

Test and Analysis Correlation of High Speed Impacts of Ice Cylinders

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Abstract

During the space shuttle return-to-flight preparations following the Columbia accident, finite element models were needed that could predict the threshold of critical damage to the orbiter's wing leading edge from ice debris impacts. Hence, an experimental program was initiated to provide crushing data from impacted ice for use in dynamic finite element material models. A high-speed drop tower was configured to capture force time-histories of ice cylinders for impacts up to approximately 100 ft/s. At low velocity, the force-time history depended heavily on the internal crystalline structure of the ice. However, for velocities of 100 ft/s and above, the ice fractured on impact, behaved more like a fluid, and the subsequent force-time history curves were much less dependent on the internal crystalline structure.

Introduction

In Chapter 11 of the Columbia Accident Investigation Board (CAIB) report [1], which was released after the space shuttle Columbia Accident, recommendation 3.3-2 requested that NASA initiate a program to improve the impact resistance of the shuttle orbiter wing leading edge. The second part of the recommendation was ...“determine the actual impact resistance of current materials and the effect of likely debris strikes.” In addition, recommendation 3.8.2 states, “Develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System (TPS) damage from debris impacts. These tools should provide realistic and timely estimates of any impact damage from possible debris from any source that may ultimately impact the Orbiter. Establish impact damage thresholds that trigger responsive correction action, such as on-orbit inspection and repair, when indicated. ”

Consequently to comply with the spirit of the CAIB recommendations, a team from NASA Glenn Research Center (GRC), NASA Langley Research Center (LaRC), and Boeing was given the following task: to develop a validated finite-element model of the Orbiter wing leading edge capable of accurately predicting the threshold of critical damage from debris including foam, ice, and ablators for a variety of impact conditions. Since the CAIB report was released, the team has been developing LS-DYNA models of the reinforced carbon-carbon (RCC) leading edge panels, conducting detailed material characterization tests to obtain dynamic material property data for RCC and debris, and correlating the LS-DYNA models with data obtained from impacts tests for both small-scale flat panels and full-size RCC flight hardware panels [2-6]. Foam impacts onto RCC panels were examined first. Once the RCC thresholds for foam impacts were determined, attention was directed to ice debris.

Ice presents one of the more serious debris impact threats to the space shuttle orbiter thermal protection systems. Ice that forms on the space shuttle external tank (ET), if dislodged during flight, can impact orbiter tiles or the reinforced carbon-carbon wing leading edge. Since the entire tank is covered with insulating foam, typically only a thin harmless frost occurs under most conditions. However, the fuel lines have bellows and brackets where it is very difficult to prevent hard ice formation. During the space shuttle Return-to-Flight (RTF) program, finite element models of the shuttle Orbiter wing leading edge RCC panels were developed that could predict the threshold of critical damage from both foam and ice debris. Since the debris may strike the orbiter at high velocity, dynamic material characterization of the debris was required for input into the finite element material models. After dynamic models for foam impacts were developed and validated [7], a search of the literature showed a scarcity of work has been performed in characterizing ice for high velocity impacts. Consequently, dynamic ice testing was begun at LaRC to determine the force-time histories and derived compressive stress-strain curves of clear, hard-ice specimens impacted at near constant velocity and hence at near constant strain-rates.

The threshold of damage to debris impacts for TPS tiles was determined primarily by a large number of impact tests using air guns to generate the required impact velocity. These tests covered the likely range of impact conditions, debris types, sizes, and velocities. Since TPS tile are relatively inexpensive and easily made, a large test program was feasible. However, full-scale wing leading edge RCC panels are very expensive, difficult and very time consuming to produce, and only a small number of spare panels exist. Consequently, the threshold of RCC panels to debris impacts were determined by a combination of testing along with validated dynamic finite element analyses.

The sprayed on foam insulation (SOFI) that impacted and critically damaged Columbia had a density of approximately 2.0 pcf. Clear ice has a density of approximately 56 pcf. Materials such as foam and ice with relatively low density (as compared to metals, for example) are rapidly decelerated in the atmosphere after dislodging. Hence the shuttle orbiter can build up a very large relative velocity with respect to these low-density materials depending on the size and mass of the debris and the distance from the release point to the impact point. Velocities of foam can reach 2500 – 3000 ft/s, while the maximum velocity of ice can reach 1000 ft/s.

The static strength of ice is difficult to measure experimentally and depends highly on directional crystalline structure and the direction of loading relative to the internal crystalline structure. Details on static material properties of ice can be found in a review paper by Schulson [8]. The dynamic material characterization of ice including strain-rate effects presented numerous challenges. A given ice specimen can have a complex crystalline structure, in which individual crystals can be very small, large, or a mixture of sizes with various orientations. A given ice specimen could be a single crystal, or if the freezing process is directional, the ice specimen could be composed of a series of parallel columnar crystals. Since ice is a difficult material to work with, strain-rate dependent data on ice for high velocities was nearly non-existent.

Ice on the external tank can form on fuel-line brackets or bellows as hard, clear masses or as icicles. Also, small particles of hard ice may form inside large regions of frost on the external tank from the cycles of melting and refreezing. This ice would be difficult to detect, but could pose a hazard if released at a point far enough away from the wing leading edge to result in a large impact velocity. Pre-liftoff inspections would detect and mitigate most large pieces of ice. However, cameras have detected ice inside the fuel-line bellows several minutes after launch.

Dynamic Material Characterization Testing of Ice

Impact testing of ice cylinders was conducted using the bungee-assisted drop tower at LaRC to accurately measure the impact force time-history for low velocity impacts and to investigate strain-rate effects by measuring the effective stress-strain curves of the crushing ice for different, near-constant velocity loading rates. This ice characterization work was performed to provide data for a dynamic LS-DYNA ice material model for use in shuttle RTF impact studies. Specifically, the ice model after validation was to be used to predict the threshold of ice impact damage to RCC wing leading edge panels. Since ice is a very brittle material, a compressive wave moves through the ice from the impact point and shatters the ice. It was postulated that as the velocity of the ice impact increased, the crystalline structure might become less and less important.

The LaRC drop tower provides accurate load measurements versus time and since the ice is not shot ballistically, the ice is not damaged prior to impact. In addition, the angle of impact is closely controlled except for a possible small misalignment angle between the drop head and the top of the ice specimen. The drop tower was configured in the intermediate strain-rate testing configuration. This configuration was very successful in measuring foam strain-rate effects. Thus, three load cells (see Figure 1) were placed below the load platform to measure the impact force of the ice. This method allows measurement of both the initial peak force and the subsequent lowered force after the ice shatters and becomes a more fluid substance consisting of multiple small snow-like particles.



Figure 1. Load platform supported by three load cells removed from drop tower.

LaRC Fabricated Ice

Initial ice tests were performed with ice fabricated at LaRC. Polyurethane foam molds with a plastic cylindrical insert were used to form the LaRC ice in a freezer, as shown in Figure 2. Good clear ice cylinders had an average density of about 56 pcf. Cylindrical specimen sizes that were constructed by this method at LaRC were 2.8-in diameter x 1.5-in long and 1.6-in diameter x 1.5-in long. The crystalline structure of the ice and the orientation of the crush axis to the crystalline structure are both very important to the static crush strength.

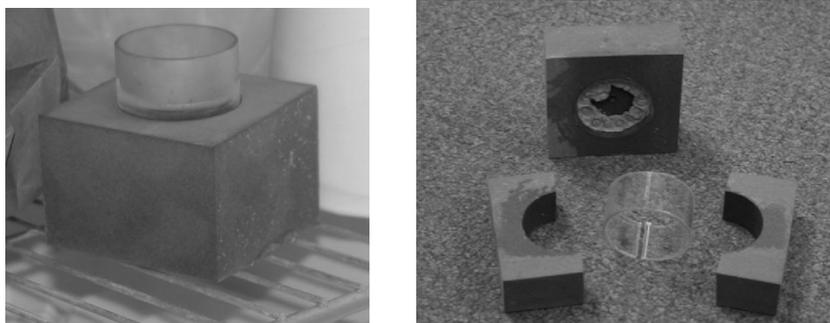


Figure 2. Mold used to make ice cylinders at LaRC.

The enclosed bungee-assist drop tower at LaRC was environmentally cooled for ice impact testing. Both air conditioning and dry ice were used to cool the tower and a band saw (Figure 3) that was used to cut the LaRC-produced ice cylinders into equal length samples. Lead stops were used to arrest the drop head and to prevent overloading the three load cells that support the ice specimen (Figure 4).



Figure 3. Drop tower and band saw in enclosed environmentally cooled chamber.

Two series of tests were performed at a strain-rate near 100/s. The impact velocity for these tests is approximately 13 ft/s. For all cases, the engineering strain-rate was approximated by the original length of the ice divided by the initial impact velocity. This approximation is reasonably accurate for small strains. Since the ice is brittle and breaks up almost immediately upon contact, the strain to failure is small. This first series consisted of 18 identical tests of LaRC produced ice cylinders, 1.6-inches in diameter and 1.5-in high. The stress-strain curves obtained are shown in Figure 5. The average strength was 741 psi, and the standard deviation was 355 psi. The highest strength recorded was 1400 psi, the lowest below 200 psi. Note that the “effective” strains (up to 3% for the fundamental pulse) computed as the change in length of the ice column over the initial length are large since the ice continues to load the platform even after the ice breaks up. This effective dynamic strain is much, much larger than the static failure strain. The strain at maximum stress is generally less than 2%. As the ice breaks up, the grains of ice flow over each other and create contact between grains that produces a residual strength after brittle failure. In other words, the ice particles behave as a fluid, which can support a dynamic pressure load.

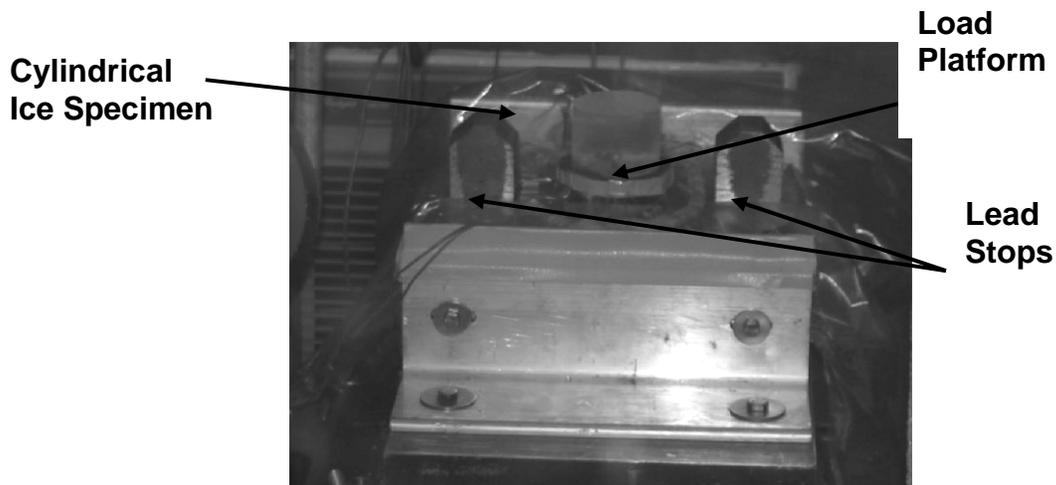


Figure 4. Ice specimen before impact. Lead stops are on each side of the specimen.

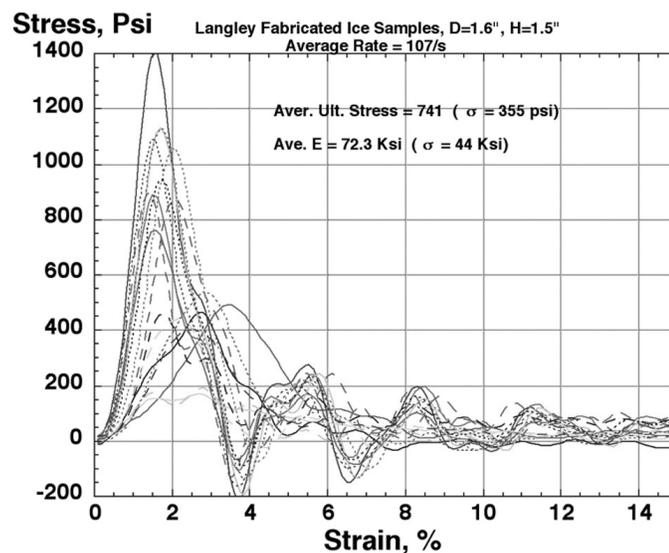


Figure 5. Stress-strain curves for LaRC fabricated ice samples with diameter of 1.6-in for an average loading rate of 107/s. (impact velocity approximately 13 ft/s)

A second series of 20 impact tests was conducted using LaRC ice of 2.8-in. diameter and 1.5-in. high. The average strength was 780 psi with a standard deviation of 240 psi. The highest strength recorded was about 1325 psi, the lowest around 350 psi. The stress-strain curves for this test series are shown in Figure 6.

Although the peak stress is about the same for both specimen diameters, the peak force depends on the surface area. Thus, the peak force for the 2.82-in diameter ice is over three times the peak force for the 1.6-in. diameter ice. Force-versus-time curves are not shown, but were generated for all impacts.

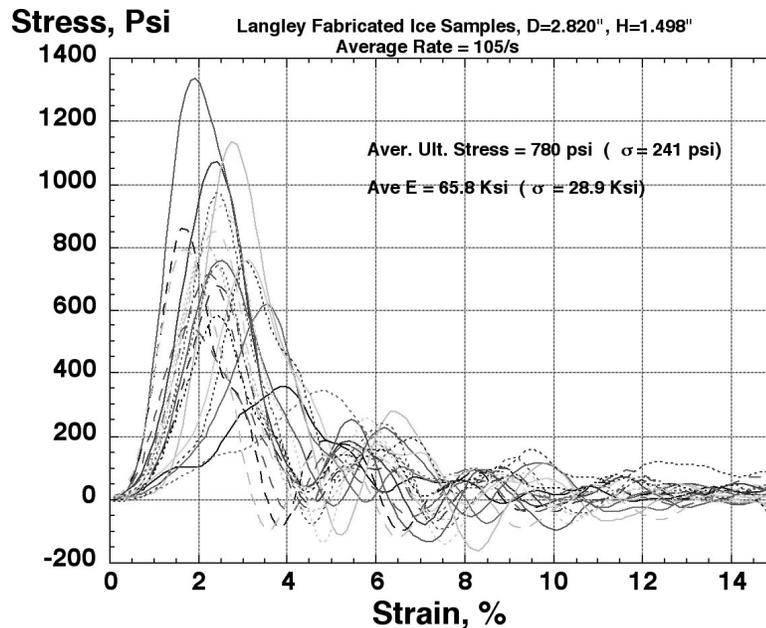


Figure 6. Stress-strain curves for LaRC fabricated ice samples with diameter of 2.82-in for impact velocity of 13 ft/s. (average strain rate of 105/s)

Vendor Supplied Ice Specimens

For consistency within the various organizations testing ice for the Shuttle Orbiter program, ice was procured from one vendor, IceCulture of Ontario, Canada. Ice cylinders from IceCulture were shipped overnight to LaRC. Twenty-five ice specimens 3.0-in. in diameter and 2.0-in. long and 75 ice specimens with 1.5-in. diameter and 2.0-in. long were received from IceCulture. The ice obtained from IceCulture was clear, near “perfect” ice, and many of the specimens were single crystals. All tests on the IceCulture ice were performed using the same drop tower configuration at LaRC as was previously described for the LaRC produced ice tests

The first tests were dynamic crush testing of the IceCulture ice samples with 3-in. diameter and 2.0-in. height. This ice had an average peak crushing strength of 994 psi with a standard deviation of 241 psi. The tests were performed at an impact velocity of approximately 17 ft/s with an average strain-rate of 104/s. The average density of the ice was 56.7 pcf. The maximum peak dynamic crushing stress was almost 1500 psi, the minimum was about 625 psi as shown in Figure 7.

The second series of IceCulture specimens were cylinders 1.5-in. in diameter and 2.0-in. high. The strain-rates of these impact tests at approximately 18 ft/s and 49 ft/s were 107/s and 295/s, respectively. As shown in Figure 8, the average peak crushing strength at the strain-rate of 107/s was 752 psi with standard deviation of 460 psi. One specimen, likely a single crystal, reached a peak stress of 2175 psi.

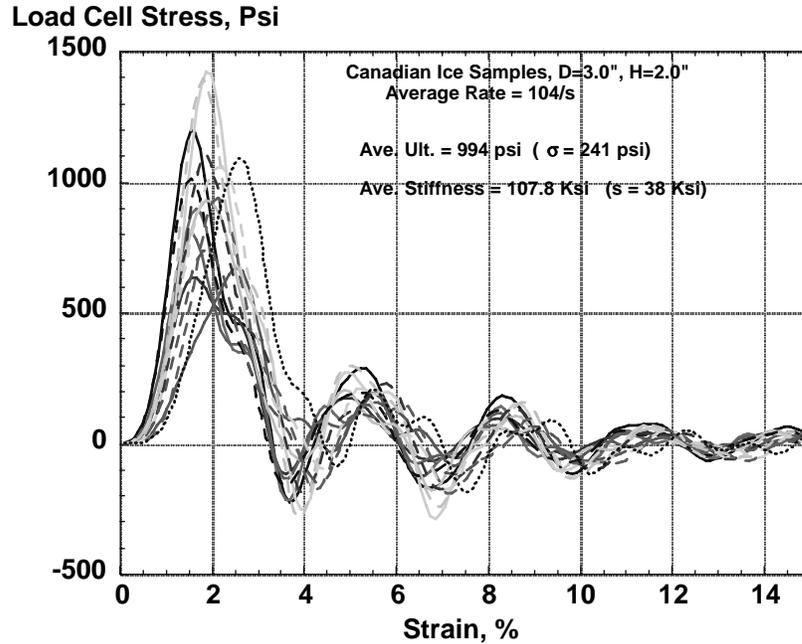


Figure 7. Stress-versus strain curves for commercial 2-in. high ice specimens with 3.0-in. diameter loaded at an average strain rate of 104/s.

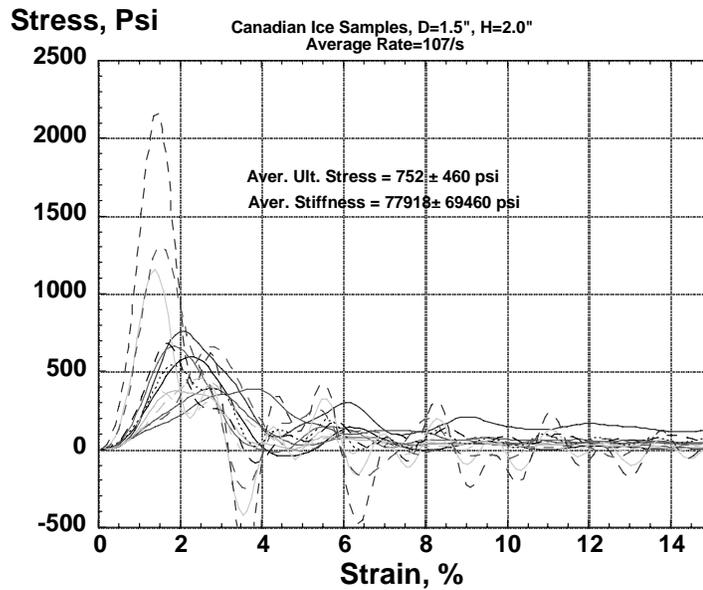


Figure 8. Stress-versus strain curves for commercial ice specimens with 1.5-in diameter loaded at an average strain rate of 107/s.

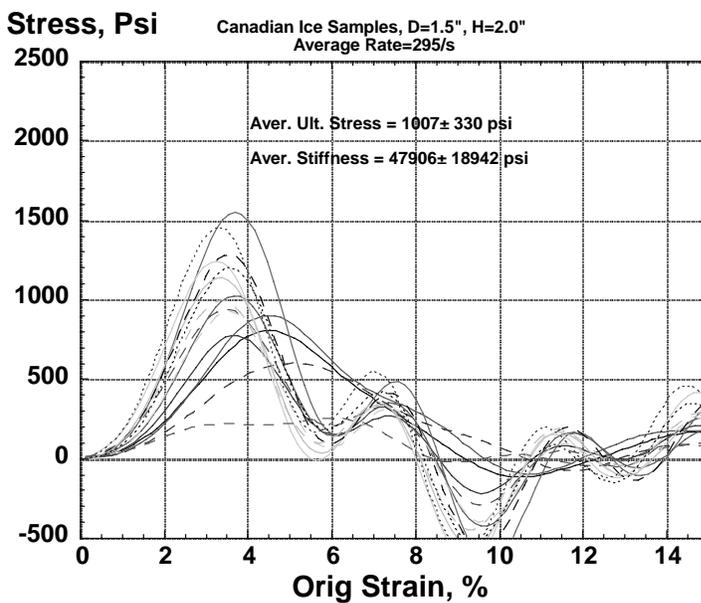


Figure 9. Stress-versus strain curves for 1.5-in. diameter specimens impacted at approximately 40 ft/s with an average strain rate of 295/s.

Identical 1.5-in. diameter by 2.0-in. high specimens were tested at a strain-rate of 295/s. The average peak stress was 1007 psi with a standard deviation of 330 psi. The resulting stress-strain curves are shown in Figure 9. For this test series, there is statistically an increase in peak stress for identical sized specimens with strain-rate. The failure stress was found to increase with strain rate for thin ice samples under compression in a Hopkinson bar as reported by Shazly [9]. The compressive failure stress was found to vary from 2900 psi at a strain rate of 90/s to 4930 psi at a strain rate of 882/s.

Professor Erland Schulson at Dartmouth University, who evaluated ice specimens for NASA [10], determined that ice obtained from IceCulture can be either a single crystal or multiple columnar crystals. Schulson determined the static strength of single crystal ice may be as high as 2175 psi, while the strength of the multiple crystal ice can range from 870 to 1305 psi. These values are consistent with the observed dynamic data.

High-speed Crush Testing at 100 ft/s

From examining the ballistic data generated at GRC, the crystalline structure of the ice at higher impact velocities appeared to have a much smaller effect than for low velocity impacts. To examine this observation, the drop tower configuration and the lead stops were optimized such that impacts of 100 ft/s could be tolerated without damaging equipment or instrumentation. At 100 ft/s, the structure of the ice, initial cracking, etc, was expected to have a much smaller effect; however, orientation effects probably still existed. Therefore, the angle of impact between the drop head and the top surface of the ice was kept as small as possible. A series of three 100 ft/s impact tests were conducted onto 1.5-in. diameter x 2-in high specimens from IceCulture. Plots showing the force time history for these three tests are shown in Figure 10. The average strain-rate for these tests is 578/s. The corresponding maximum stresses for these impact tests range from 1500 to 1700 psi.

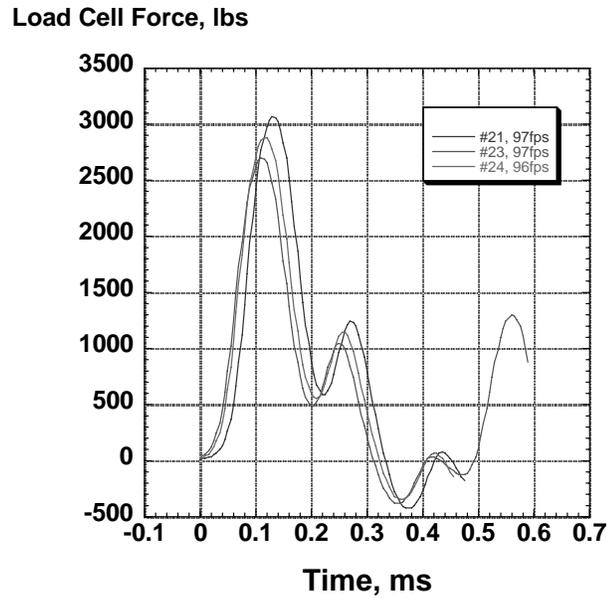


Figure 10. Force time history curves from 100 ft/s impacts onto ice specimens 1.5-inch diameter x 2.0-in high performed in Langley bungee-assisted drop tower.

High Speed Video Data

Frames from high-speed videos showed that the ice specimen breaks up into snow size particles upon first contact with the drop head at velocities near 100 ft/s (Figure 11). This response is very similar to the behavior observed in the 200+ ft/s ballistic impacts conducted at GRC. In contrast, at impact velocities of 10 - 40 ft/s (Figure 12), the ice fractured into relatively large fragments upon contact with the drop head. The force time-histories for the lower velocities were very dependent on whether one corner of the ice was contacted first (weak shear behavior), on whether there was initial cracking that promoted shear behavior, and on the internal crystalline structure of the ice. Between 40 ft/s and 100 ft/s the ice apparently changes its dynamic fracture behavior. For impacts of ice onto the shuttle, impacts at low velocity most likely will be influenced by the structure of the ice. However, most impacts will likely be in the range greater than 100 ft/s where the exact microstructure of the ice should have only a secondary effect.

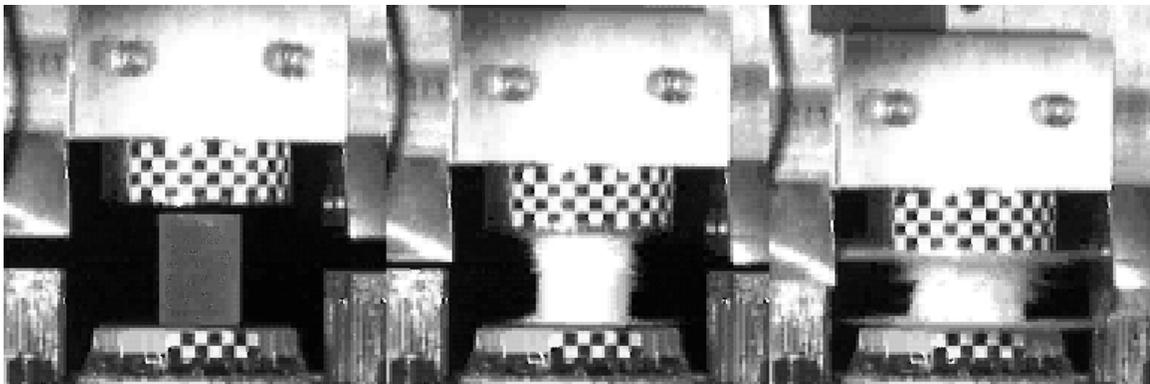


Figure 11. Sequential ice deformation after impact in drop tower at 100 ft/s.

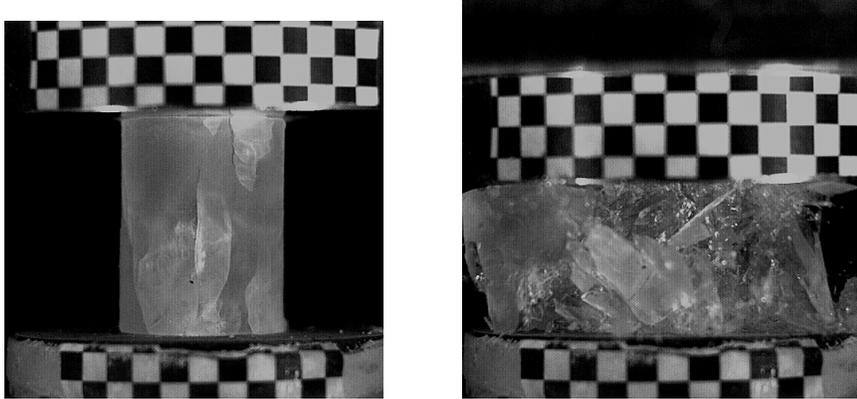


Figure 12. Ice just after contact with drop head moving at 11 ft/s (left). Large ice particles are formed for low velocity impacts (right).

Rate Sensitive Finite Element Material Model Development for Ice Impacts

A search of the literature for finite element models of ice impacts uncovered work by Kim and Kedward [11] on hail impacts simulated by DYN3D, the public domain version of LS-DYNA [12]. Although their ice material model worked well for their purpose, spherical ice impacts onto a composite plate at relatively low velocities, an attempt to use their elastic-plastic ice model for cylindrical ice impacts onto flat RCC panels did not produce good results. Consequently, a rate-sensitive plasticity material model for ice with failure was developed by Carney et. al. [13] for use in determining the threshold of ice impact damage to the shuttle Orbiter RCC wing leading edge.

This material model 155 was developed for use in modeling ice in the LS-DYNA ALE formulation. The new material model keyword designation in the production LS-DYNA version 971 code is *MAT_PLASTICITY_COMPRESSION_TENSION_EOS. The ending “EOS” indicates that an equation of state is used in the model. The isotropic elastic-plastic material model allows unique yield stress versus plastic strain curves for both compression and tension. When either the plastic strain or pressure cutoff values are exceeded, the deviatoric stresses are scaled, allowing a solid-to-fluid transition. Rate effects on the yield stress can be modeled by a Cowper-Symonds strain-rate model or by user defined load curves that scale the yield stress of the compression and tension. Material rate effects that are independent of the plasticity model can also be included.

The data generated from the dynamic crush testing of ice at NASA LaRC for velocities up to 100 ft/s along with data obtained from ballistic impacts of ice at GRC onto load cells were used to calibrate the new ice material model in LS-DYNA. Figure 13a shows a schematic of an LS-DYNA quarter-model of the 1.5-in x 2.0-in cylinder impacted at 100 ft/s and a comparison of the analysis with experimental data. The LS-DYNA model consisted of 400 rigid shell elements representing the drop head, 8280 solid elements representing the ice, and 25,484 solid “void” elements. An additional 2000 rigid solid elements were used to represent the base of the drop tower. There were approximately 40,000 nodes in the model. Simulations were executed for 0.4 milliseconds on a Linux workstation, which required about 1 hour of CPU. The maximum force of the analysis compared well with test data.

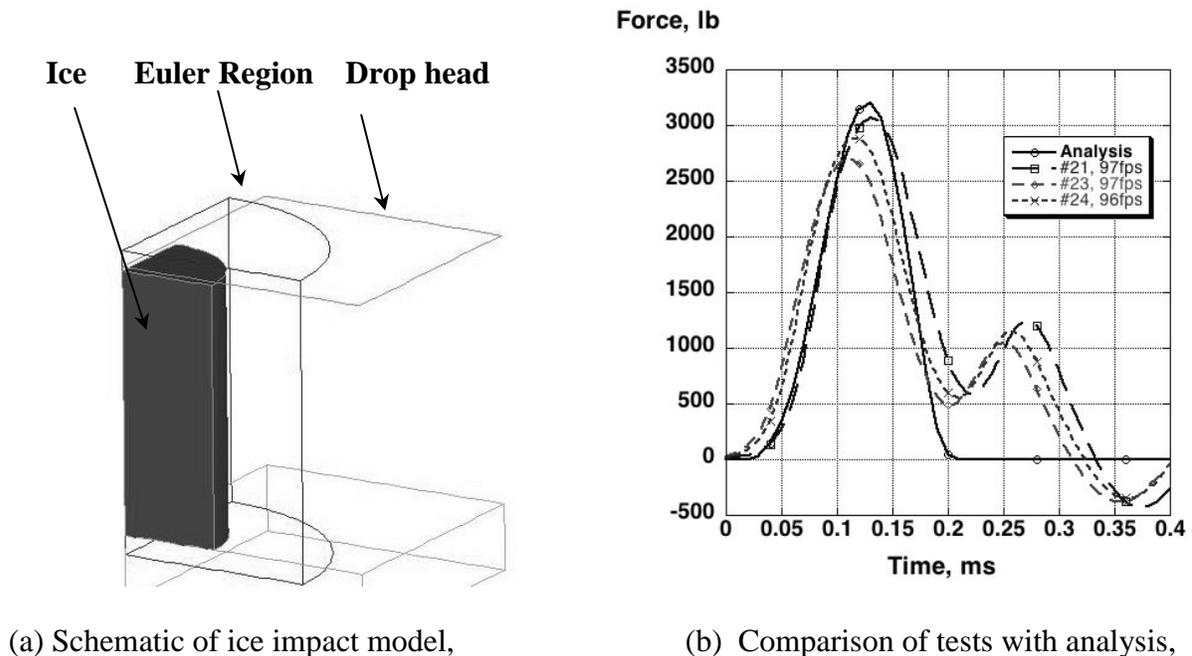


Figure 13. LS-DYNA ice model and simulation results compared with test data.

Acknowledgements

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Concluding Remarks

In the shuttle return-to-flight preparations following the Columbia accident, finite element models were needed that could predict the threshold of critical damage to the orbiter's wing leading edge from impact of ice debris. Hence, an experimental program was initiated by NASA to provide crushing data from impacted ice for use in dynamic finite element material models. A high-speed drop tower was configured to capture force time-histories of ice cylinders for impacts up to approximately 100 ft/s. At low velocity, the force-time history and resulting stress-strain curves obtained from dynamically crushing ice depended on the complex internal crystalline structure of the ice. However, for velocities of 100 ft/s and above, the ice fractured on impact, behaved more like a fluid, and the subsequent force-time history curves were much less dependent on the internal crystalline structure. The data generated from the dynamic crush testing of ice at LaRC for velocities up to 100 ft/s along with data obtained from ballistic impacts of ice at GRC onto load cells were used to calibrate the new ice material model in LS-DYNA.

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