IMPACT DAMAGE RESISTANCE OF COMPOSITE PANELS IMPACTED BY COTTON-FILLED AND UNFILLED ICE

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Abstract

Composite panels made from woven carbon-fiber / toughened epoxy were impacted by spherical ice projectiles of diameters ranging from 25.4 to 50.8 mm. These spheres were projected by a gas gun at velocities ranging from 30 to 200 m/s. The damage initiation of the composite panels, described by the failure threshold energy which is unique for each panel and ice diameter combination, was measured for ice projectiles constructed either with cotton-filling, or unfilled. The cotton-filled ice spheres were found to be significantly more lethal in the formation of initial impact damage. This is attributed to the decrease in break-up of the cotton-filled ice, relative to the unfilled ice. The cotton-filled ice remains intact and thus acts on a more concentrated area as it impinges onto the composite panel surface.

1 Introduction

Hail ice can produce significant damage to exposed composite structures. For aircraft structures, such damage can occur both while the aircraft is on the ground and while in flight. For the former situation, the ice is falling at terminal velocity in the range of 30+ m/s. An example of extensive on-ground hail impact damage is shown in Fig. 1a by the extent of repairs applied to a damaged composite fan cowl door. For in-flight events, the impact velocity is in the range of the aircraft's airspeed, e.g., 230 m/s (450 KTAS) and thus can produce considerable damage especially to forward-facing surfaces, as shown in Fig. 1b. The damage produced to composites due to hail ice impact has been investigated by Kim et al. [1, 2] and has been shown to exhibit a progression of various failure modes once a failure threshold energy (FTE) is surpassed. FTE is defined as the projectile kinetic energy level below which impacts to the composite panel produce no damage. This has been found to be unique for each panel thickness and ice sphere diameter [1].

Of interest in this study is the comparison of impact damage initiation produced by simulated hail ice constructed in two forms: unfilled (cast frozen water) and cotton-filled ice per ASTM F320 [3] specifications for the testing of aircraft transparent enclosures. The FTE is of particular interest since this parameter is a direct descriptor of the composite's resistance to impact damage. The relationship of the FTE as a function of projectile construction (cotton-filled or unfilled), projectile diameter, and panel thickness is presented.

(a) Repair of fan cowl door damaged by falling hail ice – on-ground impact

(b) In-flight hail damage

Fig. 1. Hail impact damage of composite structures

2 Experiment Description

Three series of woven fabric composite test panels were used in this investigation: Series A and B were standard-modulus carbon fiber / toughened epoxy, and Series C was intermediate-modulus carbon fiber / toughened epoxy. Series A and B experiments using unfilled ice were previously conducted [1], whereas Series C using cotton-filled ice are new data recently generated and reported herein.

The unfilled ice spheres were projected onto panel Series A and B using a nitrogen gas gun described in Ref. [1]. The cotton-filled ice was projected onto panel Series C using the ice gas gun shown in Fig. 2. This gun, built specifically for projecting ice, has a 79 mm inner diameter bore and is capable of firing up to 76 mm diameter projectiles (ice or any material) to velocities over 200 m/s. The breech piece is removable and can be frozen to aid in keeping the ice cold in the intermediate time between loading and firing. The ice projectiles are carried down the barrel by a foam sabot to insure that the ice does not get damaged or break up. The sabot is stopped at the end of the barrel, and the ice is allowed to pass through velocity measuring chronographs before impacting the target panel. The gas gun is powered by bottled nitrogen gas that is stored in a high pressure tank connected to the end of the barrel via a fast-opening valve.

Spherical-shaped ice projectiles of 25.4, 38.1, 42.7, and 50.8 mm diameter were fabricated by filling a split mold with water and freezing for several hours. The ice spheres were de-molded and stored in the freezer within an air-tight bag to prevent loss of mass via evaporation. For the cotton-filled projectiles, the appropriate mass of cotton, as indicated in Table 1, was measured and pre-soaked with water before being packed into the mold, prior to filling with water. The cotton volume fraction is quite high, as shown in Fig. 3, and thus pre-soaking aids in compacting the cotton thereby allowing proper closure of the split mold, as well as reducing entrapped air bubbles. In Fig. 4 the cotton is visible in a completed cotton-filled ice sphere. Note that blue-colored dye was mixed into the distilled water used for making the ice to aid the velocity measurement system in detecting the passing ice spheres. Since the specific gravity of cotton is close to water, the addition of cotton fiber does not increase the total mass of the projectile significantly above that of unfilled ice.

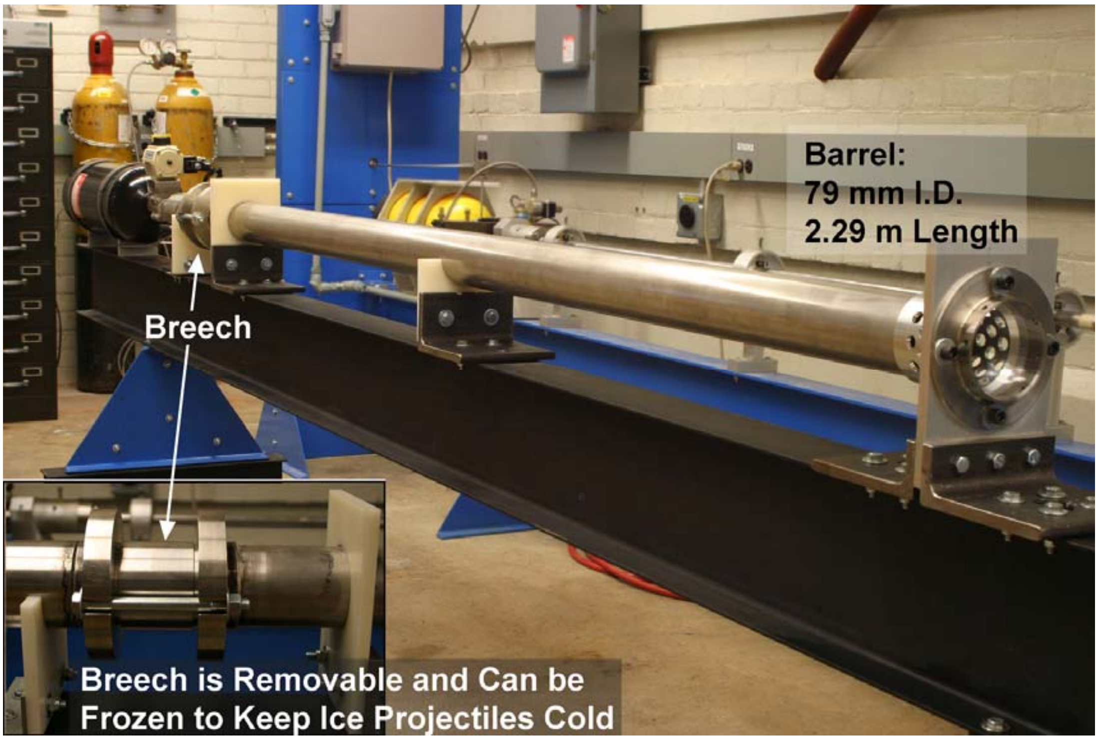


Fig. 2. Hail ice gas gun

Table.1 Cotton-filled ice per ASTM F320 [3]

Ice Dia. (mm)	Total Mass (g)	Toler-ance	Cotton Fill Mass (g)
25.4	8.2	± 5%	1.0
38.1	28.0		3.4
50.8	66.4		8.0

Fig. 3. Dry cotton fill (8 g) in 50.8 mm ice mold

Fig. 4. Completed cotton-filled ice sphere

The woven carbon/epoxy panels tested were 305 mm square having layup and thickness indicated in Table 2. Note that these layups are either quasi-isotropic or close to being quasi-isotropic, and thus comparisons between the different panels can be made based on thickness alone. These panels were held in a picture-frame fixture (see Fig. 5) that holds all four sides of the panel in a manner providing clamped support to resist bending, while permitting in-plane freedom. All impacts were at the center of the panel and normal to the target surface.

Table 2. Composite test panel layup and thickness

Series ID	Layup	Thickness (mm)	Ice Type
A	$[0/45/90]_s$	1.42	Unfilled
A	$[0/45/90/-45]_s$	1.91	Unfilled
A	$[0/45/90/-45/0/\underline{45}]_s$	2.62	Unfilled
B	$[0/45]_s$	1.22	Unfilled
B	$[0/45/90]_s$	1.83	Unfilled
B	$[0/45/90/-45]_s$	2.44	Unfilled
C	$[0/45]_s$	0.81	Filled
C	$[0/45/90/-45]_s$	1.65	Filled
C	$[0/45/90/-45/0/45]_s$	2.41	Filled

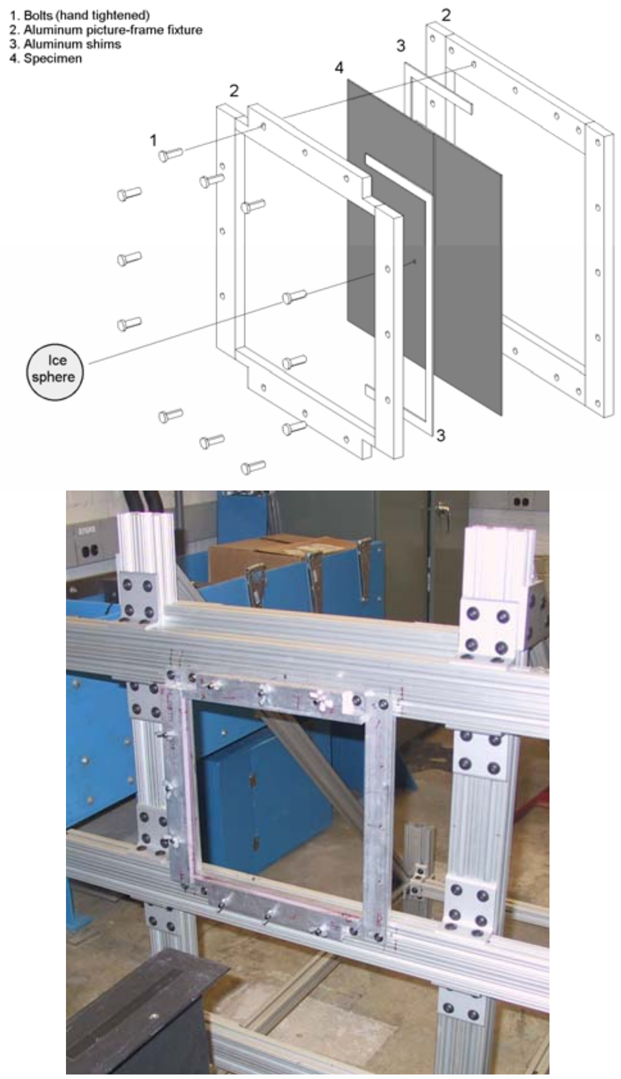


Fig. 5. Target holding fixture

3 Results

The initial damage mode for impacts above the FTE was found to be strongly dependent on the projectile type. For the unfilled ice, the panels exhibited delamination damage (see Fig. 6) as the initial mode. Higher velocities then caused a transition to small backside fiber failure with very little delamination. A distinct progression of damage modes was observed and documented to occur for unfilled ice impacts onto woven carbon/epoxy panels [1].

For the panels impacted by cotton-filled ice, the initial damage mode was backside fiber failure, as shown in Fig. 7, and not delamination. It is hypothesized that this difference in initial damage mode is due to the more concentrated contact spot over which the cotton-reinforced ice interacts with the target panel during the impact event, thereby producing higher local curvatures that create backside fiber breaks. Evidence supporting this hypothesis is visible in Figs. 8 and 9. In Fig. 8, the degree to which the cotton-filled ice remains intact is clearly visible, with a distinct flat spot has formed as a result of contact with the panel. In contrast, the crushing and break-up of the unfilled ice during the impact event is shown in the series of high speed photo images in Fig. 9. This comparison of photos clearly shows a major difference between the behavior of two projectile types. Since the unfilled ice breaks up during the impact event, the contact forces are spread out over a much larger area than the cotton-filled ice.

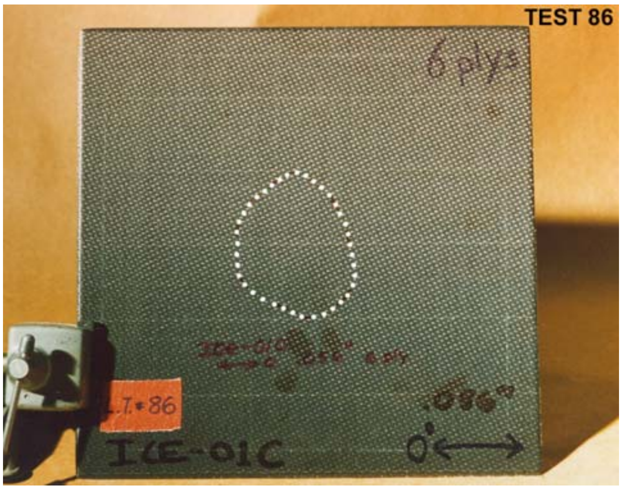


Fig. 6. Delamination damage mode for 1.42 mm panel impacted by 42.7 mm unfilled ice at 109 m/s

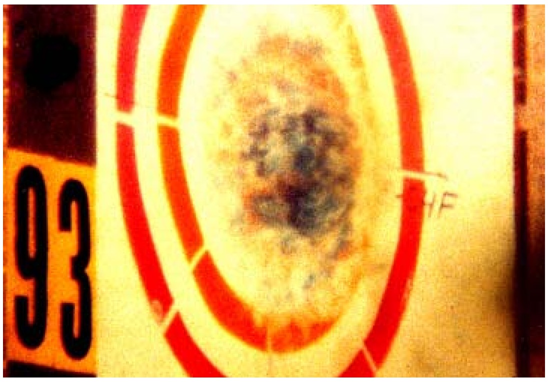
Fig. 7. Backside fiber failure for 25.4 mm cotton-filled ice at 71.6 m/s

Fig. 8. Cotton-filled ice recovered after impact test showing formation of flattened spot

FTE was measured for each combination of panel thickness and ice diameter by impacting a panel at a velocity estimated to be lower than that causing initial damage, inspecting the panel for delamination or backside fiber failure while it is still mounted in the test fixture, and if none exists, test the same panel again with a slightly higher velocity. This process was usually repeated for a maximum of no more than three times. The FTE value was taken either as the last no-damage kinetic energy level below the one at which damage resulted, or an average of those two values, depending on the degree of damage that finally occurs. The FTE for panel Series A and B impacted by unfilled ice are reported in detail in Ref. [1]. Measured FTE for panel Series C impacted by cotton-filled ice are reported in Table 3.

(a) t = 0 µs Initial Contact

(b) t = 267 µs



(c) t = 623 µs

Fig. 9. Breakup of unfilled ice during impact

Table 3. FTE for cotton-filled ice impact

Panel Series C Layup	FTE (J) for Ice Dia. (mm) 25.4	38.1	50.8
$[0/45]_s$	3.06	3.80	12.7
$[0/45/90/-45]_s$	12.9	14.9	16.8
$[0/45/90/-45/0/45]_s$	47.5	38.2	42.0

The measured FTE values were normalized by the volume of the ice sphere and the critical strain energy density related to the initiation of damage via by interlaminar shearing stresses. These normalized FTE are plotted in Fig. 10 for both cotton-filled and unfilled ice impacts as a function of the ratio of panel thickness H to ice diameter D. The unfilled ice FTE data exhibited a linear relationship with respect to H/D, while the cotton-filled ice impact exhibited a non-linear relationship and significantly lower FTE values than the unfilled ice impacts. These data quantitatively describe the degree to which the cotton-filled ice is much more lethal than the unfilled ice, particularly for thinner panels impacted by larger diameter ice, i.e., small ratios of H/D.

The data in Fig. 10 can be used for designing composite skins to be resistant to hail ice impact damage. As an example, consider sizing a panel to be resistant to damage from 30 mm diameter ice at 90 m/s. Based on the unfilled ice impact data, the requisite minimum H/D ratio is 0.034, corresponding to a panel thickness of 1.02 mm. In comparison, when sizing the panel based on the ASTM F320 type cotton-filled ice projectile, the data in Fig. 10 indicate a minimum H/D ratio of 0.08, corresponding to a panel thickness of 2.4 mm. The choice of ice construction is shown by this example to dramatically affect the weight of the structure, having direct implications on the design of minimum-gage thickness structures to be resistant to hail ice impacts.

4 Conclusions

The cotton-filled ice spheres made per ASTM specifications has been found to be significantly more lethal than unfilled ice. The lethality difference is more pronounced for thinner panels impacted by larger diameter ice (i.e., small values of H/D). This difference in lethality is due to the strengthening reinforcement that the cotton fibers provide to the ice projectile, making the projectile itself a composite of cotton fibers reinforcing an ice matrix.. Initial impact damage mode transition from delamination for unfilled ice to backside fiber failure for cotton-filled ice is due to the cotton-filled ice not breaking up during the impact event, as the unfilled ice does. This lack of breakup results in interactions with the target panel over a much more concentrated area, thereby forcing a higher local curvature response at the point of impact.

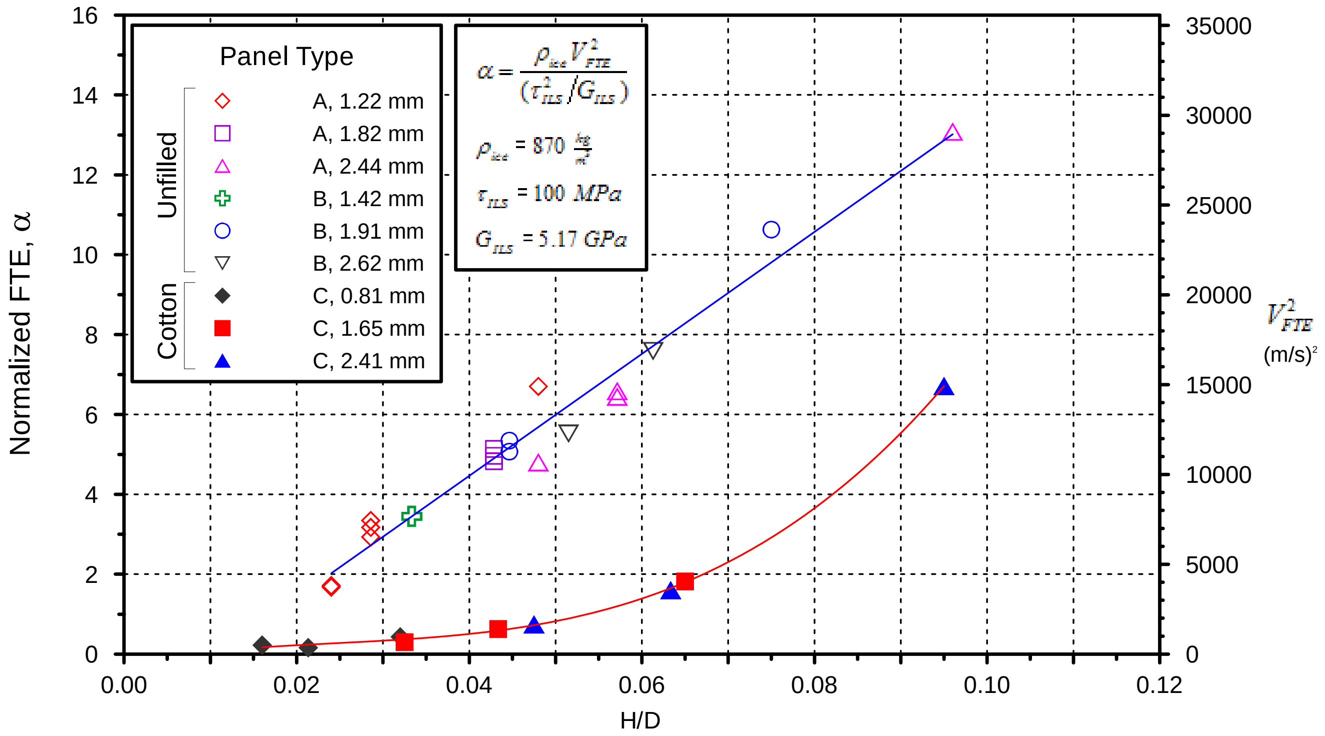


Figure 10. Normalized Failure Threshold Energy

References

[1] Kim H., Welch D.A., and Kedward K.T., “Experimental Investigation of High Velocity Ice Impacts on Woven Carbon/epoxy Composite Panels,” *Composites Part A*, Vol. 34, No. 1, pp. 25-41, 2003.

[2] Kim, H. and Kedward, K.T., “Modeling Hail Ice Impacts and Predicting Impact Damage Initiation in Composite Structures,” *AIAA Journal*, Vol. 38, No. 7, pp. 1278-1288, 2000.

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