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Drop-Weight Impact on Fiber-Metal Laminates Using Various Indenters

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ABSTRACT
Impact damage induced by drop-weight instrument on different types of Glare fiber-metal laminates (FML's) was studied experimentally. Indenters with various shapes and sizes were used in this study. For line-type Charpy indenters, the effect of angles between indenter and fiber were also investigated. Both the nondestructive ultrasonic and mechanical sectioning techniques were used to evaluate impact damage in the laminates. The results showed that cross-ply Glare 3 FML's offer higher impact resistance than unidirectional Glare 2 FML's. The first failure at low-velocity impact occurred as delamination between the non-impacted side aluminum face-sheet and the adjacent fiber-epoxy layer. It followed by a visible crack in the outer aluminum face-sheet at the non-impacted side with a crack length increasing with the higher impact energy. The more severe local damages appeared with smaller indenters whereas larger global deflection occurred if larger size indenters were used. This implies that for fiber-metal laminates impacted by smaller size indenters, the energy dissipated mainly through delamination and cracks whereas for their counterparts impacted by larger size indenters, more energy may be absorbed due to large global deformation.

INTRODUCTION
Fiber-metal laminates are a new family of hybrid materials built up from thin metal sheets and fiber-reinforced adhesives. The aim of engineering design for these materials is to combine the best properties of metals and fiber-reinforced composites. They were developed in late 1970's [1-3] and have gained wide attention in the aerospace and space industries since late 1980 for many advantages such as high specific strength, better damage tolerance to fatigue crack growth, foreign object damage, and corrosion, etc. There are two types of commercially available fiber-metal laminates: Glare (made of alternating glass-epoxy and aluminum layers) and ARALL (formed by alternating aramid-epoxy and aluminum layers). Only Glare was concerned in this study.

Damage mechanisms due to low-energy drop-weight impact onto composite panels have been studied extensively [4]. In general they are characterized by incomplete penetration with damage consisting of delamination, matrix cracking, and fiber failure. Damage patterns in composites could be different due to various indenters [5-7]. The methods used to evaluate impact damage include nondestructive techniques and destructive techniques. However only a few studies have been conducted on impact damages and other thermomechanical behaviors of fiber-metal laminates [8-12]. The main objective of this study is to develop preliminary understanding of damages caused by low-energy drop-weight impact through different shapes and sizes of indenters in these relatively newer engineering composites using common damage evaluation methods.

EXPERIMENTAL PROCEDURES
In this study all impact tests were conducted using an Instron-Dynatup 8250 pneumatic-assisted, instrumented drop-weight impact tester equipped with a pneumatic break to avoid multiple strikes [13]. Square specimens with dimensions of 100 mm x 100 mm (4" x 4") were first clamped circumferentially along a diameter of 76 mm (3") in the specimen fixture (Fig. 1). Glare 2 and Glare 3 panels were tested. The material configurations were listed in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Configuration</th>
<th>Metal Alloy</th>
<th>Metal Thickness</th>
<th>Prepreg Constituents</th>
<th>Prepreg Plies &amp; Orientation</th>
<th>Prepreg Thickness</th>
<th>Total Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glare 2</td>
<td>3/2</td>
<td>2024-T3</td>
<td>0.012&quot;</td>
<td>glass-epoxy</td>
<td>[0°] unidirectional</td>
<td>0.010&quot;</td>
<td>0.056&quot;</td>
</tr>
<tr>
<td>Glare 3</td>
<td>3/2</td>
<td>2024-T3</td>
<td>0.012&quot;</td>
<td>glass-epoxy</td>
<td>[0°/90°] cross-ply</td>
<td>0.010&quot;</td>
<td>0.056&quot;</td>
</tr>
</tbody>
</table>
Indenters with various shapes and sizes (Table 2) were dropped from a predetermined height to cause damage. Histories of impact loading were recorded using a PC-controlled high-speed A/D converter. After impact, the specimen was carefully taken out and kept for further damage evaluation. First, specimens with impact damages were scanned through UltraPAC, an immersion ultrasonic scanning system; then, mechanical sectioning technique was applied to evaluate the damages inside the impacted specimens by taking the cross-sectional micrographs.

Table 2. List of indenters (tup inserts)

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Shape</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.625” (16 mm) dia. hemispherical tup insert</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>1” (25.4 mm) dia. hemispherical tup insert</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>2” (50.8 mm) dia. hemispherical tup insert</td>
<td>825</td>
</tr>
<tr>
<td>4</td>
<td>2” spherical radius tup insert (4” spherical dia. on 2” dia. body)</td>
<td>850</td>
</tr>
<tr>
<td>5</td>
<td>0.5” spherical dia. tup insert on 5/8” dia. body</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>1.5” dia. hemispherical tup insert</td>
<td>485</td>
</tr>
<tr>
<td>7</td>
<td>1” dia. conical tup insert</td>
<td>445</td>
</tr>
<tr>
<td>8</td>
<td>2” spherical radius tup insert (4” spherical dia. on a 1.5” dia. shank)</td>
<td>850</td>
</tr>
<tr>
<td>9</td>
<td>10 mm dia. flat-face, cylindrical tup insert</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>Charpy tup insert (7/8” × 3/16”)</td>
<td>150</td>
</tr>
<tr>
<td>11</td>
<td>Charpy tup insert (3/4” × 1/8”)</td>
<td>130</td>
</tr>
<tr>
<td>12</td>
<td>0.5” radius tup insert (1-1/8” × 1/2”)</td>
<td>200</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Various factors (such as fiber orientation, thickness of laminates, different constituents, temperatures, impact energy, etc) can affect the impact response and damage patterns of fiber-metal laminates [12,13]. In this study the effect of various indenters impacting on Glare 2 and Glare 3 were investigated. First, hemispherical indenters with different diameters (from 0.5” dia. up to 4”) were used to conduct impact tests on Glare 2 and Glare 3. Figure 2 shows the impact force histories of Glare 2 and Glare 3 corresponding to various sizes of indenters under 20 and 30 joules impact, respectively. Optical pictures were taken from impacted specimens and are shown in Figs 3 and 4 for 30 joules impact. Severe damage around impact site was induced by small indenters (0.5” and 0.625” in diameter) whereas no significant local damage was found once the diameter of indenters went beyond 1 inch. For larger indenters, the impact forces were more likely to increase slightly along with the increasing of the indenter diameter. This was probably due to the larger contact area when a larger indenter was used. Glare 3 provided higher maximum impact force than Glare 2 under the same test condition because of the higher stiffness of Glare 3. As shown in the results, impact energy was dissipated through severe local damage (fracture, delamination and plastic dent) for impact with small indenters, while more energy was absorbed through global deformation when larger indenters were used.
(a) Glare 2 under 20 joules impact
(b) Glare 2 under 30 joules impact
(c) Glare 3 under 20 joules impact
(d) Glare 3 under 30 joules impact

Figure 2. Impact force histories of Glare 2 and Glare 3.

Figures 3 and 4 depict more details of damage patterns using ultrasonic C-scan and cross-sectional micrograph techniques. They are for Glare 2 and Glare 3 subjected to 30-joules impact, respectively. For C-scan results, the through-transmission technique was adopted using 25 MHz transducers.

In general, the damage zone in Glare 3 was smaller than that in Glare 2 under the same impact condition. More damage information could be found from the cross-sectional micrographs cutting through the impact center. For Glare 2, there was no severe damage induced when the larger indenters (≥ 1.5” dia.) were used; a visible crack only in the non-impacted outer aluminum layer was observed with the 1”-dia. indenter; while severe through-the-thickness cracks occurred when the 0.625”-dia. indenter was used. There was no obvious delamination observed in Glare 2. On the contrary, only delamination between the non-impacted outer aluminum face-sheet and adjacent glass-epoxy layer induced from 1.5”-dia. indenter; delamination and crack in the non-impacted outer aluminum layer occurred when 1”-dia. indenter was adopted; for Glare 3, significant cracks through the whole thickness and delamination could be induced when the diameter of indenter was reduced to 0.625”. For both of Glare 2 and Glare 3, all cracks in aluminum layers showed a 45° angle relative to the tensile direction, which indicates the fracture was ductile.

It was worth noting that the conventional through-transmission technique, which uses two flat transducers (unfocused), could not provide a clear C-scan image because of the larger diameter of ultrasonic signal beam. Hence, a modified through-transmission technique using a flat transmitter and a focused receiver was adopted in this study [14]. Figure 5 showed the comparison of C-scans from conventional through-transmission and above modified through-transmission for the same damaged specimen. The modified through-transmission C-scan picked up more details of damage and material configurations. All C-scan images were achieved by the modified through-transmission in current study unless stated otherwise.
In this study, three different line-type Charpy indenters were chosen to conduct impact tests on fiber-metal laminates (Table 2). Figure 6 shows the impact force histories of Glare 2 subjected to 30 joules impact with indenters paralleled to the fiber direction (0°). The corresponding optical photographs were depicted in Fig. 7. Again, more severe local damages occurred with smaller indenter whereas larger global deformation induced when larger indenter was used. As shown in Fig. 7, impact by a 0.75” × 0.125” indenter caused completely penetration; through-the-thickness cracks were induced from a 0.875” × 0.1875” indenter; and no visible cracks were observed from Glare 2 panel impacted by a 1.125” × 0.5” indenter.

When a line-like indenter was used, damage patterns may vary with the relative angle between the indenter and fibers. A 0.875” × 0.1875” Charpy indenter was used to investigate the effect of this relative angle on Glare 2 and Glare 3. Only 30-joules impact results were presented. For Glare 2 (aluminum with unidirectional glass-epoxy), three different relative angles were chosen, i.e. 0°, 45° and 90°. Only two different relative angles (0° and 45°) were adopted for Glare 3 (aluminum with 0°/90° angle-ply glass-epoxy). The impact force histories, optical photographs and ultrasonic C-scans were presented in Figs 8 and 9 for Glare 2 and Glare 3, respectively. As seen in Fig. 8, regardless the relative angle, two through-the-thickness cracks started at the two tips of indenter and propagated along the direction of fibers in Glare 2 when subjected to line-like impact. From Figure 9, we observed that two small visible cracks appeared at the two tips of indenter for both of 0° and 45° impact in Glare 3 with almost identical impact force histories. Both optical and C-scan images manifested that there was no significant effect by changing the relative angle of indenter and fibers for Glare 3. Once again, Glare 3 provides a higher impact resistance than Glare 2 when subjected to line-like impact.
Figure 4. Damage patterns of Glare 3 under 30 joules impact.

Figure 5. Comparison of C-scans (left: flat transmitter and receiver; right: flat transmitter with focused receiver).
Figure 6. Impact force histories of Glare 2 subjected to 30 joules impact (Charpy indenters, 0°).

Figure 7. Optical photographs of Glare 2 subjected to 30 joules impact (Charpy indenters, 0°).

CONCLUSIONS

Fiber-metal laminated panels (Glare 2 and Glare 3) impacted by various indenters were studied experimentally. The ultrasonic through-transmission and cross-sectioning techniques were adopted to evaluate the damage patterns. Based on this study, some conclusions could be drawn:

1. Glare 3 offers higher impact resistance than Glare 2.
2. The first damage of fiber-metal laminates occurred on the non-impacted side.
3. The smaller the indenter, the more severe local damages in Glare. On the other hand, larger indenter could only induce global deflection with no significant cracks and delamination.
4. For line-like impact, the relative angles between indenter and fibers did not significantly affect impact responses of Glare.

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Figure 8. The effect of relative angle between the indenter (0.875" by 0.1875") and fibers on Glare 2.
Figure 9. The effect of relative angles between the indenter (0.875” × 0.1875”) and fibers on Giare 3.
REFERENCES


