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# A NUMERICAL MODEL OF ICE CRUSHING USING A FOAM ANALOGUE

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## ABSTRACT

A numerical model for ice crushing has been constructed that takes into account the physical processes identified in many experimental studies. These include the presence and evolution of high-pressure and low-pressure zones, the rapid removal of ice through melting, and the transformation of relatively intact ice (high-pressure zone material) to low-pressure pulverized ice through the creation and shattering of spalls. The model produces cyclic sawtooth load events and pressure distributions that are roughly characteristic of observed ice behavior. The visual and quantitative results suggest that the physical principles incorporated in the model are correct. While still in the early stages of development, with refinements the model has potential for use in simulations of various ice/structure interaction scenarios.

**KEY WORDS:** Numerical simulation; ice crushing; spalling events.

## INTRODUCTION

Due to the complexity of the problem and the wide variety of impact and crushing scenarios it is desirable to have reliable numerical simulations. Over a long period ice crushing has been studied by many researchers at lab and field scales, but considerable debate still persists regarding the interpretation of results. Generally speaking some features of the behavior of ice during crushing are universally accepted, such as the presence of high-pressure zones, however there are a few differing notions about what they are, and how they form and evolve. A proper numerical description would have to be founded on the basic physics of what is happening and furthermore be compatible with experimental observations. Here is presented a model for simulation that incorporates physical principles derived from lab and field tests and that generates results that are consistent with experimental data in terms of load, contact pressure distribution and displacement time-series data. This paper therefore has a two-fold purpose, one is to demonstrate that the physical principles the model incorporates are likely correct, and that it provides a flexible numerical tool that can be readily used in simulations of ice-structure interaction, such as bergy bit / ship collisions.

## HARDWARE AND SOFTWARE

The simulations were run on a Unix based Scyld™ Beowulf Cluster presently consisting of 45 CPU's (AMD Opteron™ Processor 246). The software used was LS-Dyna™, that incorporates a full 3D Navier-Stokes solver, a number of contact algorithms and a large suite of material types that can be chosen for the interacting structures. LS-Dyna is a 3D FEA program for simulating highly nonlinear transient dynamic problems using explicit time integration. Ansys™ was used for the modeling and generation of meshes for the study. It was found that the simulations ran faster as more CPU's were used but that the speed gain with increase in CPU's also tended to level off so that 12-15 CPU's was deemed optimum. A simulation took roughly 78 hours to run.

## PHYSICAL PRINCIPLES INCORPORATED

The simulation model incorporates two fundamental characteristics of ice crushing behavior that have been observed in numerous lab and field experiments (e.g. Gagnon, 1991; Gagnon, 1994a; Gagnon, 1994b; Gagnon, 2008; Gagnon and Mρlgaard, 1991; Gagnon and Sinha, 1991). The first is rapid melting on relatively intact regions of ice commonly known as hard zones. The second feature is spalling behavior that significantly influences the size and shape evolution of hard zones during crushing. The shattered spalls provide the bulk of the crushed material, mixed with liquid produced in hard zones, and also produced at ice-ice contact between particles in the conglomerate, that typically surrounds hard zones and is greater in areal extent. Pressure in hard zone regions is high (20-70 MPa) whereas pressure in the crushed material varies depending on the thickness and level of confinement, but generally is in the 2-8 MPa range. The crushed ice, while 'softer' than hard zones does support some load due to its extent and apparently also provides some confinement for the ice in hard zone regions.

The rapid melting of ice mentioned above results from the viscous flow of melt liquid under high pressure that generates heat for further melting. The process has been described before (e.g. Gagnon, 1994a). The thickness of the melt layer is very thin, on the scales of several microns, at least at small scales where measurements have been made (Gagnon, 1994b). The combination of the melting and spalling phenomenon provides the mechanisms by which an object such as an indentor can penetrate into an ice surface and explains the characteristic sawtooth patterns that are typical of ice indentation (Gagnon, 1999). While having an understanding of these mechanisms is essential for modeling the problem numerically the details of incorporating the mechanisms are nevertheless challenging due to the differing scales at which they operate. Spalling is a relatively large-scale behavior that in principle can be meshed with elements that are similar in size to those that compose the bulk model. On the other hand modeling a thin layer of flowing liquid within the same model is completely unwieldy since the mesh elements in the liquid would be microscopic in size. How then does one deal with the situation? The answer, at least in the present case, is to use a material that can be meshed with sensibly-sized elements and that can behave as a piece of ice that is melting from the top, without having to revert to modeling the actual layer of liquid. In numerical modeling vernacular the material that behaves this way is a hard crushable foam with Poisson's ratio equal to zero. LS-Dyna has such a material (MAT_CRUSHABLE_FOAM, Material Type 63) in its suite of material models.

The isotropic foam model crushes one-dimensionally with a Poisson's ratio that is essentially zero, as described by Hallquist (1998). Unloading is elastic to the tension cutoff stress. Subsequent reloading follows the unloading curve. In the implementation it is assumed that Young's modulus is constant and the stress is updated assuming elastic behavior.

$$\sigma_{ij}^{trial} = \sigma_{ij}^{n} + E\dot{\varepsilon}_{ij}^{n+1/2} \Delta t^{n+1/2} \quad (1)$$

where $\sigma_{ij}$ is the stress tensor, E is the Young's modulus, $\dot{\varepsilon}_{ij}$ is the strain rate tensor and $\Delta t$ is the time increment. The magnitudes of the principal values are then checked to see if the yield stress is exceeded and if so they are scaled back to the yield surface, $\sigma_y$ :

$$\text{if } \sigma_y < \left|\sigma_i^{trial}\right| \text{ then } \sigma_i^{n+1} = \sigma_y \frac{\sigma_i^{trial}}{\left|\sigma_i^{trial}\right|} \quad (2)$$

After the principal values are scaled, the stress tensor is transformed back into the global system. The yield surfaces for the present application are described below.

The implementation above operates in parallel with a viscous damper that the user can control by choosing a percentage of the critical damping coefficient. This is useful to dampen resonant oscillations (below).

Application of a pressure, prescribed by the user, on a block or layer of such foam that is rigidly supported from below causes it to irreversibly compress in the direction of the applied load as though it was ice melting from the top due to the aforementioned process of high-pressure viscous flow of melt. Other details are best described in the context of the numerical model itself (below).

## MODEL CONSTRUCTION AND BEHAVIOR OF COMPONENTS

As a preamble to our model description we focus briefly on the topic of spalling. Figure 1 (Daley 1992) shows a pyramid-shaped ice formation in 2-D and how the spall fractures might progress sequentially from top to bottom in an actual test, neglecting for the moment the mechanisms that enable the platen to progress through the remaining intact ice at each spall event. Daley recognized the importance of spalling (Daley, 1992; Daley, 1990) at around the same time that Gagnon and colleagues were reporting spalling observations from experiments in the lab and field (Gagnon, 1991; Gagnon and Sinha, 1991; Gagnon and Mρlgaard, 1991). Daley and Gagnon both realized the close association of spalling with the sawtooth load patterns that often developed in ice crushing experiments. And they discussed spall patterns and angular relationships (Daley, 1992; Gagnon, 1998). Spencer and Masterson (1993) also discussed the importance of spalling, as did Evans et al. (1984) in earlier work. Daley's useful and in-depth 2-D analysis of fracture and spalling did not, however, provide the other physical mechanisms involved in the crushing process. Utilizing visual techniques and in-situ instrumentation Gagnon, in addition to documenting spalling, identified the mechanisms necessary to explain the characteristics in load, displacement and pressure data observed in lab and field ice crushing tests (Gagnon, 1999). Hence, we can now present a full 3-D numerical rendition of ice crushing, where the material and transformative characteristics of the ice are incorporated that enable the physical mechanisms required for the penetration of the indentor into the ice before and during spall events. The model naturally exhibits the compliant and resonant behavior of the whole ice/indentor system.

In the present simulation a pyramid-shaped ice formation, such as at Hobson's Choice Ice Island during the 1990 experiments (Figure 2), is crushed by a heavy flat steel plate at the nominal rate of 100 mm/s to a depth of 10 cm. In principle we could mesh the whole ice formation and then, using complex and iterative stress analysis algorithms (see below) specify that a spall surface (i.e. a fracture to a free surface), such as any of the fractures in Figure 1, occurs when load is adequate to generate the required stress to create the fracture surface plane. As the depth of penetration increases the fracture surface area rises quadratically (in 3-D) for the spalls having the same fracture angle, and the required load would rise accordingly. However, things can be greatly simplified, and the number of meshed elements greatly reduced, by modeling a portion of the full extent of the pyramid (Figure 3) and furthermore specifying that the spall events occur at fairly regular intervals as a function of *depth of penetration* into the ice. Other simplifications are that we used the same thickness for the planar spall slabs (described below) regardless of depth in the ice, and we gave all the spall fracture surfaces the same angle. Spall slabs that increase in thickness with depth, and that exhibit some variability in fracture angles, would be more realistic (Daley, 1992)

In the simulation the number of spall layers that have been modeled and meshed essentially defines the number of spall events for the 100 mm penetration. This is another artificial construct and clearly more spall events, implying thinner and more numerous meshed spall layers, would be needed to achieve the Hobson's Choice Ice Island test TFR4 number of spalls (Figure 4). That is beyond the scope of this early work but could be fairly easily implemented. Our goal here is to show the most important characteristics of the model and we leave a number of the refining aspects for future work. The intention is to show how the mechanisms involved can be handled numerically to yield the variety of behaviors underpinning the highly dynamic and complex phenomenon of ice crushing. When compared to characteristics seen in ice crushing in the lab and field the general features of the simulation are nevertheless compelling both visually and quantitatively, in spite of these early stages of development. This demonstrates that the physical processes are fairly well understood in the first place and reasonably represented in the model.

Figure 5 shows the main component from the meshed model, the central building block, used in the simulations, hereafter referred to as a 'facet'. It is triangular in shape and in this case is two mesh elements thick. The facets are slightly angled upwards, by about 8 degrees, and this is an important aspect of the model as we shall see. Each of the facets will serve as a spall of ice, or portion thereof, in the model. In LS-Dyna each facet is a separate entity whose material properties, and contact characteristics with other parts it touches, must be assigned. In reality the fracture plane that creates a spall is likely curved (Gagnon, 1998) so the facet shown in Figure 5 is a simplification. A sectional view of the fully meshed model is shown in Figure 6. It is composed of several of the facets shown in Figure 5. Note that the model has four sides because in this case we are modeling a pyramid-shaped ice formation. The method is flexible, however, and other ice formation shapes, such as a wedge or an ice sheet edge, could be modeled in a similar manner as the present model but with different shaped facets and differing overall assembly. This is left for future work. There are six layers of the thin facets in the model. Each of these layers consists of four facets, one for each quadrant. The six layers have been assigned ice characteristics (below) and the thicker bottom layer has been assigned immovable rigid body characteristics, i.e. to approximate the virgin intact bulk ice that supports the stack of facets above it. Hence the simulation was run using essentially six active layers, where in fact only the first three layers experienced spall behavior, that is, fracture-induced separation. The other three active layers were present to demonstrate that the processes involved could have carried on to create more spalls had there been a greater depth of penetration of the crushing plate.

The shape of the model top is very important (Figure 3). We noted the angle of about 8 degrees. A key point is that the model is showing the shape of the ice once some crushing has already occurred, i.e. it shows *the ice process surface*. Studies (Gagnon, 1998; Daley, 1992) show the angle for spalling that occurs in the ice is, for the most part, less than the original face angles of the ice mass. The process surface shape is, however, influenced by the original shape of the ice due to geometry-related confinement effects. This is a complex topic that is outside the scope of this paper. Here we deal only with the relatively simple pyramid geometry where test data has yielded some information about actual spall shapes (Gagnon, 1998) and some of the influences of the original ice formation shape are available (Spencer and Masterson, 1993).

The following method is used to enable the transition that occurs when solid intact ice transforms into a shattered spall. The top six layers visible in Figures 3 and 6 appear to number 24 facets when in fact there are two sets of distinct and overlapping layers, that are occupying the same space, totaling 48 facets. One set of layers has a high-stress crushable foam property, hereafter referred to as M1 (upper curve in Figure 7). The x and y coordinate pairs for the four points defining the curve are: 0.0, 0.0; 0.015, $25.0\text{x}10^6$; 0.5, $50.0\text{x}10^6$; and 1.0, $50.0\text{x}10^6$, where each pair corresponds to *Fractional Volumetric Strain* and *Yield Stress (MPa)* respectively. Also occupying the same space (in computer terms) is the other set of six layers, these having the lower-stress crushable foam property M2 (lower curve in Figure 7). The x and y coordinates for the four points defining the curve are: 0.0, 0.0; 0.015, $2.5\text{x}10^6$; 0.5, $10.0\text{x}10^6$; and 1.0, $10.0\text{x}10^6$. The combined properties of the M1 and M2 overlapping layers represents the physical strength and behavior of intact hard zone ice that rapidly melts from the top in response to high pressure (see process described by Gagnon (1994a)). When only the M2 material layer(s) is present, that is, following a spalling event, the layer represents the shattered and pulverized ice that the spall has 'instantly', i.e. one CPU time step, transformed into. The overlapping layers do not interact with each other, however, they do interact with the crushing plate above and the supporting ice below. In other words, both types of layers exert a force on the crushing plate and supporting ice. When the plate contacts and loads the ice it applies force to both types of facets if both are present. Both have crushable foam properties, so the hard zone that forms from the flattening facets in the contact zone has a pressure distribution defined by the sum of the two curves, although clearly the most significant contribution is from the high-stress curve M1. In nature during crushing the ice load builds up to a point where a fracture initiates that separates one piece of virgin ice (a spall) from the bulk piece, typically half of the contact area. In our simulation described below it will be observed that the first spall to form is comprised of two of the four top facets in Figure 3. In an actual spalling event the separated piece would shatter and become crushed ice. In the simulation this is done by having the hard (M1) overlapping ice piece completely lose its contact with all attached ice and the plate, leaving the softer (M2) overlapping piece occupying the same space in the contact zone and with material properties of crushed ice.

In LS-Dyna this is accomplished through the contact definitions that numerically handle the contact surfaces between a given facet and its neighbors and the crushing plate. LS-Dyna lets the user designate a predefined 'death time' for the contact definition of a given facet, after which the definition no longer operates and the facet no longer interacts with anything. Hence it has effectively been 'taken out of play' and simply passes through the other objects in the simulation without any influence. The fact that both types of active facets have mass, even though they overlap, has only a slight effect on the simulation results in an inertial or dynamic sense because the mass of the crushing plate is far greater. For the most part the mass of the plate determines the resonant frequency exhibited after spall events (see below) regardless of whether the relatively small mass of the ice facets is counted once or twice due to overlapping or whether facets (and their masses) are taken out of play during spalling events. To reiterate, our strategy of using overlapping facets and taking some of them out of play facilitates important ice crushing features within the simulation model. As stated above, when the M1 facet of an overlapping M1 and M2 pair is taken out of play it facilitates the transformation of intact ice to crushed ice. In another scenario, when both an M1 and partially overlapping M2 facet are taken out of play it represents the case of a piece of ice consisting of both intact ice and some attached pulverized spall material breaking away and completely leaving the contact zone (see below), as sometimes happens in nature. Clearly, in our utilization of overlapping facets in the present application we are ignoring some complications associated with mass because their effects are minimal. In future applications of the simulation model that might be more sensitive to ice mass issues the initial relative densities of M1 and M2 facets could be set to more accurately reflect the true density of ice. For example the M1 facets could be assigned a small fraction of the density of ice and the M2 facets could be assigned the greater portion so that either the combined facets, or just the M2 facets, have the approximate ice density.

When a spalling event occurs, for example, when an overlapping pair of M1 and M2 facets, or multiple sets of facets, in the contact zone transforms from intact to shattered ice, there is a drop in the load exerted by the ice on the crushing plate that causes an abrupt forward movement of the plate on the remaining ice. This is due to the reduction of hard-zone and/or soft-zone contact area. This is physically and numerically enabled by the rapid melting of ice on the remaining hard-zone portion and further compression/extrusion of the soft-zone ice if present (see walk-through below). With the continuing movement of the crushing plate ice load accumulates again and the hard-zone and soft-zone contact areas grow in size to an extent that is generally greater than they were previously until the next fracture and spall event occur. Hence, over multiple spalling events, and increasing depth penetration, the general trend is for an average increase in hard-zone and crushed-zone size so that the load generally increases, as intuitively expected. In real ice the number of spalling events for a given penetration ultimately depends on the fracture toughness of the ice, the geometry of the original ice and inherent flaws and non-uniformities that may lead to fracture. To reiterate, for the pyramid shape the fracture surface area required for spalls grows quadratically as the penetration increases. Hence the general trend is that the load required to initiate spalls successively deeper within the ice increases quadratically with depth, assuming the same spalls angles apply. A further note is that since the crushing plate loading system and virgin ice are elastic entities the time interval between load drops will increase as load peaks increase for successively greater depths of penetration, as observed in various experiments (e.g. Gagnon, 1998).

At this point it is worth reviewing our strategy for treating spalling events. First we recall that in nature a spall is created by a rapidly propagating crack. Since fracture propagation is not modeled in our simulation we simplify things by assuming the crack propagates and separates a spall from the main body of ice within one time step. This is achieved in the simulation by specifying that the facet contact definition 'dies' at a certain time, that is, that a facet loses its contact with everything it formerly had contact with within one time step. The geometries of the spalls are predefined by the facet geometries, where the fracture planes are the contact surfaces between facets. Finally by defining two types of overlapping facets we formulate a method to achieve the transformation of intact ice, i.e. the combined M1 and M2 facets, into a shattered spall by designating the death time of the contact definition for the M1 facet leaving only the M2 facet to represent the shattered/pulverized ice. Sometimes both an M1 and a partially overlapping M2 facet are taken out of play, corresponding to the case of a piece of ice consisting of both intact ice and some attached pulverized spall material completely and rapidly leaving the contact zone. Another simplification is that in this first version of the simulation model we have a limited number of facets predefined, and consequently fewer spalling events than would actually occur. These spalling events we space roughly evenly throughout the depth of penetration that will occur during the simulation, i.e. by spacing the contact definition deaths for the sequence of events roughly evenly over the time that penetration occurs.

The yield stress values for the M1 and M2 facets (Figure 7) are rough estimates obtained from laboratory and field experiments for the ranges of pressures that have been observed on high-pressure zones and crushed-ice zones. The associated volumetric strains were chosen so that pressure gradients in the appropriate ranges would be evident in the hard-zone and crushed-zone patterns that developed throughout the simulation. The simulation incorporates a confining effect for the crushed ice material, that is, the more the layer is compressed, i.e. the more confinement, the greater the pressure it exerts (M2 curve in Figure 7). This is equivalent to saying that the smaller the space the crushed ice occupies between the crushing plate above it and the undamaged ice below it the greater the pressure needed for it to flow as the crushing plate advances. Similarly, due to the combined M1 and M2 curves in the Figure 7, the hard zone material shows an increasing pressure gradient towards the center of the model where the crushable foam experiences the greatest strain. Higher pressure in the center region would be expected from squeeze film theory, although the situation is no doubt complicated by the fact that the liquid layer is not of uniform thickness since less heat and melt is generated in the central area where liquid flow is stagnant (Gagnon, 2008). Furthermore the elastic compliances of the plate and ice itself and general dynamics of the process indicate that the loading of the intact ice is not necessarily centered, that is, there could be some tendency for there to be relative tilt between the plate face and the ice face at the contact zone.

The crushing plate in the model consists of 6,400 shell elements. These were four-node elements (SHELL163). Eight-node solid brick elements (SOLID164) were used to mesh the facets, numbering 44,200 elements. The active facets were assigned a density of 900 $kg/m^3$, a Young's modulus of 9 GPa and a Poisson's ratio of 0.0. The LS-Dyna surface contact algorithm used for facets that were in contact with each other was 'CONTACT_automatic_surface_to_surface_tiebreak'. The contact algorithm used to define contact between facets and the crushing plate was 'CONTACT_automatic_surface_to_surface'. The time step for the simulation was $3.78 \times 10^{-6}$ s. All active facet nodes were constrained to move in the z direction, that is, the direction that the crushing plate was moving in.

The numerical model will hereafter be referred to as IceCrush.

## SIMULATION WALK-THROUGH

Figure 8 shows a series of ten sets of images depicting what happens at ten points in time in the IceCrush simulation. Figure 9 shows larger, more legible, views of the colored stress scales on the images for the reader's convenience. Each of the ten image sets in Figure 8 shows three vertically-stacked images. The figure illustrates the processes that occur during ice crushing and highlights the variety of complex behaviors, as observed in nature, that have been included in the simulation. Only the top three layers of active facets are depicted in each image. Sectional views are shown for the first six image sets to help with the description. Recall that each facet is two mesh elements in thickness. In the model the full stack of 6 active facet layers of M1 and M2 materials initially occupy the same space but as the crushing progresses, and some facets are taken out of play, the relative overlap of facets within the stacks varies.

The thick massive plate that crushes the ice from the top is not shown for illustrative purposes. The plate was 3.2m x 3.2m x 0.6m, and had a density of 2000 $kg/m^3$. Its Young's modulus was 100 GPa and Poisson's ratio was 0.3. Its corners moved at a fixed speed of 100 mm/s during the crushing test. Essentially the plate represents a fairly massive elastic structure with realistic inertial and flexural properties. As mentioned above the test duration was set to be 1.0 s. Six spalling events were incorporated into the model and had been specified to occur at fairly regular and generally increasing time intervals according to the strategy discussed above, that is, at 0.2 s, 0.3 s, 0.45 s, 0.62 s, 0.8 s and 0.95 s. As mentioned above this was accomplished by specifying the death times of the contact definitions for the relevant facets comprising the spalls.

The top image of each image set in Figure 8 represents the high-stress M1 material. The middle image represents the lower-stress M2 material, and the bottom image shows the result when the two materials (M1 and M2) are combined as they are in the IceCrush simulation. Recall that the hard-zone property is exhibited by the combined behavior of M1 and M2 facets where they overlap in the contact region, whereas the M2 material by itself represents crushed ice. The points at which each of the ten image sets occur in the load history of the crushing event are included as numbered markers in Figure 10. Image set #1 shows the facets before loading has begun. Image set #2 corresponds to time 0.199 s when loading has progressed to a point prior to any spalling event. The top and middle images show the stress in both materials that, when combined, correspond to the symmetric pressure distribution exerted by the ice on the plate (bottom image) as the ice is flattening due to rapid melting (see process above) at the ice/plate interface. Note that only two of the four quadrants comprising the ice process face are shown in the middle and top images so that the viewer can see a section through the contact zone. A spalling event occurs the instant after image set #2 at time 0.200 s. Image set #3 was taken about 0.1 s after the first spalling event occurred, at time 0.299 s. The first spalling event essentially cut the contact region in half. This was accomplished by having two of the triangular facets, the lower ones visible only in the bottom image of image set #2, lose their M1 high-stress property leaving only the crushed ice property M2. By the time image set #3 occurred the remaining high-stress zone, and the crushed-ice zone that is the spall remnant, had expanded in size somewhat due to the penetration of the plate and geometry of the ice. The top and middle images of image set #3 show the M1 and M2 components for the remaining hard-zone ice from the first spall event. As mentioned, the ice spall occurred on the lower half of the bottom image so it isn't visible in the upper images. The dark blue region, corresponding to high pressure, is the hard-zone ice. The spall that separated from the bulk ice has transformed into lower-pressure crushed ice, as seen in the lower half of the contact zone as yellow/green in the bottom image. The second spalling event is about to happen.

Image set #4 shows the details of how a spall forms since it occurs in the two quadrants that have been illustrated in the middle and upper images. Image set #4 corresponds to a time very shortly after the second spalling event, at time 0.302 s. The top image shows that the top triangular facet on the right side has gone from view since it effectively was taken out of play when it separated from the bulk ice, that is, its numerically defined contact algorithms for ice contact and plate contact 'died', in LS-Dyna terminology. So no force is exerted by the facet on anything. Hence the top image shows a space where the top M1 facet was. The middle image, however, does show the crushed ice facet that occupies roughly the same space as the facet that 'died' in the top image. Hence the 'combined' properties of both facets in the contact zone now shows only the crushed ice facet property (bottom image), i.e. the ice spall has transformed from intact ice (combined M1 and M2 properties) into crushed ice (low-stress property M2). From viewing the bottom images in image sets #3 and #4 we see that half of the hard-zone contact area has transformed into crushed ice. The load drop associated with this can be seen in Figure 10. Image set #5 (time 0.449 s) shows the situation about 0.15 s later, after the high-stress and low-stress contact areas have expanded due to continued penetration of the plate onto the ice. At this point the third spalling event is about to happen.

Image set #6, taken 0.003 s after image set #5, shows the situation immediately following the third spalling event. In this case the hard-zone ice left over from the previous spalling event (image set #5) itself has shattered, so that the whole area of contact consists entirely of pulverized ice. This situation was included in the simulation because in nature it happens from time to time during ice crushing that the whole region of contact shatters leaving a layer of pulverized ice between the plate and the intact ice underneath the shattered ice. Note that at this point the whole top layer of four M1 facets have 'died' (top image), whereas all the M2 facets are still present (middle image). Eventually, however, fresh intact hard ice 'pushes up through' the crushed ice to make high-pressure contact again with the plate, as is evident in image set #7, taken approximately 0.15 s later. The top and bottom images show high-pressure contact from hard-zone ice exhibited by three facets. Image set #8 was taken 0.115 s later. In the intervening time the fourth spalling event occurred at time 0.62 s on the load record. Before discussing that spalling event we note that the top and bottom images of image set #8 show how fresh hard-ice contact continued to push up through the crushed ice and expand in size in comparison to the previous set of images. Regarding the fourth spalling event, we note that it occurred in the lower left side of the images. We have included more of the model components in image sets #7 and #8 to help illustrate what has happened since this spalling event is different from the previous ones. This time not only did the M1 facet stop exerting force on the plate (top image) but the same thing happened with the M2 facet (middle image). Both of the facets have ceased to be active in the model. In other words, what has happened is that a chunk of ice consisting of former intact ice and former crushed ice has entirely left the bulk ice leaving a gap in the region of contact that eventually closes when new facets move up from below as penetration progresses.

Image set #9 shows the situation about 0.18 s later when both the high-stress and low-stress contact areas have expanded. The fifth spall is about to occur, and it has the same characteristics as the fourth spall. Image set #10, taken 0.002 s after image set #9, shows that during the spall event the high-stress and low-stress facets in the lower right hand corner have been taken out of play, that is, another chunk of ice consisting of former intact and former crushed ice has broken away, leaving a gap as in the previous case. We note also that a 'fresh' M2 facet that was under the previous spall is beginning to make contact with the crushing plate as seen in the lower left quadrant of the middle and bottom images. The final spalling event that is evident in the load record (Figure 10) is not shown in the figure for brevity since its characteristics are similar to those already discussed.

We note from the discussion of Figure 8 that the relative contributions of load from the high-pressure and low-pressure ice contact areas is subject to considerable variation in the IceCrush simulation, as has been observed in nature. On average, however, both hard-zone and crushed-zone areas increase in extent with penetration.

## SUMMARY OF THE OBSERVED FEATURES OF THE SIMULATION

The simulation, while crude, nevertheless exhibits many of the characteristics that are observed in field and lab experiments. Load drops are prominent and are the direct result of spalling events (i.e. the classic sawtooth pattern, such as in Figure 4). Load drops are roughly a half to a third the load magnitude just prior to the load drop. High-pressure hard zones (melting intact ice) surrounded by low-pressure soft zones (shattered spalls and pulverized ice) are seen. Sharpe changes in pressure at hard-zone / crushed-zone boundaries are present. Instances of fresh undamaged ice (hard-zones) pushing up through damaged ice (soft-zones) as crushing progresses can be seen. Intermittent movement of the crushing plate towards the ice, that is, relatively slow movement between spall events and abrupt fast movements at spall events (Figure 11) are evident that are similar to physical experiments (Gagnon, 1999). The elastic response of the crushing plate / ice system is furthermore evident in the resonant oscillations seen at the bottoms of the load drops and in the displacement record of the central region of the crushing plate. For example see the oscillations in load (Figure 10) and displacement (Figure 11) associated with the $5^{th}$ and

6th spall events. From actual experiments, Figures 12 and 13 show resonant oscillations following load drops in the load record from test TFR4 at Hobson's Choice Ice Island and from a small-scale ice crushing test in the lab (Gagnon, 2008). To continue, the expected general increase in contact area for soft and hard zones as the penetration progresses, with consequent general increase in load, is evident. Furthermore the spalls are a significant portion of the ice contact area and their inner extent passes through the center of the contact zone, as frequently observed in real experiments (e.g. Gagnon, 2008).

Finally, the shape of the original ice influences confinement characteristics that in turn influence the shapes and locations of spalls. This ultimately leads to patterns of ice contact, such as the 'X' pattern that was evident in the pyramid Ice Island experiment (Gagnon, 1998). The simulation showed evidence of an 'X' pattern in the early stages, but this did not persist because of the highly-simplified spall shapes. A fairly simple refinement of the spall shape, discussed below, does lead to an 'X' pattern of ice contact that persists throughout the simulation.

In light of the extensive list of observed features above that reflect what has been seen in actual ice crushing tests, we take this opportunity to remind the reader that one of the dual purposes of this work is to show that the physical processes that have been incorporated into the IceCrush model are likely correct. We contend that numerical simulations can, and should, be used to help resolve some of the ongoing debate regarding the physical processes responsible for ice crushing behavior. Simply put, if a simulation can produce realistic features to a substantial level of detail then its likely that the physical processes, assuming that they are physically sound, incorporated in the model are correct. Otherwise the incorporated processes are suspect.

Regarding the resonant oscillations mentioned above, we note that they dampen out in the simulation and in the experimental studies cited. In reality the damping is due to several things, such as fatigue in the apparatus components and the generation of sound and heat. But the dominant factor in ice crushing may likely be the rate sensitivity of the viscous flow of the thin layer of melt produced on ice hard zones (Gagnon 1994a; 1994b). That is, the liquid generation process is a natural damper of oscillations since it is sensitive to penetration rate. As mentioned above the LS-Dyna crushable foam model operates in parallel with a viscous damper that the user can control by choosing a percentage of the critical damping coefficient, as was done here, so that resonant oscillations don't continue indefinitely.

## FURTHER CONSIDERATIONS

The number and thickness of spalls that form when crushing occurs in an ice/structure interaction event ultimately influences the sawtooth load history. No doubt this is why the simulation reached a load comparable to that of the Ice Island experiment with roughly half the penetration of the actual test, that is, there were far fewer spalling events in the simulation. Every spall event is associated with dissipation of some energy. In the case of a collision, before contact is made there is a finite amount of kinetic energy associated with the relative speed of the structure and ice. How many and how precisely should the spall shapes and frequency be defined depends to a certain extent on what the purpose of the particular simulation is. If the user is more interested in testing the dynamic response of a structure to ice loading during indentation, more so then the ultimate load achieved, then less emphasis is needed on spall definition. For example, Sodhi (1991) has studied crushing induced vibration in structures. In cases where more emphasis on spall definition is needed then methods such as the detailed stress analysis strategy described below and detailed observations from controlled experiments where spall characteristics and frequency can be determined, such as the Ice Island experiments (Gagnon, 1998) or extreme high-speed video of ice crushing experiments in the lab (Gagnon, 2008), could potentially be utilized.

As mentioned above, the number of spalls that occurs during the simulation determines the number of the load drops. In principle this has nothing to do with element size since a given spall facet could have the same dimensions using fewer but larger elements or a greater number of smaller elements. Generally, however, the behavior of any component of a numerical simulation, such as a facet, requires a certain level of mesh refinement to ensure good behavior. The optimum element size strikes the balance between a manageable number of elements and stable behavior of the model components. Identification of the optimum element size for a facet of given dimensions is left for future work. We have already noted that the present simulation is deficient in terms of the number of spalling events. To have more events for a given depth of penetration would necessitate having smaller element sizes in order to define more spall facets.

It may be feasible to investigate spall shape and frequency from elastic stress simulations of ice models. That is, one could apply load to an unfractured ice formation model to identify a potential fracture surface in the stress field that would define a spall. Then that 'spall' could be removed, or replaced with crushed ice material properties, and the model loaded again to identify the next spall from the stress field. This process would be repeated to obtain a sequence of the spall shapes. It is likely this would be an intensive process for the user. The other approach is to get spall shape information from carefully designed experiments. And of course results from the iterative process could potentially be validated using data from experiments, if available. Real experiments to date, however, show that even for very well defined ice geometry and uniform material properties that it becomes difficult to map the precise spall shapes in 3-D and in time. In view of the difficulties associated with using these methods it might be necessary, and easier, to use spall shapes that can only be estimated from the original shape of the ice and from whatever relevant information that is available from past experiments, as was done here. Another reality is that the shapes of some types of ice masses, such as bergy bits, are often quite complex and therefore amenable only to the latter approach for simulating collisions that include spalling. Clearly there is much to be done regarding these issues.

It can easily be argued that the spall shapes associated with the facets shown in Figures 5 and 6 are too simple, particularly since the 'X'-shaped pattern of hard-zone contact, while evident early in the simulation (Image set #2, Figure 8) does not persist and develop as this particular model is crushed. That is simply a matter of how the spall shape is defined however. The IceCrush process surface shape inherently contains information about the confining aspects of the ice due to the original geometry of the ice mass. Hence, the user can judiciously alter the shapes of the original mesh structure to take account of expected confining patterns that will occur during crushing. For example if the real ice face is a truncated pyramid, as was the case in test TFR4 at Hobson's Choice Ice Island, then a priori it is known from the ice geometry that the confinement is higher in the vicinity of the ridges where the flat faces of the pyramid meet. Consequently in the actual experiments an 'X' pattern of hard-zone ice contact developed (Gagnon, 1998) along the ridges. If the detail of the ice hard-zone/soft-zone pattern is important in any particular simulation that a user is running then a relatively simple adjustment can be made that will ensure the pattern is evident, such as the 'X' shaped pattern in the present case. The method is to give the triangular shaped facets a degree of concave curvature that ensures the ridges are relatively high compared to the 'valley' between them on the ice process surface. Figure 14 illustrates this for a facet in the present case. The results of a simulation using curved facets and the same parameters as before are shown in Figure 15. The times of the images in the figure are the same as for the image sets in Figure 8. The 'X' pattern is clearly discernible in both the low and high-pressure areas, similar to the Ice Island test. Hence, the process surface model can be modified to take account of areas of confinement by elevating those areas relative to the less confined regions. No particular consideration of this was incorporated in the first simulation where a generally square contact area develops indicating somewhat higher confinement at the ridges, but not enough for the 'X' hard-zone pattern to fully develop and persist. The load record for the latter simulation is similar to that of the former simulation but is about 2/3 the magnitude, since the sizes of the contact areas are reduced due to the shape of the process surface constructed with facets that have concave curvature.

In summary we note that ideally a perfect simulation of ice crushing would determine exactly where, when and with what shape every spall was created in addition to having the capability to reproduce the other complex crushing behaviors discussed above. Software with such capability and accuracy does not yet exist, although we have shown that the physical processes are fairly well understood and have demonstrated one strategy, at least, for incorporating them. Progress is being made on other remaining key issues such as numerically tracking fractures in ice (e.g. Kolari et al., 2009). In the meantime, while recognizing that spalling behavior is complex, we can nevertheless say that spalling events occur fairly regularly in continuous crushing and that the number of events is a function of the geometry of the ice and the depth of indentation/penetration. Hence, it may not be unreasonable to forgo the computationally expensive process of determining exactly when and where spalls occur and what shapes they have, either directly within the simulation or in prior elastic stress simulations using fracture toughness criteria and critical stress analysis within the ice. By specifying that the spalls will occur at fairly regular intervals of depth of penetration and giving them the best shapes that can be estimated from the original ice geometry, and whatever visual data that is available, a realistic sequence of events and load history can be generated.

Having discussed a simulation in some detail (Figure 8), we remind the reader that the curves in Figure 7 are not intended to mean that the actual ice is experiencing the volumetric strains implied by the curves or that its strength increases as it deforms. Rather the curves represent the volumetric strain and yield stress of the *crushable foam material* as an analogue so that essential behaviors of the actual ice can be realized in the simulation. One desired effect is the melting of hard-zone ice from the top, as stated above, and the consequent outward radial flow of pressurized fluid that for a symmetrically-shaped hard zone would have an increasing pressure gradient from the periphery to the center. This is facilitated by the M1 and M2 crushable foam facets experiencing more strain, and showing increasing pressure (according to Figure 7), towards the center of the stack of facets comprising the ice feature. A second desirable effect is related to the crushed material being squeezed out of the wedge-shaped space between the crushing plate and the ice process surface below the material. This would generate an increasing pressure gradient from the periphery to the center of the ice process surface, and this is facilitated by the M2 crushable foam facets being more compressed in the center of the stack of facets, as in Figure 8. Another desirable consequence of the general formulation is that the pressure increases, up to limiting values, on hard zones and crushed zones as they increase in size.

A final consideration is that the model is suitable for differing scales. The yield curves in Figure 7 were generated from data from small-scale lab experiments and large-scale field experiments where the ranges of pressures on the high-pressure zones and low-pressure zones were basically invariant with scale. This is one of the remarkable things about ice crushing, the same processes, and pressure magnitudes, apparently occur at all scales investigated to date (Gagnon, 1999). Hence, as far as our present knowledge is concerned, the model that has been presented can be scaled down to the size of a lab test quite simply. For example, considering the simulation shown in Figure 8 and scaling it by 1/12, the base dimension becomes ~12 cm on a side and the penetration becomes ~ 0.8 cm. Without having to run the simulation at the smaller scale we know that the same spalling sequence will yield a load record that looks the same as that in Figure 10 but the magnitude will be reduced by a factor of 1/144 since the pressure distributions, as governed by the curves in Figure 7, stay the same. All that has changed are the sizes of the ice contact regions that scale by the square of the linear scale factor, i.e. 1/12 x 1/12 = 1/144. Consequently the maximum load towards the end of the simulation will be roughly 60 kN which, given more than an order of magnitude difference in scale, roughly compares with results of about 30 kN from ice crushing experiments in the lab (e.g. Gagnon, 1994a; 1994b). Furthermore, the lab tests had more spalling events and the pyramid-shaped samples had steeper sloped sides, that result in less confinement, so that we expect somewhat lower loads. Hence, this numerical model has shown its capability to generate reasonable results for loads and pressure distributions for experiments conducted at small and intermediate scales.

## SUGGESTIONS FOR USE OF THE MODEL FOR IMPACT SIMULATIONS

In the case of continuous penetration crushing at a given rate, such as the Ice Island tests in 1990, the penetration as a function of time is known beforehand. This permits the user to assign whatever number of spalls that may be desired for a given depth of penetration.

On the other hand, in the case of an ice/structure impact scenario we suggest the following three-stage method to make the best use of the spalls that the user may have incorporated in the geometry of their model. Consider an ice mass of relatively large extent compared to the modeled portion that is actually crushed against a structure, such as a bergy bit colliding with a ship. The ice process surface model can be attached to the simply-modeled bulk ice mass at the location where the impact will occur. One has to get some idea of the duration of the impact, and the final depth of penetration, in order to assign times, or alternatively depths of penetration, when the spalling events will occur. For the given impact scenario, first a simulation can be run where no spall events are allowed to occur and where all of the ice process surface model behaves as hard-zone ice. This will yield a minimum possible impact duration and penetration depth. Next, a second simulation is run with the same parameters and where now only the M2 facets are active, that is, the model behaves as crushed ice. This will yield an impact duration and penetration depth that will approximate the longest possible duration and greatest depth of penetration. One can then choose an impact duration and penetration depth that is intermediate between these lesser and greater values and use this to assign spall event times that distribute the number of spalls they have in their model fairly uniformly throughout the range of penetration depth available.

## CONCLUSIONS

A numerical simulation method for ice crushing, known as IceCrush, has been presented. It incorporates physical processes and geometrical characteristics that have been identified in field and lab experiments. Other ice models for numerical simulation have been used before, such as in bergy bit impact simulations (Gagnon and Derradji-Aouat, 2006) and growler impact simulations (Gagnon, 2007), that yielded reasonable results, however this is the first model to incorporate complex spalling behavior. Here we have presented the essential aspects of a potential new tool. The model is not complete since various aspects may need refinement, such as spall shapes, sizes and frequency. The model's sensitivity to these factors has only been investigated in one case, that is, by altering the facet shapes to achieve a significantly more realistic pressure pattern. This positive result, and the model's inherent flexibility, bodes well for future investigations and model versions. The present model results exhibit actual characteristics of ice crushing that demonstrate that the physical processes incorporated are probably correct. Depending on the particular interest of a user, the numerical modeling technique can be used judiciously to study the behavior of structures in response to ice impacts and indentation where all known ice crushing behaviors, to varying degrees of refinement, are taken into account.

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**FIGURE CAPTIONS**

Figure 1. A pattern of sequential ice fractures in a two-dimensional ice formation that is crushed by a plate (not shown) from the top. Each fracture produces a spall. (Drawing reproduced from Daley (1992)).

Figure 2. Schematic of a truncated pyramid ice formation similar to the one that was crushed by a flat 'rigid' indentor during test TFR4 at Hobson's Choice Ice Island, 1990. The nominal penetration rate for the Ice Island test was 100 mm/s and the penetration depth was approximately 170 mm. The sloping sides of the pyramid are tilted upwards by 18 degrees from the base.

Figure 3. Three views of the numerical model used for the simulation described in this paper. The model consists of many stacked triangular facets (described in greater detail below). The model represents the *ice process surface* during crushing. (a) and (b) show different perspectives of the outer structure and (c) shows some detail of the inner structure. The base measures 1.47 m x 1.47 m.

Figure 4. Load record for ice crushing test TFR4 conducted at Hobson's Choice Ice Island in 1990. The nominal penetration rate was 100 mm/s and the depth of penetration was approximately 170 mm. The ice formation had a truncated pyramid shape. The record shows a typical sawtooth pattern where each sharp drop in load corresponds to a spalling event (Gagnon, 1998).

Figure 5. View of a meshed triangular facet, the central component of the numerical model. The facet is two elements in thickness. The actual thickness of the facet in the vertical direction with respect to the full model (Figure 3) is 0.04 m.

Figure 6. A sectional view of the fully meshed model. Six layers of thin facets, with differing colors, are shown sitting on top of one layer of thick facets that forms the base.

Figure 7. Stress versus volumetric strain curves for the M1 (high-stress) and M2 (low-stress) crushable foam facets that are used in the simulation. Where M1 and M2 facets overlap in the region of ice contact at the ice-structure interface their combined stress behavior corresponds to hard-zone, relatively intact, ice. In regions where only M2 facets are present at the ice-structure interface, those areas correspond to crushed ice.

Figure 8. Ten sets of images depicting what happens at ten points in time in the IceCrush simulation. Each of the ten image sets shows three vertically-stacked images, where the top image corresponds to M1 facets, the middle image corresponds to M2 facets and the bottom image corresponds to the combination of the M1 and M2 facets. Only the top three layers of the active facets are depicted in each image. Sectional views are shown for the first six image sets to help with the description. The times corresponding to the image sets are indicated with numbered markers on the load history for the simulation (Figure 10).

Figure 9. Z-stress color scales for the image sets in Figure 8. The positive z-axis is upwards and aligns with the central axis of the model and is normal to the crushing plate. The left, center and right color scales correspond to the top, middle and bottom images of each image set. The unit on each scale is Pa. The scales are the same as the small ones visible on each image in Figure 8 but enlarged for legibility.

Figure 10. Load time series for the IceCrush simulation. Numbered markers (solid circles) indicate the points on the record corresponding to the ten sets of images comprising Figure 8 that show the progressive ice behavior.

Figure 11. A portion of the displacement time series for the central region of the crushing plate during the IceCrush simulation. The record shows the abrupt forward movements associated with the $5^{th}$ and $6^{th}$ spalling events, at 0.80 s and 0.95 s, shown on the load time series (Figure 10). A string of resonant oscillations follows each rapid forward movement.

Figure 12. A portion of the load record for test TFR4 (Figure 4) conducted at Hobson's Choice Ice Island in 1990. Resonant oscillations, due to the elasticity of the ice/apparatus system, are evident at the bottoms of the load drops.

Figure 13. A portion of the load record for a small-scale ice crushing experiment on freshwater ice conducted in the lab. Significant resonant oscillations, associated with the elasticity of the ice/apparatus system, are evident following each of the three spalling events that are shown. (Reproduced from Gagnon, 2008).

Figure 14. View of a meshed triangular facet that has been given a degree of curvature that ensures that the ridges where the facets join are 'higher' than the valleys in between, that is, in closer proximity to the crushing plate with respect to the ice process surface. Hence, the shape of the process surface reflects that the ridges are areas of the ice formation that have more confinement. Spalls that form from such facets reflect their curvature.

Figure 15. Ten sequential images, running from the top left to bottom right, depicting the patterns of ice contact and pressure that develop on the ice process surface during an IceCrush simulation with the same parameters as the one shown in Figure 8, but using curved facets (Figure 14) instead of flat facets. The ten sequential images correspond to the same times indicated for the image sets in Figure 8.