Challenges of generating controlled one-inch impact damage in thick CFRP composites

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In this paper, an attempt has been made to conduct controlled low velocity impact experiments in quasi-isotropic carbon fiber reinforced polymer (CFRP) composites of different thicknesses to generate barely visible impact damage (BVID) that causes 1" internal delamination. Various 2-mm, 4-mm and 6-mm thick quasi-isotropic CFRP composite plates having similar stacking sequence were manufactured in a compression molding machine. These plates were cut into various 6" x 4" coupons to be impacted in accordance with ASTM D7136 standard on a Dynatup impact testing machine. The goal of the experiments was to identify the combination of impactor mass, energy and momentum at which approximately 1" delamination could be produced for test coupons of different thicknesses. Interesting observations were made with respect to the size and shape of the impact damage as the thickness of the composite coupons was increased from 2-mm to 6-mm.

I. Nomenclature

\[ v_i = \text{impact velocity} \]
\[ w_{1,2} = \text{distance between flag prongs} \]
\[ t_1 = \text{time first flag prong passes detector} \]
\[ t_2 = \text{time second flag prong passes detector} \]
\[ t_i = \text{time of initial contact} \]
\[ v = \text{velocity} \]
\[ g = \text{acceleration due to gravity} \]
\[ F = \text{Impact force} \]
\[ m = \text{mass of impactor} \]
\[ \delta = \text{displacement} \]
\[ E_a = \text{absorbed energy} \]

II. Introduction

In carbon fiber reinforced polymer (CFRP) composites, barely visible impact damage (BVID) can occur due to tool drops during manufacturing on the shop floor or low velocity impact of small and large debris during the service life of the structure. In low velocity impact events, the impactor may not penetrate the composite material but still may lead to BVID causing various types of damage such as delamination, matrix cracks and fiber fracture. BVID represents surface indentations which are too small to be seen during visual aircraft inspections and can cause the formation and growth of considerable internal damage. Under compressive loading scenarios such damage can propagate and can lead to extensive overall strength reduction of the structure.

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The earliest work on impact testing of composites was conducted on unidirectional laminates in the 1970’s by Butcher [1] and Toland [2] under different loading conditions to understand how an impact event affects the structural behavior of composites and how impact damage begins to propagate in composites. In the 1980’s Cantwell et al. began to conduct low and high velocity impact tests on different stacking sequence of composites materials to see the influence of varies parameters like geometry and projectile mass on impact response of composites [3-7] Cantwell also began to look into methods that could be used to detect impact damage [8]. Subsequently researchers began to conform to ASTM standard of drop weight impact testing [9] for conducting their impact experiments. Ishai and Shragai [10] looked at the effect of impact loads on damage and residual compressive strength of CFRP laminated beams. Stellbrink [11] looked at the fatigue behavior of impact damaged CFRP laminates. After conducting impact experiments, it became important to come up with prediction models to quantify the residual strength of a composite after impact. This work was spearheaded by Caprino [12]. Shortly after prediction models were developed, finite element methods to model impact damage began to be explored by Clark [13] and other researchers [14-17]. In some recent work, Schoeppner et al. [18] investigated used low velocity impact load –time histories from the AFRL database to impact load level at which impact damage will begin. Caputo et al. [19] developed numerical FEM models for impact scenarios in composites and proposed model described damage initiation and propagation of impact damage. Flores et al. [20] used 3D DIC to analyze the deformation in coupons subjected to low velocity impacts in the order of 10 J. Wallentine et al. [21] conducted serial sectioning microscopy and Ultrasonic scans to characterize BVID in unidirectional CFRP composites. Bogenfeld et al. [22] conducted a comprehensive review of impact analysis methods and discussed analytical and numerical models to predict impact damage and fiber failure.

The concept of BVID was introduced in the 1980’s with respect to understanding the damage tolerance of composite laminates [23, 24]. In subsequent years, BVID became important in the inspection of composite aircraft where the damage needed to be characterized as BVID or visible impact damage (VID). BVID is defined as damage that is visible at a distance of less than 1.5 m and VID is defined as damage that is visible at a distance of 1.5 m [25]. This clear distinction between BVID and VID during aircraft inspections can determine if a composite repair is needed or not. If a damage is characterized as VID it needs repairs to be conducted to the composite. However, a situation may arise where damage is characterized as BVID based on visual inspections but may have an impact damage size of 1” or greater. An impact damage size of 1” or greater may significantly deteriorate the compressive strength of the composite part (see Fig. 2) and may need immediate repairs and must not be discounted despite being characterized as BVID. This is the significance of 1” impact damage size.

With the increasing occurrence of BVID in composites, detection methods needed to be developed to characterize the impact damage. Ultrasonic testing was one of the first methods to be used for impact damage inspection and detection [8, 26]. Guided wave propagation in composite laminates has been used to see the interaction with impact damage [27, 28]. Eddy current methods have been explored by researchers to detect manufacturing flaws and operational damage such as impact damage in CFRP composites [29, 30]. Researchers have also explored microwave nondestructive evaluation techniques to investigate low velocity and high velocity impact damage in composites due to environmental effects [31-35]. Infrared thermography is also being explored by scientists as a viable option of detecting impact damage in a rapid manner [36, 37]. X-ray computed tomography is also being used by researchers to give a 3D assessment of impact damage in composite structures [38, 39]. Advanced guided wave methods are currently being explored by authors of this paper for rapid, reliable and large area assessment of composite structures subjected to controlled impact damage.

The objective of this paper is to conduct controlled impact events in CFRP composite coupons of different thicknesses to produce a specific size of damage i.e. 1”. ASTM D7136 standard of impact testing has been used to conduct impact experiments on 6” x 4” quasi-isotropic coupons having a thickness ranging from 2-mm to 6-mm. The goal of the impact experiments was to identify a combination of mass, energy, and momentum of the impactor for which a controlled damage of 1” can be produced. Ultrasonic testing in an immersion tank was used to visualize the size and extent of impact damage that was produced in each experiment. The results demonstrate that controlled damage is much easier to be obtained in thin laminates compared to thick laminates.

III. Manufacturing Process and Experimental Setup

A. Manufacturing of quasi-isotropic CFRP composite plates

To make the coupons for impact testing, composite plates were manufactured using the CYCOM ® 5320-1 epoxy resin system with the Hexcel IM7 12K fiber in a compression molding (hot press) machine with the manufacturer’s cure cycle. To manufacture quasi-isotropic composite plates with different thicknesses an appropriate stacking sequence with the appropriate number of layers had to be chosen. The quasi-isotropic stacking sequence was chosen based on the work done by previous researchers [19, 20]. A [-45/90/+45/0]_{2S} stacking sequence was chosen for
manufacturing the 2-mm composite plate with 16 layers. To manufacture a 4-mm composite plate, a [-45/90/+45/0]_{1S} stacking sequence with 32 layers was chosen and to manufacture a 6-mm composite plate a [-45/90/+45/0]_{2S} stacking sequence with 48 layers was chosen. After the manufacturing process in the compression molding machine, the thickness of the manufactured plates was a little higher than anticipated, i.e. the 2-mm plate had an average thickness of 2.14 mm, the 4-mm plate had an average thickness of 4.15 mm and the 6-mm plate had an average thickness of 6.28 mm. The cure cycle, compression molding machine and one of the manufactured composite plates is displayed in Fig. 2. From the large composite plates, the 6” x 4” standard size coupon for the ASTM D7136 testing was cutout as displayed in Fig. 2 (c).

B. Experimental setup and procedure for ASTM drop weight impact testing

A drop tower with low friction guide rails is used to induce collision between a mass of known weight (impactor) and a fixed composite coupon of dimensions 6” x 4”. The controlled impact event is recorded by a piezoelectric load cell which can accurately record data of the applied impact force, energy absorbed by the coupon and the displacement of the coupon during the event. Using variable impact heights, data is collected that shows how the coupon behaves under impacts of varied magnitude, and these impact tests can be conducted in sequence to see how damage forms in the coupon over repeated impacts. This data can then be used to predict future behavior of the material such as crack propagation and other damage formation. These tests are particularly useful when studying composite materials. Since composites are designed to distribute damage throughout the volume of a material, damage formation and the propagation of cracks can be difficult to predict accurately through theory and simulation alone. Also, difficulties in predicting important properties such as stiffness of the material and the amount of energy it is capable of absorbing before experiencing failure make drop weight impact testing a valuable process in material science.

Before the test is conducted, it is important to make sure that the impact carriage and conveyor is secured safely above the clamping platform. The sample is placed on top of the support fixture centering it on top of the 5” x 3” cut-out and the assembly is clamped into place. A protective cover is placed over the coupon to prevent accidental damage. After this the conveyor is slowly raised or lowered using the hoist control to the desired distance above the sample and is fastened into place using the shaft collars. This distance is measured using the laser height indicator and determines the drop height. All the equipment is checked to ensure that the data acquisition system is recording the data properly and then it is engaged; also checked is that the sample cover is removed. The trigger mechanism is then activated, initiating the drop impact event. The impactor can be caught safely after rebounding from the coupon to avoid secondary impact. It is also possible to avoid secondary impact if the drop weight impact testing machine has an anti-rebound device or stop block. The data is saved and the impact carriage is lifted away from the sample and is locked back into place on the conveyor. The sample cover is placed over the coupon to ensure no further damage to it as the conveyor’s shaft collars are unlocked and the hoist mechanism is used to lift the carriage away from the clamping assembly. The entire experimental setup is displayed in Fig. 3.

IV. Impact Testing Analysis and Damage Behavior

A. Analyzing the impact testing data

Behavior of a sample during the impact event can be observed in the data that is recorded from the load cell. The impact force-time history is converted from the load cell output voltage. Following ASTM D7136 [9], the impact velocity is calculated by:

$$v_i = \frac{w_{12}}{(t_2-t_1)} + g \left( t_i - \frac{(t_1+t_2)}{2} \right) \quad (1)$$

Where $w_{12}$ = distance between flag prongs, $t_1, t_2$ = time first and second flag prong passes detector, and $t_i$ = time of initial contact.

The velocity and displacement history of the impactor is calculated by:

$$v(t) = v_i + gt - \int_0^t \frac{F(t)}{m} \, dt \quad (2)$$

$$\delta(t) = v_it + \frac{gt^2}{2} - \int_0^t \left( \int_0^t \frac{F(t)}{m} \, dt \right) \, dt \quad (3)$$

Where $v_i$ = impact velocity, $t$ = time, $g$ = acceleration due to gravity, $F$ = impact force, and $m$ = mass of impactor. Furthermore, the energy absorbed by the coupon can be calculated using:
\[ E_a(t) = \frac{m(v^2 - \nu(t)^2)}{2} + mg\delta(t) \]  

(4)

This data provides insight into how the sample performs under the stresses applied by the impact weight and can preview how the sample absorbs energy and how damage propagates. Questions about how brittle the sample is and whether it was destroyed during the impact event can be indicated by the force-time curve.

B. Impact tests conducted on 2-mm quasi-isotropic coupons

Impact tests were conducted on various 6” x 4” coupons having the stacking sequence of [-45/90/+45/0]_{2S} which had thickness in the range of approximately 2-mm. The details of the impact tests are given in Table 1. This table indicates that 2 coupons were used for the same potential energy with an impactor mass of 3.06 kg. Coupons B and C were impacted with 5.85 J, coupons D and E were impacted with 9.66 J, coupons F and G were impacted with 14.05 J and coupons H and I were impacted with 16.04 J. All the energies were incremental and were estimated to try and obtain 1” delamination size in the 2-mm thick coupons in an iterative process. In coupons H and I with impactor energy of 16.04 J we were able to obtain 1” delamination size.

The force-time history of the impacts is given in Fig. 4. The load curve shows peaks at certain maximum load and is parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage.

The energy-time history of the impact events in the 2-mm coupons begins from being positive initially as the impactor is dropped towards the coupon then it becomes zero upon contacting the coupon and becomes negative as the impactor rebounds from the coupon and moves upwards. The negative velocity indicates the upward rebounding of the impactor after impacting the coupon. The displacement-time history of the coupons begins from zero and becomes maximum upon contacting with the impactor and then goes back to zero as the impactor is rebounded upwards as can be clearly observed in Fig. 5. We can clearly observe that the maximum displacement is obtained in coupons H and I for an impact energy of 16.04 J which causes an internal delamination of 1”.

The energy-time plots given in Fig. 6 is taken from the force-time curve through integration of the data. The energy-time plots better describe the peak energy experienced and energy absorbed by the coupons. Here, the energy absorbed is the difference between the value at the end of the plot and the initial value. The difference between the peak energies observed and the energy absorbed can be used to determine the efficiency of energy absorption by the material. Furthermore, the energy-time history clearly is able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. For coupons H and I where 1” delamination is formed, over 65% of the impact energy is absorbed by the coupons.

After performing two impact tests per energy/ drop height, the data obtained was further extrapolated to obtain a linear relationship between maximum impact force and potential energy of impactor. A linear relationship was also obtained between delamination size and potential energy of impactor. Similarly, a linear relationship was also obtained between the absorbed energy and potential energy of impactor. These relationships are displayed in Fig. 7. From these impact experiments, we can also infer the effect of impact energy and impact momentum on delamination size and penetration of damage across the thickness of these coupons as indicated in Fig. 8. Hence a mass, height and energy combination of the impactor was obtained to initiate a 1” size impact damage in a [-45/90/+45/0]_{2S} 2-mm thick quasi-isotropic coupon.

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size. From the B-scan, it can be seen that although, the center of the damage area undergoes permanent deformation similar to a dent, it does not have a delamination as a clear reflection from the center of the damage can be seen in the B-scan. From the C-scan image, we can clearly see the fiber cracking and pushout in the -45° fiber direction and this can be seen by looking at the rear surface of the coupon. A quad plot of coupon I, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Fig. 9. Profilometry scans of coupon I which produced a 1” damage were conducted using a Veeco Dektak 3ST surface profiler to observe the profile of the top and bottom surface after impact. The profilometry images are displayed in Fig. 11. Using the top surface scan we were able to estimate that the dent depth is approximately 54 µm and using the bottom surface scan we were able to estimate the pushout height as 80 µm. Some of the irregularities in Fig. 10 (b) can be attributed to the rough bottom surface of the composite. This roughness was fixed in subsequent manufacturing of the composite plates. It is also interesting to observe that the dent profile seems hemispherical with a small dimple. The dimple is attributed to the tup which was used for the impact and was not ground well.

C. Impact tests conducted on 4-mm quasi-isotropic coupons
Similar to the previous section, impact tests were conducted on various 6” x 4” coupons having the stacking sequence of [-45/90/+45/0]_s which had thickness in the range of approximately 4-mm. The details of the impact tests are given in Table 2. This table indicates that all coupons were impacted with an impactor mass of 3.06 kg. Coupons A, B, K and L were impacted with 16.04 J, coupons C and D were impacted with 10.53 J, coupons E and F were impacted with 13.46 J, coupons G and H were impacted with 14.75 J, coupon I was impacted with 11.71 J and coupon J was impacted with 14.05 J. All the energies were incremented/decremented based on the previous tests and were estimated to try and obtain 1” damage size in the 4-mm thick coupons. There seems to be a threshold phenomenon occurring where a very narrow range of energy exists where the damage size significantly increases with a small change in height for the same mass. In coupons A, B, K and L with impactor energy of 16.04 J we were able to obtain approximately 1.3” delamination size which was closest to 1”.

The force-time history of the impacts is given in Fig. 11. The load curve shows peaks at certain maximum load and is parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage. These irregularities can be observed in force-time plots of coupons A, B, K and L and they seem to be very consistent. This can also be seen for coupon H which is clearly an outlier.

The velocity-time history of the impact events in the 4-mm coupons begins from being positive initially as the impactor is dropped towards the coupon then it becomes zero upon contacting the coupon and becomes negative as the impactor rebounds from the coupon and moves upwards. The displacement-time history of the coupons begins from zero and becomes maximum upon contacting with the impactor and then goes back to zero as the impactor is rebounded upwards as can be clearly observed in Fig. 12. We can clearly observe that the maximum displacement is obtained in coupon G for an impact energy of 14.75 J. Coupon H was an outlier as the same energy did not create any significant damage in coupon G. If we look at the force curves of coupons G and H we will observe that they have almost the same maximum force but their damage mechanisms are different due to their difference in strength which is anomalous.

The energy-time plots given in Fig. 13 is taken from the force-time curve through integration of the data. The energy-time history clearly able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. For coupons A, B, K, L and G (outlier) where 1.3” delamination is formed, over 76% of the impact energy is absorbed by the coupons.

After performing these impact tests, the data obtained was further extrapolated to obtain a linear relationship between maximum impact force and potential energy of impactor. Similarly, a linear relationship was also obtained between the absorbed energy and potential energy of impactor. An exponential relationship was obtained between damage size and potential energy of impactor. These relationships are displayed in Fig. 14. From these impact experiments, we can also infer the effect of impact energy and impact momentum on damage size and penetration of damage across the thickness of these coupons as indicated in Fig. 15. Here we can see a clustering effect where coupons impacted with the same energy have similar characteristics. Hence a mass, height and energy combination of the impactor was obtained to initiate a 1.3” size delamination in a [-45/90/+45/0]_s 4-mm thick quasi-isotropic coupon which was closest to 1” damage.

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size. From the B-scan, it can be seen that although, the center of the damage area undergoes permanent deformation similar to a dent, it does not have a delamination as a clear reflection from the center of the damage can be seen in the B-scan and it aligns with the bottom surface of the coupon. In addition, it can also be observed that the impact damage has propagated all the way through the thickness of the composite similar to the 2-mm coupon. From the C-scan image, we can clearly see that there is a small fiber pushout in the -45º fiber direction, and this can be seen by looking at the rear surface of the coupon as well. A quad plot of a representative coupon, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Fig. 16. Profilometry scans of the coupon were conducted similar to the previous section to observe the profile of the top and bottom surface after impact. The profilometry images are displayed in Fig. 17. Using the top surface scan, we were able to estimate that the dent depth is approximately 87 µm and using the bottom surface scan we were able to estimate the pushout height as 97 µm. As can be observed, the bottom surface of this coupon in Fig. 17 (b) has much lesser the irregularities when compared to the bottom surface of the 2-mm coupon in Fig. 10 (b). It is also interesting to observe that the dent profile seems a little flatter compared to the 2-mm coupon with a small dimple.

D. Impact tests conducted on 6-mm quasi-isotropic coupons
Impact tests were conducted on various 6” x 4” coupons having the stacking sequence of [-45/90/+45/0]₆S which had thickness in the range of approximately 6-mm. The details of the impact tests are given in Table 3. This table indicates that coupon Q-6-A was impacted 6 times with different mass and heights, coupon Q-6-B and coupon Q-6-C were impacted twice, and coupons Q-6-D, Q-6-E and Q-6-F were impacted only once. Multiple impacts were conducted to try and obtain 1” damage size in the 6-mm thick coupons. Despite numerous attempts there seems to be a threshold phenomenon occurring where the damage size significantly increases from less than 0.5” to more than 1.7” after multiple impacts.

The force-time history of the impacts are given in Fig. 18, Fig. 19 and Fig. 20. The force-time curve shows peaks at certain maximum load and is parabolic in shape. When the load curve is symmetric, its shape indicates that the impact energy is primarily deflected and little or no damage has occurred in the coupon. When there are irregularities in the parabolic shape of the load curve this indicates that the coupon has undergone extensive damage. These irregularities can be observed in all coupons at the final impact where the damage significantly increases in the coupons.

The velocity-time history of the impact events in the 6-mm coupons is similar to the behavior described for the 2-mm and 4-mm coupons. The displacement-time history of the coupons also has a similar trend as displayed by previous coupons and can be clearly observed in Fig. 21, Fig. 22 and Fig. 23.

The energy-time plots given in Fig. 24, Fig. 25 and Fig. 26 is taken from the force-time curve through integration of the data. The energy-time history clearly is able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. Similar to the 4-mm plate, there seems to be a threshold phenomenon occurring where if the absorbed energy is more than 79 %, it creates a delamination of 1.7” or more in the 6-mm plate.

From these impact experiments, we can also infer the effect of impact energy and impact momentum on delamination size and penetration of damage across the thickness of these coupons as indicated in Fig. 27. Hence a mass, height and energy combination of the impactor was obtained to initiate a 1.8” or greater size damage in a [-45/90/+45/0]₆S 6-mm thick quasi-isotropic coupon.

Ultrasonic immersion tank scans were conducted to obtain the B-scan and C-scan images of the impact damage to observe its shape and size similar to the previous two sections. From the B-scan, it can be observed that the impact damage has not propagated all the way through the thickness of the composite coupon which did occur in the case of the 2-mm coupon and the 4-mm coupon. From the C-scan image, we can clearly see that the damage size is 1.79” which was the damage size that was closest to 1” that could be obtained. It can also be observed from the C-scan that the maximum damage size is now in the 90’ fiber direction as opposed to the -45’ fiber direction in the 2-mm and 4-mm coupons because the damage had propagated through the thickness for the 2-mm and 4-mm coupon and has not propagated through the thickness for the case of the 6-mm coupon. A quad plot of a representative coupon, displaying the force-time history, the energy time history, The B-scan and C-scan is observed in Fig. 28. Profilometry scans of the coupon were conducted similar to the previous section to observe the profile of the top and bottom surface after impact. The profilometry images are displayed in Fig. 29. Using the top surface scan we were able to estimate that the dent depth is approximately 119 µm and using the bottom surface scan we were able to estimate the pushout height as 93 µm. As can be observed, the bottom surface of this coupon in Fig. 29 (b) does not cover the entire damage since it is greater than 1” and the scanning area is also limited by the bounds of the surface profiler when compared to the bottom surface of the 2-mm coupon in Fig. 10 (b) and 4-mm coupon in Fig. 17 (b). It is also interesting to observe that the dent profile seems flatter in Fig. 29 (a) compared to the 2-mm and 4-mm coupon with a small dimple. This is an interesting observation and has not been reported before in literature. From this observation, we can assume that the thickness of the impacted coupons increases the profile of the impacted surface becomes flatter and less hemispherical.

V. Summary, Conclusion and Future Work

In this paper, drop weight impact experiments were conducted on quasi-isotropic CFRP composite coupons of different thicknesses ranging from 2-mm to 6-mm conforming to the ASTM D7136 standard. The purpose of the impact experiments was to find the mass-height combination to obtain approximately 1” impact damage size. Force-time history, displacement-time history and energy-time history plots were obtained for each coupon that was tested using different mass-height combinations. Ultrasonic immersion tank scans were used to visualize the size of damage and profilometry scans were used to evaluate the dent depth and the pushout height of the top and bottom surfaces of the impacted coupons respectively. Representative coupons from each thickness that produced closest to 1” impact damage size were represented in a quad plot with the force-time history, energy-time history, B-scan image and C-scan image.
From the impact experiments, it was observed that the mass-height combination to obtain controlled 1” impact damage size can be obtained in relatively thin composite coupons (2-4mm) and becomes much harder to obtain in thick composite coupons (5-6mm). From the profilometry scans, it was observed that as the thickness of the composite coupon being tested is increased, the dent of impact becomes flatter. The tip of the tup has a hemispherical shape in accordance with the ASTM D7136 standard. For thin coupons, the hemispherical shape of the tup was recovered in the hemispherical shape of the indentation. However, for thicker coupons, the indentation developed a flat bottom in spite of the fact that the tip of the tup was hemispherical. This phenomenon may be attributed to the microscale failure process taking place in the composite under the tip of the impactor tup. In thinner composites, this process seems to be different from the process taking place in thicker composites. To the best of our knowledge, this observation has not been previously reported in the literature.

After having some difficulties in obtaining the mass, height and energy combination to obtain 1” delamination size in the 4-mm and 6-mm thick coupons, it was assumed that due to the thickness of the coupons being more than 2-mm, the in-plane dimensions (aspect ratio) needed to be increased so that the coupon could be bent more in flexure upon impact. Since the ASTM D7136 fixture has maximum in-plane dimensions of 12” x 6”, the coupon dimensions will be changed from 6” x 4” to 12” x 6” (since that is the in-plane dimension of the fixture). Two rectangular frames have been constructed that will hold the larger coupon and be clamped to the D7136 fixture to conduct impact tests on the same drop tower. These tests will not conform to ASTM D7136 standards. The modified experimental setup is displayed in Fig. 30. These tests will be conducted in the future to try and obtain close to 1” impact damage size in thick composite coupons. Guided-wave based methods will also be explored to detect impact damage of different sizes and distinguish impact damage from a simulated delamination. The use of X-ray computed tomography will also be explored as an impact damage detection technique in addition to the aforementioned methods.

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References


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## Tables

**Table 1: Impact tests conducted on quasi-isotropic coupons with a stacking sequence of \([-45/90/+45/0]_2S\)**

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Avg. thickness (mm)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
<th>Energy (J)</th>
<th>Impact velocity (m/s)</th>
<th>Momentum (Ns)</th>
<th>Damage size (in)</th>
<th>Ei (J)</th>
<th>% of Ei absorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>2.15</td>
<td>3.059</td>
<td>19.512</td>
<td>5.855</td>
<td>1.791</td>
<td>5.478</td>
<td>0.6</td>
<td>4.906</td>
<td>64</td>
</tr>
<tr>
<td>C</td>
<td>2.13</td>
<td>3.059</td>
<td>19.512</td>
<td>5.855</td>
<td>1.772</td>
<td>5.420</td>
<td>0.63</td>
<td>4.802</td>
<td>52</td>
</tr>
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<td>D</td>
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<td>32.194</td>
<td>9.661</td>
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<td>6.740</td>
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</tr>
<tr>
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<td>6.757</td>
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<td>7.463</td>
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<td>46.828</td>
<td>14.052</td>
<td>2.626</td>
<td>8.034</td>
<td>0.95</td>
<td>10.550</td>
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<td>3.059</td>
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</tr>
<tr>
<td>I</td>
<td>2.17</td>
<td>3.059</td>
<td>53.462</td>
<td>16.042</td>
<td>2.899</td>
<td>8.866</td>
<td>1.04</td>
<td>12.850</td>
<td>65</td>
</tr>
</tbody>
</table>

**Table 2: Impact tests conducted on quasi-isotropic coupons with a stacking sequence of \([-45/90/+45/0]_4S\)**

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Avg. thickness (mm)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
<th>Energy (J)</th>
<th>Impact velocity (m/s)</th>
<th>Momentum (Ns)</th>
<th>Damage size (in)</th>
<th>Ei (J)</th>
<th>% of Ei absorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.18</td>
<td>3.059</td>
<td>53.462</td>
<td>16.042</td>
<td>2.884</td>
<td>8.822</td>
<td>1.317</td>
<td>12.724</td>
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<td>C</td>
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<td>3.059</td>
<td>35.121</td>
<td>10.539</td>
<td>2.283</td>
<td>6.984</td>
<td>0</td>
<td>7.9721</td>
<td>58</td>
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<tr>
<td>D</td>
<td>4.14</td>
<td>3.059</td>
<td>35.121</td>
<td>10.539</td>
<td>2.332</td>
<td>7.134</td>
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<td>8.3188</td>
<td>64</td>
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<tr>
<td>E</td>
<td>4.21</td>
<td>3.059</td>
<td>44.877</td>
<td>13.466</td>
<td>2.575</td>
<td>7.877</td>
<td>0.32</td>
<td>10.142</td>
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</tr>
<tr>
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<td>3.059</td>
<td>44.877</td>
<td>13.466</td>
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<td>12.122</td>
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<tr>
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<td>49.169</td>
<td>14.754</td>
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<td>8.526</td>
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<tr>
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<td>3.059</td>
<td>46.828</td>
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<td>8.126</td>
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<td>10.795</td>
<td>59</td>
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<tr>
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<td>53.462</td>
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<td>8.855</td>
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<tr>
<td>L</td>
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<td>3.059</td>
<td>53.462</td>
<td>16.042</td>
<td>2.839</td>
<td>8.683</td>
<td>1.34</td>
<td>12.323</td>
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</tbody>
</table>
Table 3: Impact tests conducted on quasi-isotropic coupons with a stacking sequence of [-45/90/+45/0]s

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Avg. thickness (mm)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
<th>Energy (J)</th>
<th>Impact velocity (m/s)</th>
<th>Momentum (Ns)</th>
<th>Damage size (in)</th>
<th>Ei (J)</th>
<th>% of Ei absorbed</th>
</tr>
</thead>
<tbody>
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<td>Q-6-A</td>
<td>6.29</td>
<td>3.059</td>
<td>53.462</td>
<td>16.042</td>
<td>2.980</td>
<td>9.12</td>
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<td>2.060</td>
<td>11.14</td>
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<tr>
<td>Q-6-A</td>
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<td>5.406</td>
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<td>21.801</td>
<td>2.850</td>
<td>15.41</td>
<td>0.44</td>
<td>21.970</td>
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<td>Q-6-A</td>
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</tr>
<tr>
<td>Q-6-B</td>
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<td>7.628</td>
<td>28.391</td>
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<td>6.566</td>
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<td>3.540</td>
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Fig. 1 Effect of impact damage diameter on compressive strength of composite [25]
Fig. 2 Manufacturing of quasi-isotropic composite plates: (a) Cure cycle; (b) compression molding machine; (c) Final composite plate with 6” x 4” cut-outs
Fig. 3 Dynatup 8200 drop weight impact testing machine
Fig. 4 Force-time history of [-45/90/+45/0]_{2S} coupons
Fig. 5 Displacement-time history of [-45/90/+45/0]_{2S} coupons
Fig. 6 Energy-time history of [-45/90/+45/0]_{2S} coupons
Fig. 7 Maximum impact force, delamination size and absorbed energy of \([-45/90/45/0]_2S\) coupons
Fig. 8 Effect of impact energy and momentum on delamination size in [-45/90/+45/0]_2s coupons
Fig. 9 Quad plot of 2-mm coupon with force-history, energy-history, B-scan and C-scan
Fig. 10  Profilometry scans of 2-mm coupon: (a) Top surface; (b) Bottom surface
Fig. 11  Force-time history of [-45/90/+45/0]\textsubscript{LS} coupons
Fig. 12  Displacement-time history of [-45/90/+45/0]_{as} coupons
Fig. 13  Energy-time history of [-45/90/+45/0]_{as} coupons
Fig. 14  Maximum impact force, delamination size and absorbed energy of [-45/90/45/0]_4S coupons
Fig. 15  Effect of impact energy and momentum on delamination size in [-45/90/+45/0]_{as} coupons
Fig. 16  Quad plot of 4-mm coupon with force-history, energy-history, B-scan and C-scan
Fig. 17  Profilometry scans of 4-mm coupon: (a) Top surface; (b) Bottom surface
Fig. 18  Force-time history of [-45/90/+45/0]_s coupon Q-6-A for multiple impacts
Fig. 19  Force-time history of [-45/90/+45/0]_s coupons Q-6-B and Q-6-C for multiple impacts
Fig. 20   Force-time history of [-45/90/+45/0]_{ss} coupons Q-6-D, Q-6-E and Q-6-F
Fig. 21  Displacement-time history of [-45/90/+45/0]_{6S} coupon Q-6-A for multiple impacts
Fig. 22  Displacement-time history of [-45/90/+45/0]_{6S} coupons Q-6-B and Q-6-C for multiple impacts
Fig. 23 Displacement-time history of $[-45/90/+45/0]_{6s}$ coupons Q-6-D, Q-6-E, and Q-6-F
Fig. 24  Energy-time history of [-45/90/+45/0]_S coupon Q-6-A for multiple impacts
Fig. 25  Energy-time history of [-45/90/+45/0]_S coupons Q-6-B and Q-6-C for multiple impacts
Fig. 26  Energy-time history of [-45/90/+45/0]_S coupons Q-6-D, Q-6-E, and Q-6-F
Fig. 27  Effect of impact energy and momentum on delamination size in [-45/90/+45/0]_s coupons
Fig. 28  Quad plot of 6-mm coupon with force-history, energy-history, B-scan and C-scan
Fig. 29  Proflometry scans of 6-mm coupon: (a) top surface; (b) bottom surface
Fig. 30   Proposed modification of the coupon holding fixture on the Dynatup 8200 drop weight impact testing machine