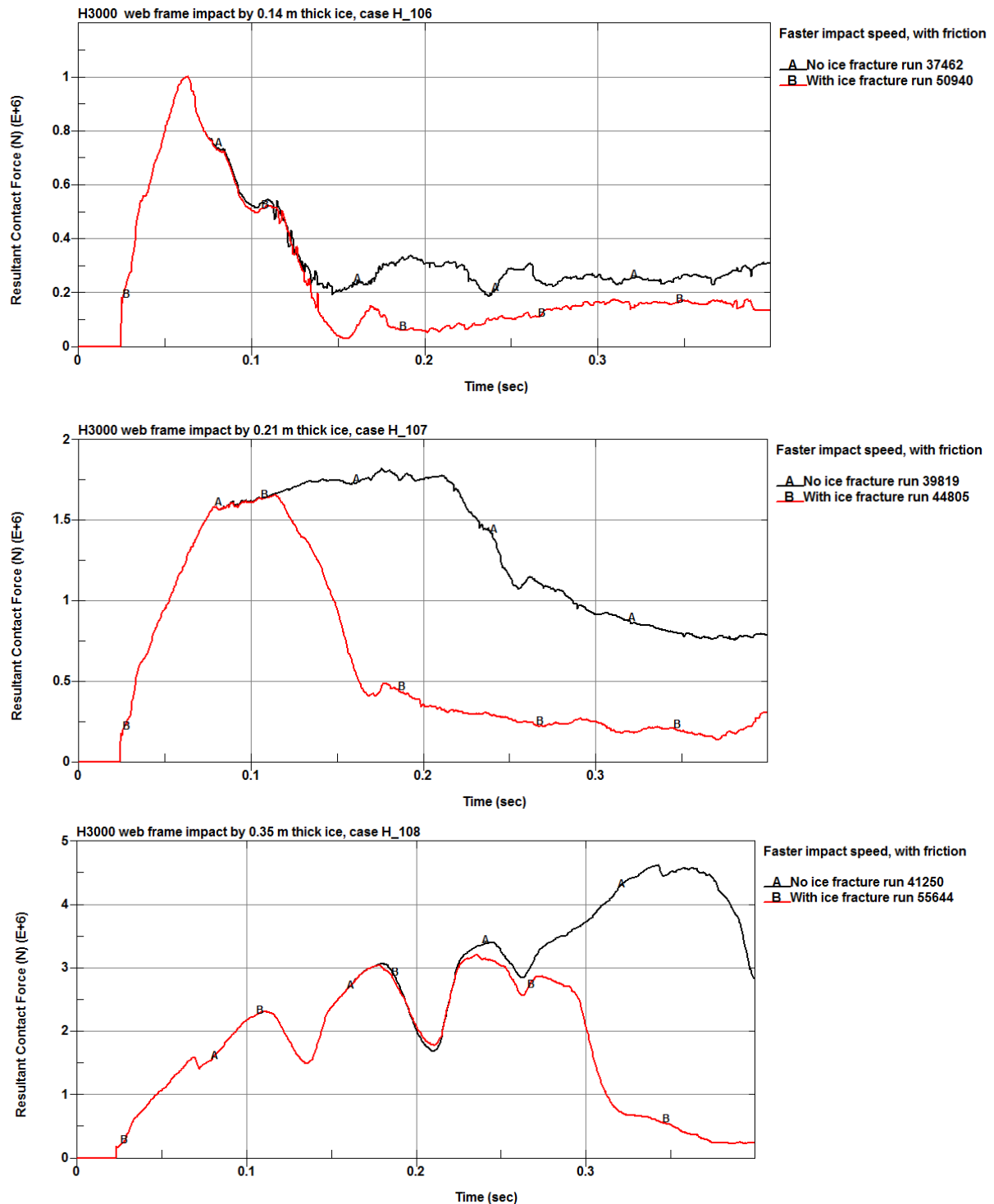
Note: * Peak plastic strain probably continues to increase after 0.4-s simulation timespan.

Figure 44 contains time histories of contact forces for the cases listed in Table 26. Frictionless scenario results appear first, followed by the cases with contact surface friction. Distinct lower-frequency oscillations of contact force occur in the case of 0.35-m-thick ice collision with nonzero interface friction. This behavior, postulated to be due to structural vibration excited when loading rate is more dynamic and already seen in the final plot of Figure 31, occurs whether ice slab fracture is allowed or not.



(a) Frictionless Contact

Figure 44. Contact Force Time Histories With and Without Ice Fracture for Increased Approach Speed, Loading on Transverse Web Frame

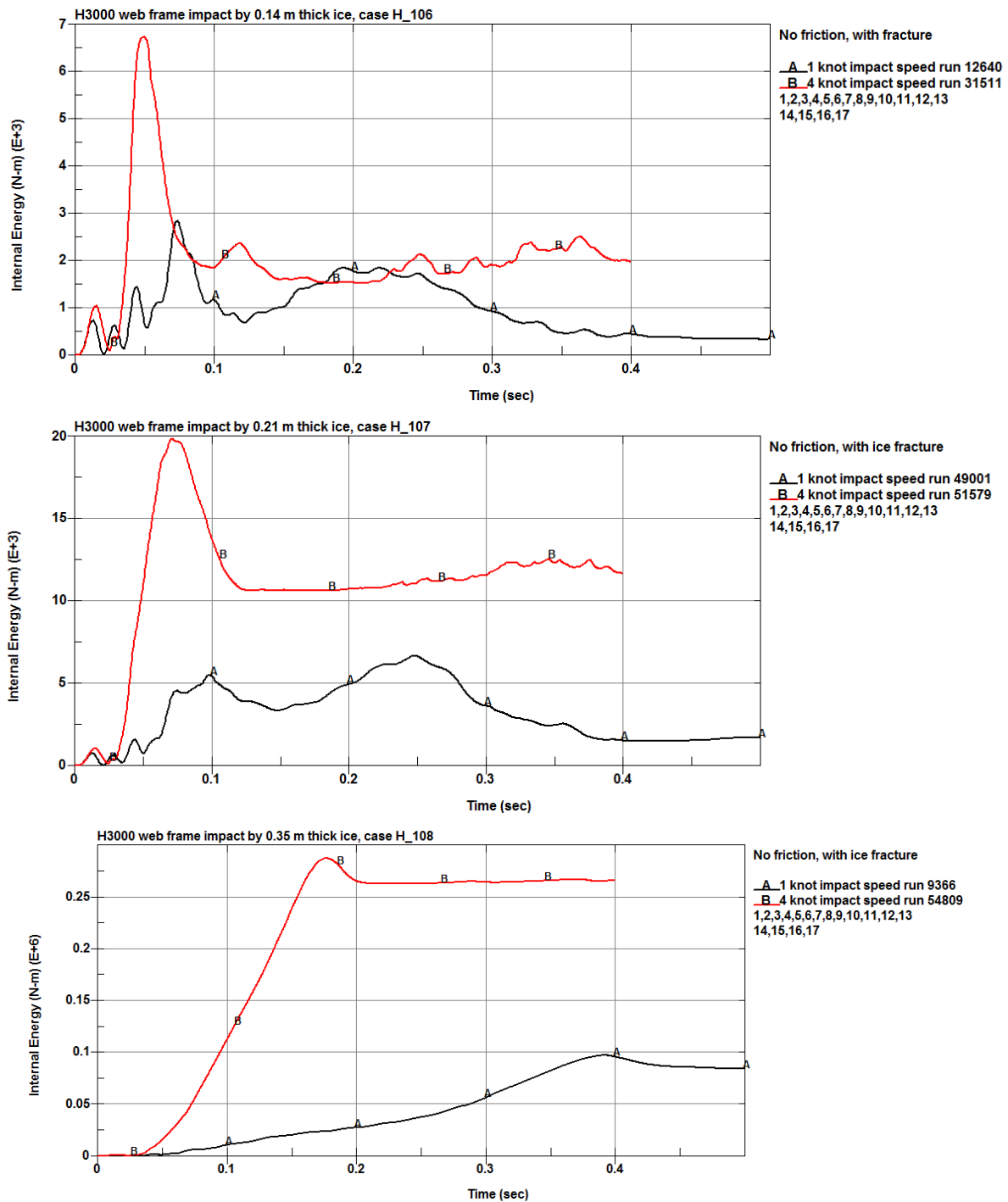


(b) With Contact Surface Friction

Figure 44. Contact Force Time Histories With and Without Ice Fracture for Increased Approach Speed, Loading on Transverse Web Frame (cont'd)

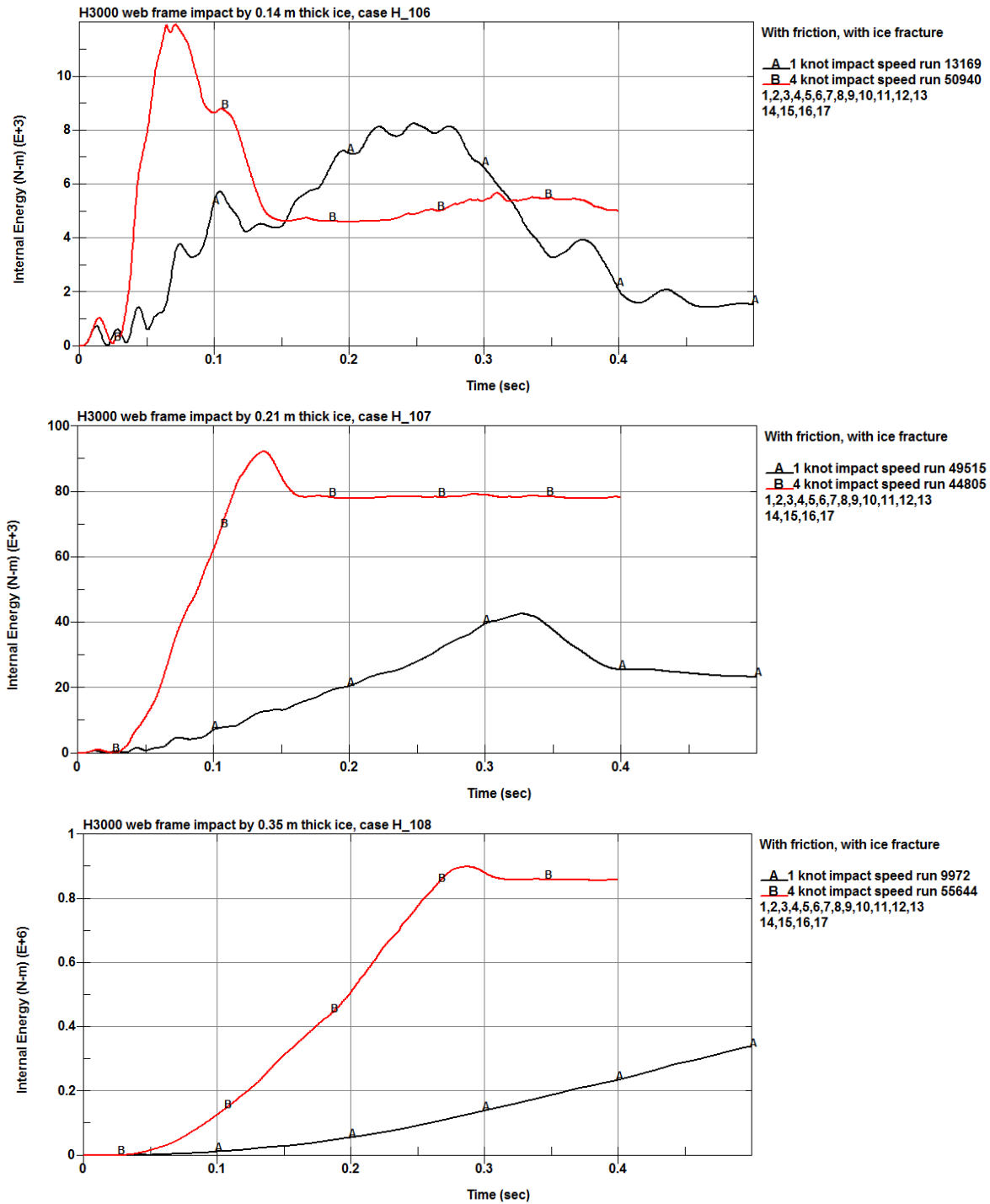
Differences between the peak inelastic strains in the major structural parts in the slower- and faster-impact analyses are confusing and inconsistent when presented in tabular form. Since energy dissipated in plastic deformation is included in the internal energy reported by LS-DYNA, graphical comparisons of the structural⁹ residual internal energy remaining at the final simulation time show trends with impact velocity in a more concise way than tables of plastic strain values. Graphs pertaining to the slower/faster impact scenario pairs listed in Table 25 are presented in Figure 45. Results for cases with contact surface friction follow frictionless scenario results. When comparing the net internal energy remaining in structural parts at the end of the simulation (energy dissipated in plastic deformation), there is a clear trend for the higher velocity scenario to be more damaging.

⁹ The time history plots omit the internal energy in the ice portion of the models. Only the sum of internal energies in the metallic structural parts are plotted.



(a) Frictionless Contact

Figure 45. Comparison of Dissipated Energies for Baseline and Increased Approach Speed, Loading on Transverse Web Frame



(b) With Contact Surface Friction

Figure 45. Comparison of Dissipated Energies for Baseline and Increased Approach Speed, Loading on Transverse Web Frame (cont'd)

Though the collision velocity assumed in the great bulk of analyses reported here might be overly low, this limited study on collision speed does not support invalidation of conclusions reached (i.e., great sensitivity to contact friction, little consistent dependence on ice fracture

occurrence). This does not mean that the speed of impact is unimportant; rather, speed of impact remains a key factor in quantifying structural impact capacity and damage propensity.

4.4.3 Effect of Ice Crushing Material Model

In all H3000 analyses reported thus far, a tuned elastic-plastic material model with strain hardening (LS-DYNA MAT3) was used for the portion of the ice slab nearest to the ice/structure contact zone. In report section 3.2.1, this model was compared in general terms with the distinctly different ice crushing model based on LS-DYNA's crushable foam material model, MAT63. The relative ease and quickness of the simulations conducted in this effort (wall-clock time of less than ½ h per run) prompted a brief consideration of the MAT63 crushing model and comparison with results using the MAT3 model.

LS-DYNA simulations with crushable foam in the crushing zone were carried out only for no-fracture assumptions, to maintain focus on crushing behaviors. These web frame impact analyses were performed for zero- and nonzero-contact-surface-friction conditions and assumed the faster relative ice/structure velocity of 4 kn. Table 27 lists the parameters specified for LS-DYNA MAT63; these are roughly the same¹⁰ as those assumed by the model's originator (Gagnon & Derradji-Aouet, 2006; Gagnon & Wang, 2012). A bilinear curve of yield stress versus volumetric strain prescribes the material nonlinearity. Apart from mass density and elastic modulus, note the great dissimilarity with respect to parameters used in MAT3-modelled crushing ice, as listed in Table 3.

Table 27. LS-DYNA MAT63 Parameters for Ice in the Crushing Zone

Parameter	Value
Mass Density	900 kg/m ³
Elastic Modulus	9 GPa
Poisson's Ratio	0.003
Yield Stresses (Corresponding Volumetric Strain)	0.1 MPa (eps = 0.0) 0.1 MPa (eps = 0.065) 4.5 GPa (eps = 1.0)*
Tensile Stress Cutoff	50 MPa

Note: * Tangent modulus of 4.8127 GPa implied (~½ of elastic modulus)

LS-DYNA's disallowance of thick-shell elements with MAT63 forced usage of 3D solids in these simulations. In addition, there is no meshing change to compensate for the drastic through-thickness integration point loss. A MAT3 analysis set with 3D solids substituting for thick shells provided a new baseline, and results therefrom are included in Table 28, which contrasts MAT3 and MAT63 peak force and peak plastic strain results.

¹⁰ Gagnon had presumed a tangent modulus of 4.7 GPa and a tensile cutoff stress of 800 MPa. The small modulus difference (4.8127 versus 4.7 GPa) is not likely significant, and the tensile stress cutoff is not a limiting factor in four of six simulations. In the remaining two cases, tensile stresses in the ice are not encountered until late in the collision event.

Table 28. Peak Force and Ice Slab Failure Results for Elastic-Plastic and Crushable Foam Ice Crushing Models, Loading on Transverse Web Frame

LS-DYNA Run ID	Case ID	Ice Thickness (m)	Time of First Ice Element Failure (s)	Number of Failed Ice Elements	Peak Force (MN)	Time of Peak Force (s)	Time of Peak Plastic Strain (s)
A	ELASTIC-PLASTIC MAT3 CRUSHING MODEL, 3D solids, no contact friction						
10939	H_106	0.14	N/A	None	0.681	0.0484	0.300
12447	H_107	0.21	N/A	None	1.220	0.0644	0.184
13844	H_108	0.35	N/A	None	2.641	0.182	0.392
B	ELASTIC-PLASTIC MAT3 CRUSHING MODEL, 3D solids, with contact friction						
11655	H_106	0.14	N/A	None	0.984	0.0604	0.292
13115	H_107	0.21	N/A	None	1.680	0.117	0.396
14486	H_108	0.35	N/A	None	4.831	0.360	0.400*
C	CRUSHABLE FOAM MAT63 CRUSHING MODEL, 3D solids, no contact friction						
7208	H_106	0.14	N/A	None	1.236	0.0568	0.064
8116	H_107	0.21	N/A	None	1.477	0.0544	0.156
41882	H_108	0.35	N/A	None	3.284	0.350	0.360
D	CRUSHABLE FOAM MAT63 CRUSHING MODEL, 3D solids, with contact friction						
7660	H_106	0.14	N/A	None	1.322	0.0580	0.068
16780	H_107	0.21	N/A	None	2.600	0.169	0.396
3905	H_108	0.35	N/A	None	4.246	0.326	0.396

Figure 46 provides time histories of contact forces for the cases listed in Table 28. For all thicknesses, the MAT63 ice provides a steeper force rise and, in all but one case (thickest ice with friction), higher peak force. For the lower two ice thicknesses, the MAT63 model provides sustained high contact force over a longer timespan, especially when nonzero friction allows more prolonged structure/ice contact. However, since the applicability of the glacial ice-derived MAT63 ice model parameters to sea-ice-slab-edge crushing behavior is unknown, it is unwise to attribute much more to the curves in Figure 46 than the fact that the contact force behaviors (and the accompanying structural responses) are different for the two crushing-zone ice models.

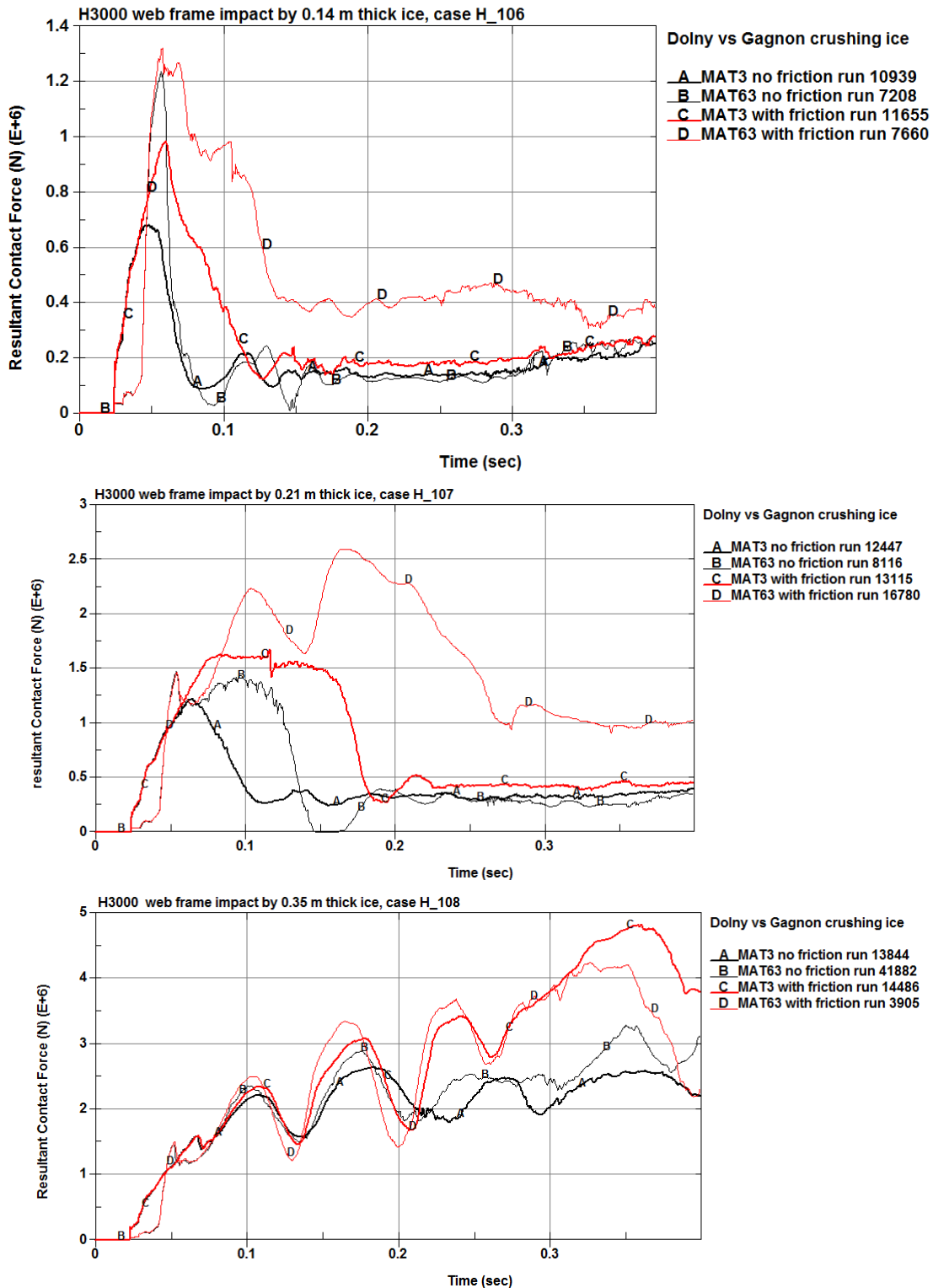
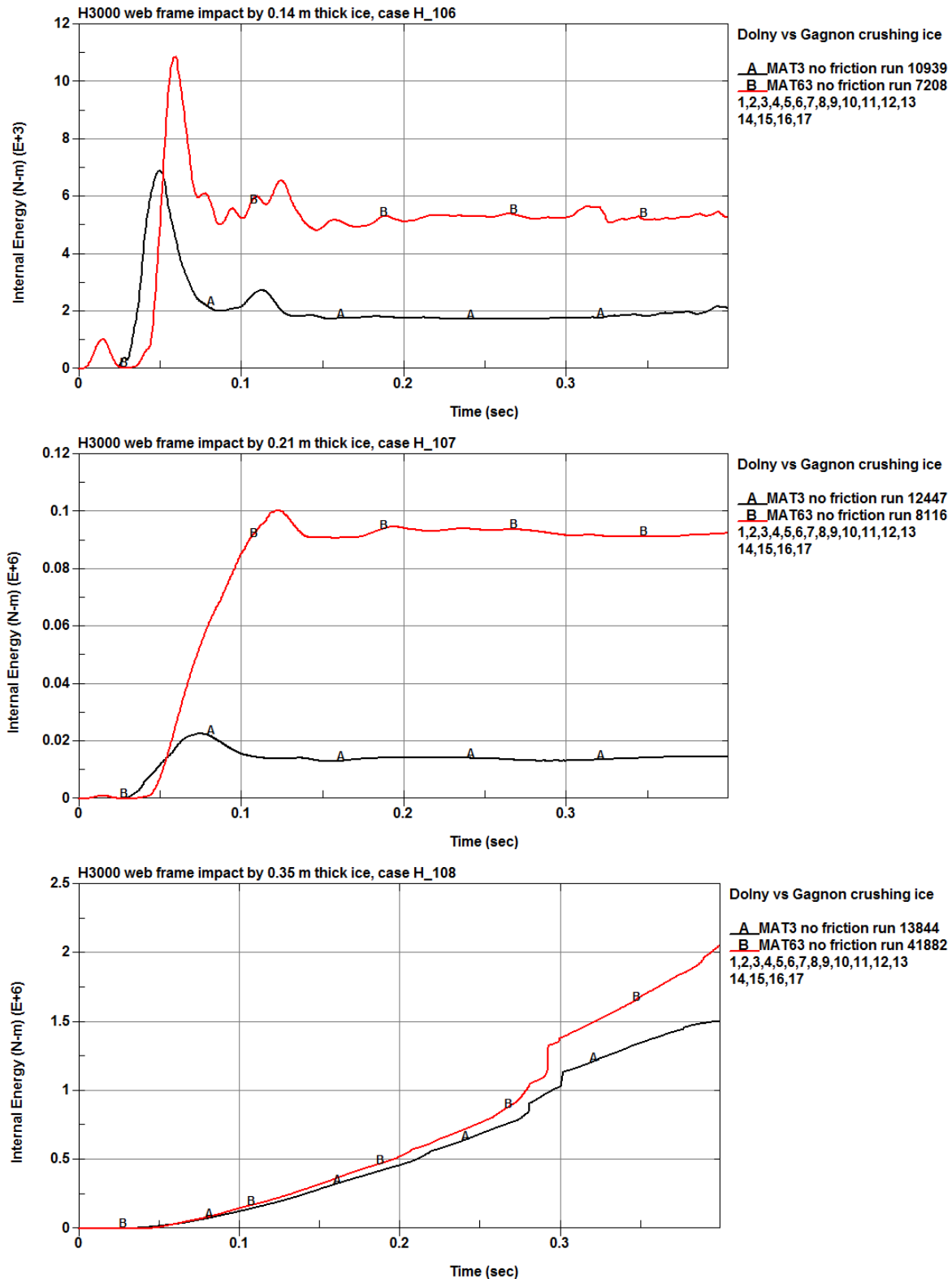


Figure 46. Comparison of Contact Force Time Histories for Two Methods of Ice Crushing Modeling, Loading on Transverse Web Frame

Figure 47 shows comparisons of structural internal energy time histories between the two approaches for modeling crushing-zone ice. Without detailing inelastic strains in the structure part by part, this data presentation gives a quick feel for the relative structural damage incurred

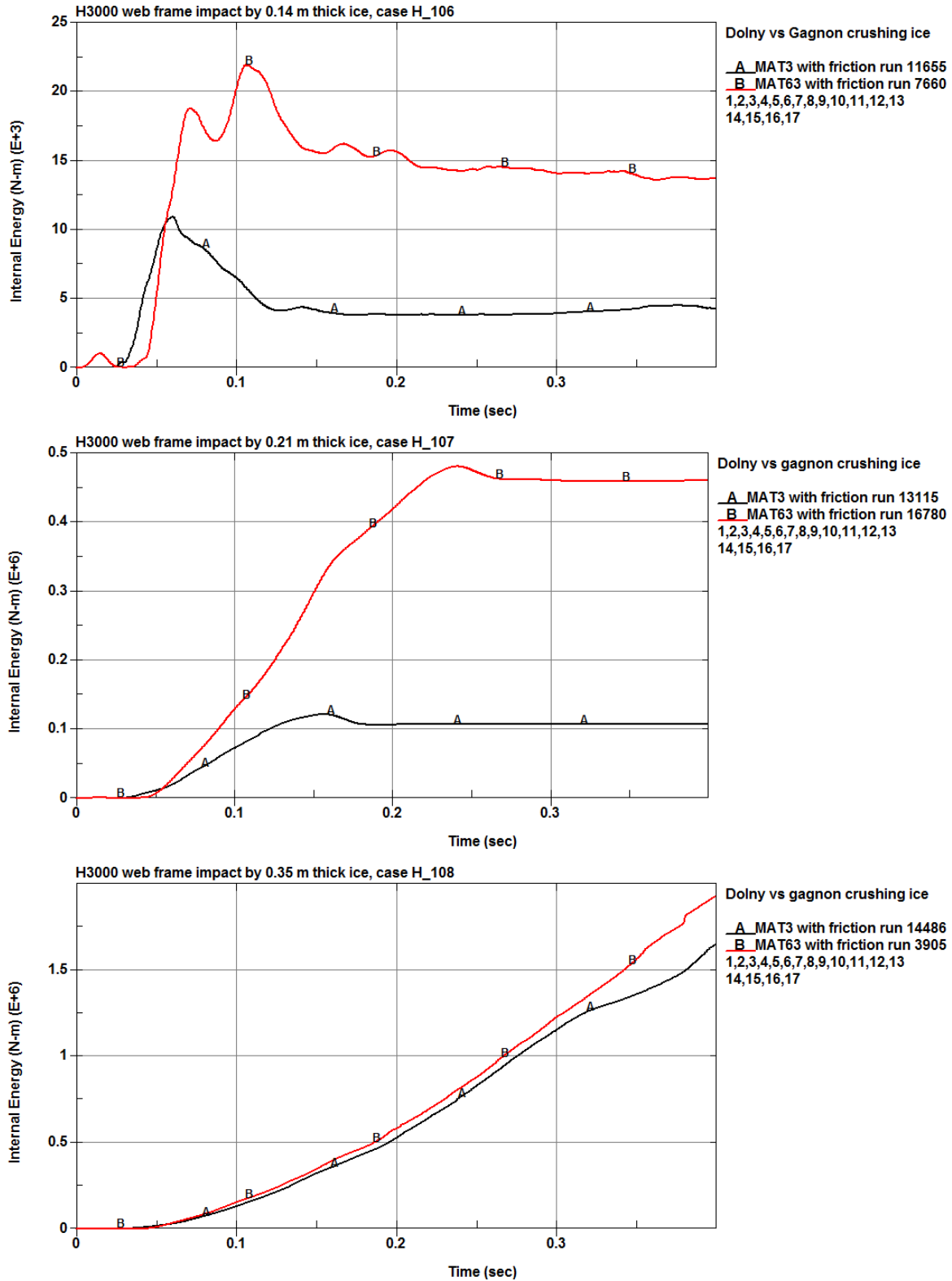
with the two ice models. Graphs for the three ice thickness cases for frictionless contact are followed by graphs for the three thickness cases with contact friction. In all variations, the final irrecoverable structural internal energy level (and hence plastic deformation) is higher for the MAT63 ice than for the MAT3 ice. The plastic strain magnitudes attained in the H3000 structural components also reflect the greater damage inflicted by MAT63 ice versus MAT3 ice, when using the material model parameters optimized for glacial ice bodies. For the two lower thicknesses, structural permanent set has reached a maximum attained level within 0.4 s, and since ice fracture is not allowed, the only load-relieving mechanism is ice/structure contact loss due to ice slab bending. In the highest-thickness case, permanent set deformation has not reached a final value in the simulation timespan, as the ice bending stiffness is high.

The modeling exercises discussed in this section illustrate that the stress-versus-strain properties assumed for the small region of ice close to the structure/ice contact zone that suffers crushing during collision strongly influence permanent set deformations in the structure.



(a) Frictionless Contact

Figure 47. Comparison of Dissipated Energies for Two Methods of Ice Crushing Modeling, Loading on Transverse Web Frame



(b) With Contact Surface Friction

Figure 47. Comparison of Dissipated Energies for Two Methods of Ice Crushing Modeling, Loading on Transverse Web Frame (cont'd)

5. Conclusions

In this report, the FEM is used in collision interaction studies of floating ice slabs in the 0.14-m-to-0.35-m-thickness range with an idealization of a localized portion of notional naval surface ship hull structure. Crushing and flexural ice fracture is enabled in the ice slabs, and inelastic permanent deformation of the structure is allowed.

At the highest-level, this study showed that, for the ice slab thicknesses and sizes considered, typifying ice floes that would be frequently encountered in the MIZ, flexural fracture of the slabs does not strongly and consistently influence prediction of structural loading and permanent set damage. This is despite the relatively low slab thicknesses considered. Reliance on a “flexural limit” in future development of ice loading criteria for relatively wall-sided non-ice-classed naval surface ship hull structures does not seem to be advisable.

This study also supports the following conclusions on structure/ice collision modeling details and assumptions:

- a) The LS-DYNA material models MAT3 and MAT124 for ice crushing and ice flexural fracture simulation, shown in prior work to be promising in earlier ice beam fracture and simulations of ice slabs loaded by rigid indenters, are effective for treatment of ice slab collision interaction with flexible hull structures with realistic scantlings.
- b) Ice-structure impact modelers must take care when designating the number of ice element integration points needing to reach failure condition before elements representing ice are deleted. Allowing element deletion when only one of several integration points has reached failure is likely to lead to premature failure.
- c) Contact friction assumptions on the ice/structure interface drastically impact loads placed on the structure and resulting structural damage. Nonzero friction enhances contact and prolongs loading duration, increasing damage.
- d) The degree of ice slab displacement constraint on the slab boundary remote from the impact zone strongly influences ice and structural damage. Greater constraint increases the damage in both media.
- e) Based on limited study, higher relative velocity between ice and structure increases structural permanent set damage. This is a finding consistent with the few existing previous studies of structure/ice collision with inelastic structural response allowed.
- f) Effective hourglassing control in structural shell elements and suppression of extraneous structural motion on local structural FEM truncation boundaries is necessary. Imposing structural damping to suppress extraneous vibrations significantly reduces plastic deformation in the structure and should be avoided by modelers, if possible.
- g) The LS-DYNA crushable foam material model (MAT63), with parameters optimized for glacial ice, provides more severe structural damage predictions than the elastic-plastic MAT3, with parameters tuned for seawater floe ice, when used in the ice crushing zone.

6. Recommendations

The author recommends study of the following modeling concerns, not addressed in the simulations reported here, but identified in the predecessor effort (Lesar, 2017):

- a) Multiple analyses over systematic mesh refinements are needed to manage the inherent mesh sensitivity of the erosion approach for simulating ice fracture.
- b) Means of mitigating mesh sensitivity in the ice FEM need to be examined, particularly nonlocal methods and progressive failure models utilizing fracture toughness parameters to scale the unloading process.

This report is wholly concerned with computational structural mechanics simulations applied to the floating ice/ship structure collision problem area. Practically all physical measurements of such phenomena, whether full-scale, model-scale, in the field, or in the laboratory, involved relatively rigid structures responding elastically. None of the computations reported here have corroborating experimental validity evidence. There is a general need for experimental data to validate the modeling approaches and assumptions used in this work and future extensions thereof. Future laboratory testing of flexible ice-loaded structures in support of the U.S. Navy and allied navies, planned for 2019 and beyond, will begin to fill this information void.

Based on this reported work, the author also recommends material response and failure model research in the following areas:

- a) Extension of metallic hull structure material response modeling is needed to account for tearing and rupture. This will necessitate usage of material response models accommodating dependence of failure criteria on stress triaxiality, pressure, and strain rate. Edge dimensions of shell elements relative to thickness need special attention to obtain valid results.
- b) Evaluation of progressive material failure models with unloading phases governed by fracture toughness is needed for ice failure simulation. Laboratory experiments are needed to calibrate and validate toughness-dependent ice material failure models.
- c) Access to the Liu-Amdahl LS-DYNA user-defined material model for glacial ice response and failure (Liu et al., 2011b), which includes hydrostatic pressure dependence of the failure criterion, is highly desirable. This is particularly important if stronger and brine-free glacial ice impacts are of operational concern.

As mentioned in the main body of this report, the H3000 locally detailed FEM was used in recent LS-DYNA studies that sought finite-structural-deformation “corrections” to the spreadsheet-based ice impact analysis tool DDePS, which normally presumed a rigid structure. The full-ship H3000 hull form was also used in a recent benchmarking study (Hagan, 2017) comparing ice impact loadings obtained by DDePS, the NSWCCD-developed program ICELOAD (Hagan & Devine, 2014), and an innovative Discrete Element Method for modeling ice (Song, Parno, West, & O’Connor, 2018). It is wholly logical to adapt, extend, and/or couple the detailed local H3000 hull structure model to a less-detailed LS-DYNA representation of the entire H3000 so that whole-body inertias and collision momentum transfer is captured. This

would better align the kinematic assumptions of the FE models with the lower-fidelity modeling of DDePS and would be for the purposes of baselining the high-fidelity modeling methods of this report with respect to less sophisticated approaches.

Developing high-fidelity modeling of complex ice/structure impact and damage phenomena is difficult but ultimately useful. Although the efforts documented in this report and others referenced are gradually establishing better guidelines for modeling relevant phenomena in high-fidelity ice/structure collision simulations, such simulations still require development and execution by “experts” and will not devolve to quickly executing black-box-level tools in the immediate future. Nevertheless, painstaking research in developing and validating high-fidelity methods reveals phenomena that must be accounted for in lower-fidelity methods and suggests simplifying approximations that can validly be made in improving lower-fidelity tools rapidly applicable to operational risk evaluation questions.

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Appendix A

Physical and Mechanical First-Year Sea Ice Properties in the Marginal Ice Zone

A.1 Ice Floe Size, Thickness, and Mass

Ice floe diameter and thickness data for ice concentrations of 60 % or less acquired during the 1986 USCGC Polar Sea (WAGB 11) Bering Sea marginal ice zone (MIZ) trial (St. John, 1986) have been assembled (Schultz, 1988) and are reproduced here in Table A1 and Table A2. Schultz categorizes these data as representative of “North Pacific” conditions. There is no clear trend for floe diameters to decrease as ice concentration decreases; however, floe sizes do decrease systematically as larger floes are disregarded as collision risks under the presumption that floes “larger than the ship” will be avoided by maneuvering, at least under high-visibility conditions. The very high standard deviations of floe size relative to mean values are notable. Ice thickness shows a gradual but uneven increase as ice concentration increases, though the thickness dropoff above 40 % concentration is an exception to this trend.

Table A1. Bering Sea MIZ Ice Floe Diameters

All Floes Included		
Ice Concentration (%)	Mean Floe Diameter (ft [m])	Standard Deviation (ft [m])
0 - 20	20.4 [6.2]	14.8 [4.5]
21 - 40	22.4 [6.8]	16.2 [4.9]
41 - 60	14.9 [4.5]	12.4 [3.8]
0 - 40	20.9 [6.4]	15.2 [4.6]
Larger Floes Avoided by Maneuvering		
Floes Included (ft)	Mean Floe Diameter (ft [m])	Standard Deviation (ft [m])
< 70	20.5 [6.2]	14.4 [4.4]
< 60	19.8 [6.0]	13.2 [4.0]
< 50	18.8 [5.7]	11.7 [3.6]
< 40	17.0 [5.2]	9.2 [2.8]
< 30	15.7 [4.8]	7.7 [2.3]

Note: Data adapted from *Ice Conditions for U.S. Navy Surface Ship Operations in the North Atlantic and North Pacific Marginal Ice Zone* (Report No. 8500-264-1), by L. A. Schultz, 1988, Columbia, MD: NKF Engineering Inc. Arctic Technology Group.

Table A2. Bering Sea MIZ Ice Floe Thicknesses

Ice Concentration (%)	Average Ice Thickness (ft [m])	Average Maximum Ice Thickness (ft [m])	Maximum Observed Ice Thickness (ft [m])
< 5	1.0 [0.30]	2.0 [0.61]	6.0 [1.8]
10	0.9 [0.27]	2.6 [0.79]	6.0 [1.8]
20	1.4 [0.43]	4.0 [1.2]	8.0 [2.4]
30	1.6 [0.49]	3.5 [1.1]	8.0 [2.4]
40	2.5 [0.76]	4.8 [1.5]	8.0 [2.4]
50	1.00 [.30]	3.2 [0.98]	6.0 [1.8]

Note: Data adapted from *Ice Conditions for U.S. Navy Surface Ship Operations in the North Atlantic and North Pacific Marginal Ice Zone* (Report No. 8500-264-1), by L. A. Schultz, 1988, Columbia, MD: NKF Engineering Inc. Arctic Technology Group.

Not having parallel data for “North Atlantic” regions, Schultz (1988) mentions that the chief difference in the north Atlantic relative to the north Pacific will be the presence of stronger multiyear and glacial ice. Schultz also cautions that MIZ ice is extremely variable in terms of strength and thickness, as floes can be composed of fragments from multiyear ice, and effects of wind, wave action, and weather makes uniformly thick, level ice more of an exception than a rule. Nevertheless, the data in Table A1 and Table A2 are useful for bounding the present problem. The ICELOAD program study (Hagan & Devine, 2014) considered rather wide ranges in ice floe diameter (20 ft to 100 ft, or 6.1 m to 30.5 m) and thickness (0.5 ft to 6 ft, or 0.16 m to 1.83 m). These bounds were likely meant to show predictive structural design adequacy trends over a wide ice loading range.

A different approach for bounding the likely MIZ ice floe sizes and thicknesses is demonstrated in a recent report by one of the Direct Design of Polar Ships (DDePS) developers (Dolny, Daley, Quinton, & Daley, 2016). A series of DDePS ice floe/hull collision force calculations for the Polar Sea hull form were carried out, covering a range of ice floe thicknesses and sizes, and compared to measured forces reported by St. John (1986) for collision events at (roughly) known ship speeds. This study found that the ice floe diameter range from 10 m to 35 m (33 ft to 115 ft), and a thickness range of 0.3 m to 1.2 m (1 ft to 4 ft) enveloped the highly variable measured field data. These thicknesses are consistent with Schultz’s (1988) maximum averages, and exactly cover the ice thickness range designated by the World Meteorology Organization (WMO) for “first year thin” (30 cm to 70 cm) and “first year medium” (70 cm to 120 cm) ice types (Joint Technical Commission on Oceanography and Marine Meteorology [JCOMM] Expert Team on Sea Ice, 2014, Appendix 1, nomenclature table items 2.5.1 and 2.5.2). Although the floe diameter upper bound (35 m or 115 ft) is much higher than Schultz’s mean value plus one standard deviation (11 m or 36 ft), it falls into the lower portion of the WMO maximum floe width range for “small floes” (20 m to 100 m).

It is useful to provide perspective to the ice slab sizes, thicknesses, and masses considered in the many simulations reported in this document’s main body. Table A3 compares data for the ice slabs considered in the main body of this report to lower- and upper-bound size, thickness, and mass data for “small” ice floes according to WMO categorization (JCOMM Expert Team on Sea Ice, 2014, Appendix 1 nomenclature table item 4.3.2.5) and for two ice floe impact studies

conducted by the American Bureau of Shipping (ABS)/Memorial University (MUN), team in 2016 and 2017. The slab thicknesses firmly lie on the thin side of WMO categorization, and the slab masses are also closer to the lower end of the range considered in the prior ABS/MUN efforts.

Table A3. Assessment of Ice Slab Dimensions and Masses Used in this Study

Case	Thicknesses (m)	Sizes (m)	Lower Bound Mass (kg [long ton])*	Upper Bound Mass (kg [long ton])
Polar Sea Calcs⁺	0.3 to 1.2	10 to 35 (diameter)	2.12e4 [20.9]	1.039e6 [1022.6]
DDePS Study[^]	0.1 to 1.0	20 to 80 (side dimensions of squares)	3.6e4 [35.4]	5.76e6 [5669.6]
WMO, Small Floes[%]	0.3 to 1.2	20 to 100 (assume diameter)	8.48e4 [83.5]	8.48e6 [8346]
LS-DYNA Simulations, This Report	0.14 to 0.35	1214.3 m ²	[150.6]	[376.5]

Notes:

* Ice mass density of 900 kg/m³ is assumed.

+ Data adapted from *ONR Ice Capability Assessment and Experimental Planning, Deliverable #1: DDePS_SafeCheck Technical Background and Safe Speed Assessment of NSWCCD Hull 3000* (section 3.1.2) [Technical report], by J. Dolny, C. Daley, B. Quinton, and K. Daley, 2016, Houston, TX: American Bureau of Shipping.

[^] Data adapted from *ONR Ice Capability Assessment and Experimental Planning, Deliverable #2: Advanced Modeling and Re-Assessment of NSWCCD Hull 3000* (section 4.4) [Technical report], by J. Dolny, C. Daley, B. Quinton, and K. Daley, 2017, Houston, TX: American Bureau of Shipping.

[%] Data adapted from *WMO sea-ice nomenclature, volumes I, II and III* (WMO-No. 259) [Working document], by JCOMM Expert Team on Sea Ice, 2014, retrieved from https://www.jcomm.info/index.php?option=com_oie&task=viewDocumentRecord&docID=14598

A.2 Sea Ice Physical and Mechanical Properties

The complexities of sea ice physical and mechanical properties are well described by Devine (1987, Appendix B). Sea ice strength properties are highly dependent on temperature, salinity, crystal structure, load orientation, and load rate. Sea ice typically exists at very nearly its melting temperature, so observed stiffness and strength properties vary in a wide range. Despite these facts, sufficient sea ice stiffness and strength data have been acquired through the years to define property ranges useful for design purposes.

A useful summary of physical and mechanical properties of sea ice for use in cold-environment engineering has been recently published by Timco and Weeks (2010). Their survey indicated a fairly good grasp of the properties of first-year ice but revealed relatively little data for multiyear ice. The amount and quality of data is relatively good for some properties of interest in this work (e.g., mass density, elastic modulus, compressive strength, and flexural strength) but not as good for others. Table A4 is extracted from the works of Timco and Weeks (2010, Table 1), retaining data of greatest interest. Note the poor state of knowledge of multiyear ice properties. On thickness of first-year sea ice, Timco and Weeks remark that a maximum level

ice thickness of about 2 m is typical for the American and Canadian Beaufort Sea at the end of winter, greater than the 1.2-m maximum floe ice thickness extracted from Bering Sea ice edge data gathered in the 1986 Polar Sea field trial.

Table A4. State-of-Knowledge Summary of Sea Ice Strength Properties

Property	Knowledge Quality	
	First Year Ice	Multiyear Ice
Microstructure	Good	Reasonable
Salinity and Porosity	Good	Reasonable
Thickness	Good	Limited
Mass Density	Reasonable	Limited
Tensile Strength	Limited	Limited
Compressive Strength	Good	Reasonable
Flexural Strength	Good	Nonexistent
Shear Strength	Poor	Nonexistent
Multi-Axial Strength	Reasonable	Poor
Elastic and Strain Modulus	Good	Poor
Poisson's Ratio	Poor	Nonexistent
Fracture Toughness	Reasonable	Nonexistent
Friction	Poor	Nonexistent

Note: Adapted from "A Review of the Engineering Properties of Sea Ice," by G. W. Timco and W. F. Weeks, 2010, *Cold Regions Science and Technology*, 60, p. 126.

The known ranges of first-year sea ice mechanical property and strength data in Table A5 are presented and discussed in the paper by Timco and Weeks (2010). All properties demonstrate dependencies to varying degrees on temperature, brine content, porosity, and loading rate. A few general comments on dependencies are included in Table A5, but the reader must consult the work of Timco and Weeks and their extensive reference list for details. The breadth of the variations indicate the challenges in defining reasonable properties for design calculations, evaluations, and concept studies. The engineer's first inclination would be to choose property upper bounds with the objective of achieving "conservatism," but such an approach could unduly penalize designs with loading severities that will never be experienced in reality. Careful consideration of the environment typical of intended high-latitude operational areas needs to be part of the process of deciding on ice properties to assume in parametric or point design studies.

Table A5. Ranges of Mechanical Properties of First Year Sea Ice

Property	Values or Range	Comments
Mass Density	920 kg/m ³	Decreases with decreasing brine volume
Tensile Strength	0.2 MPa to 0.8 MPa	Strong inverse function of temperature and brine volume
Compressive Strength	0.5 MPa to 5.0 MPa	Strong dependence on loading rate and higher in columnar (vertical) direction
Flexural Strength	0.5 MPa to 1.5 MPa	Square-root dependence on brine volume
Elastic and Strain Modulus	1.7 GPa to 9.1 GPa	Strong inverse function of temperature and brine volume
Poisson's Ratio	0.30 to 0.33	
Fracture Toughness	115 kPam ^{0.5} to 250 kPam ^{0.5}	Few measurements; specimen size effect impacts range
Friction Coefficient (Painted Steel)	0.05 to 0.1	0.1 is a good overall assumption
Friction Coefficient (Corroded Steel)	0.1 to 0.2	

Note: Adapted from "A Review of the Engineering Properties of Sea Ice," by G. W. Timco and W. F. Weeks, 2010, *Cold Regions Science and Technology*, 60, pp. 107-129.

A.3 References

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Appendix B

Ice Flexural Failure Modeling Improvements

Validation, refinements, and parametric study of LS-DYNA modeling methods for capturing ice slab flexural failure have been previously reported (Lesar, 2017). The LS-DYNA elastic-plastic material model *MAT_PLASTICITY_COMPRESSION_TENSION (MAT124) was used, enabling specification of an ersatz ice material with different compressive and tensile yield stresses and element erosion (crude fracture simulation) using maximum principal stress as a criterion for failure. After successful modeling of essentially two-dimensional ice beam failure in four-point bending, a study of fracture of ice slabs loaded by inclined and rigid planar indenters was carried out. Figure B1 shows a typical LS-DYNA FEM. The ice slab was modeled with several thick-shell elements stacked through the slab thickness, and with five element integration points through the depth of each shell. This modeling method allowed accurate capture of through-thickness stress gradients. Although flexural fractures with plausible radial and circumferential crack patterns were obtained, the cracks were generally not continuous over circumferential arcs and radial lines, and some portions of the slab “dissolved” where amorphous masses of elements failed.

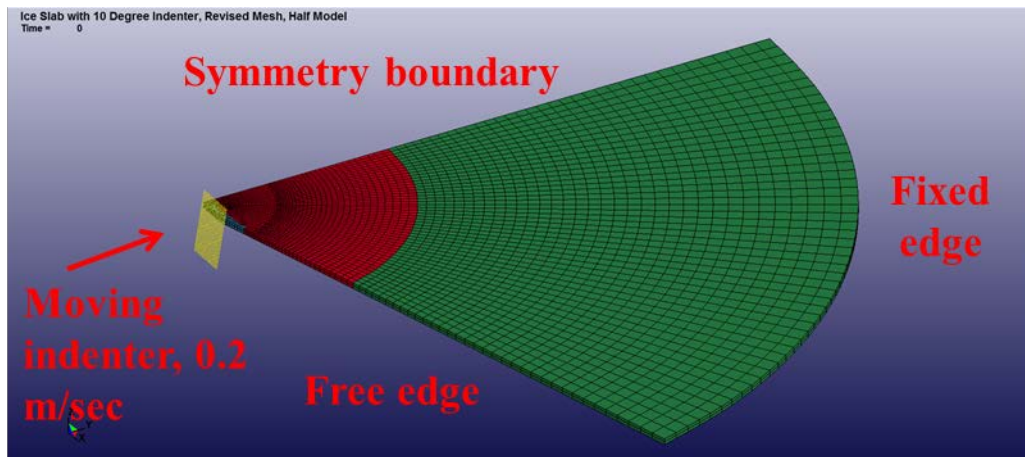


Figure B1. LS-DYNA FEM of a Fracture-Enabled Ice Wedge Loaded by an Inclined Rigid Indenter

This behavior prompted reconsideration of the user-specified number of integration points required to reach the chosen maximum principal stress failure condition before element deletion. In the analysis series reported previously (Lesar, 2017), elements were removed if only one integration point reached the specified maximum principal stress. Under the suspicion that this specification allowed excessive failures, a number of ice slab flexure simulations were rerun with element deletion allowed only when more than one element integration point reaches the limiting maximum principal stress.

Figure B2 shows the ice slab/rigid indenter contact force time histories for three LS-DYNA simulations for a 0.3-m-thick ice slab with frictionless ice/indenter contact. The number of integration point failures required for element deletion are one, three, and five. The maximum force prior to slab failure increases as the element deletion criterion becomes more stringent.

Figure B3 contrasts LS-DYNA-computed crack patterns produced by the three analyses, with the baseline case being element deletion with one integration point reaching failure. The increasing cleanliness of the crack patterns as the deletion criterion becomes more stringent is obvious, as well as the lessening of the diffuse cloud of element removal in the fracture-enabled portion of the slab close to the symmetry plane. The favorable improvements in the physical plausibility of slab failure patterns with less-permissive element deletion criteria prompted adaptation of the stipulation of element removal only when all integration points have reached the maximum principal stress failure condition.

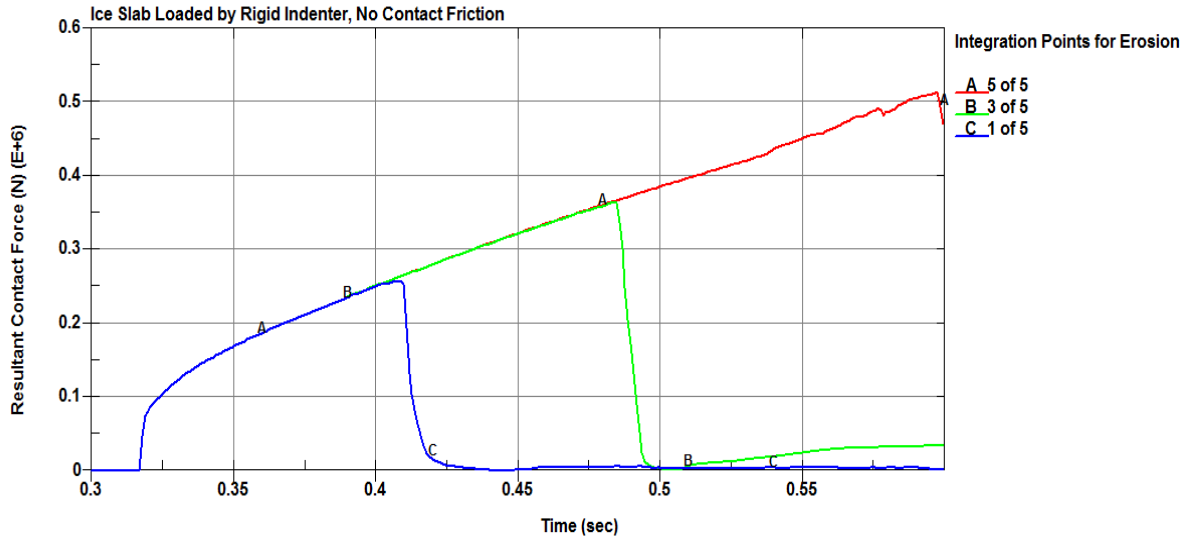


Figure B2. LS-DYNA Contact Force Time Histories for Indenter-Loaded Ice Wedge for Three Element Deletion Criteria Assumptions

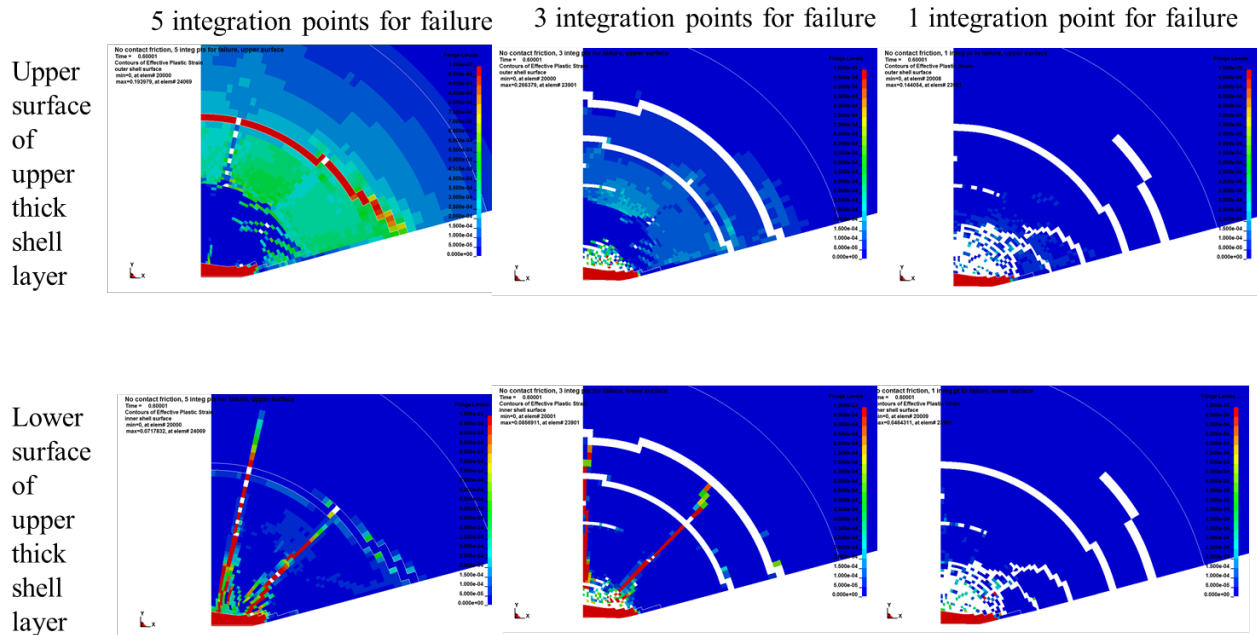


Figure B3. LS-DYNA Crack Patterns for Indenter-Loaded Ice Wedge for Three Element Deletion Criteria Assumptions

