Impact damage detection in composite plates using acoustic emission signal signature identification

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ABSTRACT

Barely visible impact damage (BVID) due to low velocity impact events in composite aircraft structures are becoming extremely prevalent. BVID can have an adverse effect on the strength and safety of the structure. During aircraft inspections it can be extremely difficult to visually detect BVID. Moreover, it is also a challenge to ascertain if the BVID has in-fact caused internal damage to the structure or not. In this paper, multiple 2-mm quasi-isotropic carbon fiber reinforced polymer (CFRP) composite coupons were impacted using the ASTM D7136 standard in a drop weight impact testing machine to determine the mass, height and energy parameters to obtain approximately 1” impact damage size in the coupons iteratively. For subsequent impact tests, four piezoelectric wafer active sensors (PWAS) were bonded at specific locations on each coupon to record the acoustic emission (AE) signals during the impact event using the MISTRAS micro-II digital AE system. Impact tests were conducted on these instrumented 2-mm coupons using previously calculated energies that would create either no damage or 1” impact damage in the coupons. The obtained AE waveforms and their frequency spectrums were analyzed to distinguish between different AE signatures. From the analysis of the recorded AE signals, it was determined if the structure had indeed been damaged due to the impact event or not. Using our proposed structural health monitoring technique, it could be possible to rapidly identify impact events that cause damage to the structure in real-time and distinguish them from impact events that do not cause damage to the structure. An invention disclosure describing our acoustic emission structural health monitoring technique has been filed and is in the process of becoming a provisional patent.

Keywords: Barely visible impact damage (BVID); Composite structures; Damage detection; carbon fiber reinforced polymer (CFRP); Acoustic emission; Structural health monitoring; Piezoelectric wafer active sensors (PWAS)

1. INTRODUCTION

1.1 Background and motivation

Recent advances in manufacturing technologies have led to the increasing usage of composite materials being used in aerospace primary and secondary structures due to their high strength to weight ratio and light weight. Structures manufactured using composite materials, whether thermosets or thermoplastics, must be made in a nearly perfect state such that they do not introduce any dangerous risks during the operational lifetime of the aerospace structure. The manufacturing process of composite structures can introduce significant manufacturing flaws and operational damage during its service lifetime. These types of defects may lead towards catastrophic failures if they are not detected at the earliest stages of development using efficient structural health monitoring techniques.

Barely visible impact damage (BVID) is a type of damage that can occur during manufacturing due to accidental tool drops on the shop floor or due to low velocity impacts of small and large debris during the service life of the structure. In low velocity impact events, the impactor may not completely 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 indentation which are either too small to be seen or are not clearly visible due to the coating of paint, 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.

The concept of BVID was introduced in the early 1980’s with respect to understanding the damage tolerance of composite laminates [1][2]. 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 or greater [3]. This clear distinction between BVID and VID during aircraft inspections can determine if a composite repair is needed or not at the location where an impact has occurred. If a damage is characterized as VID it needs repairs to be conducted to the composite immediately. However, a situation may arise where the 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 Figure 1) and may need immediate repairs and must not be discounted despite being characterized as BVID. From Figure 1 we can also observe that in comparison to a 1” damage diameter of any damage type (delamination, porosity, open hole), an impact damage having a diameter of 1” or greater can significantly reduce the compressive strength of the composite structure. This is the significance and importance of detecting and monitoring impact damage having a diameter of 1” or greater [4].

![Figure 1: Effect of impact damage size on compressive strength of composite [3]](image)

With the increasing occurrence of BVID in composites, nondestructive evaluation and structural health monitoring 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 [5], [6]. Guided wave propagation in composite laminates has been used to see the interaction with impact damage [7]-[11]. Eddy current methods have been explored by researchers to detect manufacturing flaws and operational damage such as impact damage in CFRP composites [12], [13]. Researchers have also explored microwave nondestructive evaluation techniques to investigate low velocity and high velocity impact damage in composites due to environmental effects [14]-[18]. Infrared thermography is also being explored by scientists as a viable option of detecting impact damage in a rapid manner [19], [20]. X-ray computed tomography is also being used by researchers to give a 3D assessment of impact damage in composite structures [21], [22]. 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.

In recent years extensive work has been done to understand effective acoustic emission methods for structural health monitoring of impact damage in composite materials. Prosser et al. [23] analyzed AE signals created by impact sources in thin aluminum structures and graphite/epoxy composites subjected to low and high velocity impacts. Rosa et al. [24], [25] have primarily focused on post-impact behavior of natural fiber composites and hybrid composites using acoustic emission methods. Other researchers [26], [27] used acoustic emission sensor networks to reconstruct the force-time history to better understand the loading phenomena from the impact event and compare it to the experimental force-time history. The uniqueness in our research is to use existing PWAS sensors to record AE signals in real-time during impact events and ascertain if a sizable damage has occurred or not. This will greatly reduce system downtime and ensure that necessary composite repairs are conducted.

1.2 Objectives of this paper

In this paper, the authors have described an AE based structural health monitoring method that can analyze the AE signal signatures obtained from an impact event and can ascertain if the impact event has indeed caused an extensive internal damage in the composite structure or not. To do this, preliminary drop weight impact tests were conducted on various 2-mm quasi-isotropic CFRP composite coupons conforming to the ASTM D7136 standard for drop weight impact testing.
These preliminary experiments were useful in estimating the mass, height and energy combination to obtain a certain size of impact damage in the composite coupon iteratively.

After estimating the mass, height and energy combination for creating approximately 1” impact damage size in a 2-mm composite coupon, subsequent impact tests were conducted on AE instrumented composite coupons on which four PWAS were bonded at specific locations based on the fiber orientation angles in the composite coupons. The drop weight impact testing system along with the AE signal capture using the MISTRAS AE system is displayed in Figure 2. Two sets of experiments were conducted – one experiment with low energy (1 J) impact that created no damage in an instrumented composite coupon and the second test with a higher energy (16 J) impact which created approximately 1” impact damage size. AE signal analysis and mode separation study was performed to understand both the impact events and clearly differentiate between a catastrophic impact that creates a sizable damage and a benign impact that creates no damage.

![MISTRAS AE System](image)

Figure 2: Drop weight impact testing with AE signal capture

### 2. MANUFACTURING PROCESS AND EXPERIMENTAL SETUP

#### 2.1 Manufacturing of quasi-isotropic CFRP composites

To cut out the coupons with the correct sizes for impact testing conforming to the ASTM D7136 standard, 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 using the manufacturer’s cure cycle. To manufacture quasi-isotropic composite plates with the correct 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 [29]-[31]. A [-45/90/±45/0]_{2S} stacking sequence was chosen for manufacturing the composite plate with 16 layers having a nominal thickness of approximately 2-mm. Similarly, if a 4-mm composite plate were to be manufactured, a [-45/90/±45/0]_{4S} stacking sequence with 32 layers would have been chosen and to manufacture a 6-mm composite plate a [-45/90/±45/0]_{6S} stacking sequence with 48 layers would have been 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 cure cycle, compression molding machine and one of the manufactured composite plates is displayed in Figure 3. From the large composite plates, the 6” x 4” standard size coupon for the ASTM D7136 testing was cutout as displayed in Figure 3 (c).
2.2 Experimental setup for ASTM drop weight impact testing

A drop weight impact 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 on the same coupon or on different coupons. This data can then be used to predict future behavior of the material such as crack propagation and other complex 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 experimental mechanics of composites.

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 coupon 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 coupon and is fastened into place using the shaft collars. This distance is measured using the laser height indicator and determines the drop height which is calculated before based on the potential energy of the impactor. All the equipment is checked to ensure that the data acquisition system is recording the data properly and then the impactor is engaged; also checked is that the coupon cover is removed. The trigger mechanism is then activated, initiating the drop impact event and capturing the force and velocity data of the impact test. The impactor can be caught safely after rebounding from the coupon to avoid a secondary impact on the composite coupon. It is also possible to avoid secondary impact if the drop weight impact testing machine has an anti-rebound device or stop block installed. The data is saved and the impact carriage is lifted away from the coupon and is locked back into place on the conveyor. The protective 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 Figure 4.

Figure 3: Manufacturing of quasi-isotropic composite plates: (a) Cure cycle; (b) compression molding machine; (c) Final composite plate with 6” x 4” cut-outs
2.3 Experimental setup for acoustic emission recording of impacted composite coupon

Preliminary drop weight impact experiments were conducted on numerous 2-mm 6" x 4" quasi-isotropic CFRP composite coupons to determine the mass, height and energy combination to obtain a certain size of impact damage. After this, real-time acoustic emission experiments were supposed to be carried out on more 2-mm 6" x 4" quasi-isotropic CFRP composite coupons. In order to do this, four piezoelectric wafer active sensors (PWAS), 7-mm in diameter and 0.5-mm in thickness, were bonded on each composite coupon at different locations corresponding to fiber orientation angles in the stacking sequence of the composite. PWAS 1 was bonded 45-mm from the impact location in the 90 degree fiber direction. PWAS 2 was bonded 75-mm away from the impact location was installed in the -45 degree fiber direction. PWAS 3 was bonded 75-mm away from the impact location in the 0 degree fiber direction. PWAS 4 was bonded 75-mm away from the impact location in the 45 degree fiber direction as can be observed in Figure 5. In this way the impact coupons were instrumented to carry out real-time acoustic emission recording of impact tests to be conducted on them.
To conduct the real-time acoustic emission experiment, the instrumented coupon with the four PWAS was clamped on the ASTM D7136 fixture on the drop weight impact testing machine. The wires from the four PWAS were connected to a pre-amplifier and the connections from the pre-amplifier were connected to the MISTRAS AE system for capturing the AE signals during the drop weight impact testing experiment so that all the signals associated with the impact event using the four PWAS bonded in the different fiber orientation angles could be analyzed. This complete experimental setup with the AE instrumentation used is displayed in Figure 6.

![Figure 5: Location of four PWAS with respect to impact location on composite coupon](image)

![Figure 6: Experimental setup of ASTM drop weight impact test on AE instrumented coupon](image)

### 3. PRELIMINARY IMPACT TESTING ANALYSIS

#### 3.1 Methodology of analyzing the impact testing data

Behavior of a coupon 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 [28], the impact velocity is calculated by:

\[
v_i = \frac{w_{12}}{(t_2 - t_1)} + g \left( t_i - \frac{(t_1 + t_2)}{2} \right)
\]

Where \( w_{12} \) = distance between flag prongs used for velocity measurement, \( t_1, t_2 \) = time first and second flag prong passes velocity detector, and \( t_i \) = time of initial contact of the impactor with the coupon.
The velocity and displacement history of the impactor is calculated by using equations:

\[ v(t) = v_i + g t - \frac{\int_0^t F(t)}{m} dt \]  
(2)

\[ \delta(t) = v_i t + \frac{gt^2}{2} - \frac{\int_0^t \left( \frac{\int_0^t F(t)}{m} dt \right) dt}{2} \]  
(3)

Where \( v_i \) = impact velocity calculated before, \( t \) = 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:

\[ E_a(t) = \frac{m(v_i^2-v(t)^2)}{2} + mg\delta(t) \]  
(4)

This data provides insight into how the coupon performs under the stresses applied by the impact weight and can demonstrate how the coupon absorbs energy and how the damage propagates inside the coupon. Questions about how brittle the sample is and whether it developed any damage during the impact event can be indicated by the irregularities observed in the force-time curve.

### 3.2 Preliminary impact experiments conducted on 2-mm quasi-isotropic coupons

Impact tests were conducted on various 6" x 4" coupons having the stacking sequence of \([-45/90/\pm 45/0]_{2S}\) 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 and were impacted with increasing potential energies. 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" impact damage 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 approximately 1" impact damage size. For each impact experiment, the data was analyzed to obtain a force-time history, velocity-time history, displacement-time history and energy-time history [4].

#### Table 1: Impact tests conducted on quasi-isotropic coupons with a stacking sequence of \([-45/90/\pm 45/0]_{2S}\)

<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>
<tr>
<td>D</td>
<td>2.11</td>
<td>3.059</td>
<td>32.194</td>
<td>9.661</td>
<td>2.204</td>
<td>6.740</td>
<td>0.77</td>
<td>7.427</td>
<td>67</td>
</tr>
<tr>
<td>E</td>
<td>2.19</td>
<td>3.059</td>
<td>32.194</td>
<td>9.661</td>
<td>2.209</td>
<td>6.757</td>
<td>0.8</td>
<td>7.463</td>
<td>69</td>
</tr>
<tr>
<td>F</td>
<td>2.14</td>
<td>3.059</td>
<td>46.828</td>
<td>14.052</td>
<td>2.626</td>
<td>8.034</td>
<td>0.95</td>
<td>10.550</td>
<td>61</td>
</tr>
<tr>
<td>G</td>
<td>2.02</td>
<td>3.059</td>
<td>46.828</td>
<td>14.052</td>
<td>2.679</td>
<td>8.193</td>
<td>0.93</td>
<td>10.972</td>
<td>60</td>
</tr>
<tr>
<td>H</td>
<td>2.19</td>
<td>3.059</td>
<td>53.462</td>
<td>16.042</td>
<td>2.858</td>
<td>8.743</td>
<td>1.015</td>
<td>12.495</td>
<td>54</td>
</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>

UT (Ultrasonic testing) scans were conducted in the ultrasonic immersion tank on all the CFRP composite coupons before and after impact to obtain the B-scan and C-scan images and compare a pristine coupon with a coupon that underwent impact damage and to see the size and shape of the impact damage. A 10 MHz, 1" focused, 0.375" diameter ultrasonic transducer was used in the pulse-echo mode for conducting the UT scans. The experimental setup is displayed in Figure 7 with the composite plate placed inside the immersion tank with the focused transducer scanning in the in-plane x-y direction. Post-processing of the data obtained from the ODIS software interface is able to give us a clear C-scan image, B-scan image and A-scans in the pristine and impacted coupons.
A quad plot of coupon I, displaying the force-time history, the energy time history, the B-scan and C-scan is observed in Figure 8. The force-time history plot shows peaks at certain maximum load of 4.54 kN 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 force-time history plot this indicates that the coupon has undergone extensive damage.

The energy-time history plot is taken from the force-time curve through integration of the data. The energy-time history plot better describes the peak energy experienced and energy absorbed by the coupon. 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 is clearly 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 approximately 1” impact damage size is formed, over 65% of the impact energy is absorbed by the coupons.

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, since a clear back wall 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 as well.

Figure 8: Quad plot of 2-mm coupon I consisting of force-time history, energy-time history, B-scan and C-scan from UT
4. AE SIGNAL ANALYSIS FROM INSTRUMENTED IMPACT TESTS

4.1 1 J impact test on AE instrumented 2-mm composite coupon – no damage

The first instrumented impact test conducted on a 2-mm composite coupon is a low energy impact i.e. about 1 J impact that produces no damage in the composite coupon. To conduct this impact test, the instrumented coupon displayed in Figure 5 was clamped on the ASTM D7136 fixture and the real time AE signals were acquired by all the four PWAS using the MISTRAS AE system as displayed in the experimental setup given in Figure 6. Since the impact energy is only 1 J, the height from which the impactor is dropped on the composite coupon is only a few centimeters. In such a scenario it become very difficult to avoid a rebounding or secondary impact on the composite coupon after the first impact. The AE hits acquired at all the four PWAS for this 1 J impact event can be observed in Figure 9.

![Figure 9: AE hits observed at the four PWAS due to 1 J impact event](image)

We can clearly observe in Figure 9 that there are two successive AE impact hits due to the rebound of the impactor on the composite coupon. These two hits are obtained by all the four PWAS and are clearly separated from other low amplitude hits which could consist of background noise or boundary reflections from the edges of the composite coupon, since we are assuming that this low energy of approximately 1 J did not create any damage in the composite coupon.

If we separate the time domain signals and their FFT’s, received at all four PWAS from the 1st and 2nd impact hits as observed in Figure 10 and Figure 11, we can clearly observe that the signals from these two successive impact hits had a major frequency content in the low frequency range below 200 kHz which indicates low frequency flexural modes in the composite coupon. We can also observe that the signal amplitude for the 1st impact hit was higher at PWAS 1 which was in the 90 degree direction and PWAS 3 which was in the 0 degree direction.

![Figure 10: Signal correspondence at all four PWAS due to the 1st impact hit](image)
Figure 11: Signal correspondence at all four PWAS due to the 2nd impact hit

4.2 16 J impact test on AE instrumented 2-mm composite coupon – 1” impact damage

The second instrumented impact test conducted on a 2-mm composite coupon is a 16 J energy impact based on the preliminary impact tests conducted on various 2-mm composite coupons as displayed in Table 1. The energy of 16 J was chosen such that it produces an impact damage size of approximately 1” in the 2-mm composite coupon. To conduct this impact test, the instrumented coupon labelled AE1-Q2A similar to the coupon displayed in Figure 5 was clamped on the ASTM D7136 fixture and the real time AE signals during the impact event were acquired by all the four PWAS using the MISTRAS AE system as displayed in the experimental setup given in Figure 6. Since the impact energy for this impact event was 16 J, the height from which the impactor is dropped on the composite coupon is her than the previous impact test and it was easily possible to catch the impact cart with weights after the 1st impact to avoid a secondary or rebound impact on the composite coupon. The AE hits were acquired at all the four PWAS for this 16 J impact event. The force-time history for this impact event was acquired by the dynamic load cell attached to the impactor and the energy-time was deduced using the force-time history data and the impact velocity measured by the velocity sensor.

Figure 12: Quad plot of 2-mm coupon AE1-Q2A consisting of force-time history, energy-time history, B-scan and C-scan from UT
A quad plot of coupon AE1-Q2A, displaying the force-time history, the energy time history, the B-scan and C-scan is observed in Figure 12. The force-time history plot is parabolic in shape and shows peaks at certain maximum load of 4.48 kN which is very similar to the maximum load experienced by coupon I in the preliminary impact tests as can be seen in the top left plot of Figure 8. Irregularities in the parabolic shape of the force-time history plot indicates that the coupon has undergone extensive damage.

The energy-time history plot here also compares very well to that of coupon I. 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 is clearly able to demonstrate the percentage of impact energy that is absorbed by the coupon to create the irreversible process of damage. For coupon AE1-Q2A where approximately 1" impact damage size is formed around 62% of the impact energy was absorbed by the coupon which is very similar to coupon I.

The B-scan and C-scan images obtained from the UT scans tell a very similar story to that of coupon I. 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, since a clear back wall 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 as well.

Comparing coupon I from the preliminary impact tests, with coupon AE1-Q2A, it can be observed that bonding the four PWAS on the composite coupon had little to no change in its impact characteristics. We were also able to obtain additional information about the damage formation in the composite coupon when a 1” impact damage size is created in a 2-mm quasi-isotropic coupon.

Next, we analyze the AE signals received at all four PWAS. We can clearly observe in Figure 13 that the impact hit i.e. the hit which is received at the four PWAS when the first contact is made between the impactor and the composite coupon, can be clearly separated from the remaining hits received by the four PWAS. The other low amplitude hits consist of hits obtained due to the damage propagation within the composite coupon mixed with background noise and boundary reflections from the edges of the composite coupon. It is also important to note that at the PWAS 1, only the impact hit was received and after that no more hits were received by PWAS 1. This issue occurred at PWAS 1 because at the moment of impact, one of the cables connected to the PWAS 1 got unintentionally or accidentally detached from the PWAS 1 after the high amplitude flexural wave was experienced at the location where PWAS 1 was bonded to the composite coupon. Due to the detachment of the cable from PWAS 1 it was only able to capture the impact hit and was not able to capture any of the other low amplitude hits which could have valuable information about the impact damage propagation. In future...
experiments all the cables will be properly reinforced so that signals at all PWAS can be received in an uninterrupted manner.

If we separate the time domain signals and their FFT’s, received at all four PWAS from the impact hit as observed in Figure 14, we can clearly observe that the signals from the impact hit has a major frequency content in the low frequency range below 200 kHz with a large amplitude which indicates low frequency flexural modes in the composite coupon.

![Figure 14: Signal correspondence at all four PWAS due to the 1st impact hit](image)

If we separate the time domain signals and their FFT’s, received at all four PWAS from a hit that corresponds to damage propagation in the composite as observed in Figure 15, we can clearly observe that the signals from this hit at all the PWAS has a major frequency content in the frequency range between 300 and 500 kHz with a much lower amplitude in comparison to the impact hit. It is also important to note that there is no signal correspondence at PWAS 1 for a hit that corresponds to damage growth since no AE hits were received by PWAS 1 other than the impact hit as stated earlier.

![Figure 15: Signal correspondence at all four PWAS due to a hit corresponding to damage formation](image)

As observed from the C-scan image in the quad plot displayed in Figure 12, we can clearly see that the maximum extent of damage due to the impact event occurs at the negative 45 degree direction. Therefore, we take a closer look at the signals obtained from some of the hits at PWAS 2 which is bonded in the -45 degree direction in Figure 16. We can clearly separate the high amplitude, low frequency impact hit and its signal from some other hits and their signals that correspond to damage propagation. Within the class of hits and their signals that correspond to damage, there are subtle differences in the signals because they may represent different types of damage such as matrix cracking, fiber break, and delamination growth. One of the goals in future experiments will be to separate the damage signals from different types of damage experienced by the composite coupon upon impact.
4.3 Mode separation study of AE signals due to impact event

After acquiring all the AE hits and performing the signal analysis from the AE hits, it is important to perform a mode separation study. To do this, we first use the Semi-Analytical Finite Element (SAFE) method to obtain the group velocity dispersion curve for the 2-mm composite coupon with a stacking sequence of \([-45/90/45/0]_2S\) as displayed in Figure 17.

![Figure 17: Group velocity dispersion curve for 2-mm composite coupon having a stacking sequence of \([-45/90/45/0]_2S\)](image)

To perform the mode separation study for the AE due to the impact event, we first analyze the impact hits from the 1 J impact hit that caused no damage in a 2-mm composite coupon, and the 16 J impact hit that caused a 1” impact damage in a composite coupon. We conduct the time-frequency analysis for both the impact hits and superimpose it with the group velocity dispersion curve of the 2-mm composite coupon. These plots can be observed in Figure 18 (a) and (b). If we compare these two plots, we can clearly observe that the strong A0 mode can be observed due to the impact hit in both the plots. We can also observe that 16 J impact hit has a stronger A0 content. We can also see the signals obtained at PWAS 2 for both impact hits in Figure 18 (c) and (d). Upon comparing these two plots we can observe that the 16 J impact hit has an additional higher frequency content due to a higher energy impact of 16 J compared to a lower energy impact of 1 J.
To perform the mode separation study for the AE due to damage growth, we analyze an AE hit that corresponds to damage growth from the 16 J impact event that caused a 1" impact damage in the composite coupon. We conduct the time-frequency analysis of the signal and superimpose it with the group velocity dispersion curve of the 2-mm composite coupon. This plot can be observed in Figure 19 (a). We can also observe the signal due to the damage growth obtained at PWAS 2 displayed in Figure 19(b). From these plots we can clearly observe that the damage growth has a strong S0 and SH0 mode. We can also see that the damage growth has weak A0 mode along with many boundary reflections. If we were to conduct a preliminary inspection, we can see that SH0 mode is found stronger than the S0 mode. Previous work [9], [11] has also indicated that SH0 mode is very sensitive to impact damage and can be used to detect impact damage.

Figure 19: (a) Time-frequency plot from 16 J damage hit (b) Signal at PWAS 2 due to 16 J damage hit
5. SUMMARY, CONCLUSIONS AND FUTURE WORK

5.1 Summary
In this paper, the AE signal signature identification was used to ascertain if an impact event creates a sizable damage in a composite coupon or not. This was done by modifying the existing ASTM D7136 standard test method for drop weight impact testing by introducing an instrumented composite coupon to acquire real-time AE signals.

The first set of preliminary impact tests were conducted on various 2-mm quasi-isotropic composite coupons to generate controlled impact damage sizes in a repetitive manner to obtain the mass, height and energy combination to create a 1” impact damage size in a 2-mm quasi-isotropic composite coupon having in-plane dimensions of 6” x 4” which is standard coupon size for ASTM D7136 drop weight impact testing.

The second set of experiments involved bonding four PWAS on two composite coupons at locations corresponding to fiber orientation angles and then performing drop weight impact tests conforming to ASTM D7136 standard on these instrumented composite coupons. On the first instrumented coupon a 1 J impact that creates no damage, was conducted and on the second instrumented coupon a 16 J impact that creates 1” impact damage was conducted. We found that we could separate the impact AE hit from an AE hit corresponding to damage growth and perform a mode separation study.

5.2 Conclusions
Preliminary impact tests conducted on 2-mm quasi-isotropic coupons were used to estimate the mass, height and energy combinations to obtain approximately 1” impact damage size using incremental energy impacts on various test coupons and post impact data analysis to estimate force-time histories and energy-time histories. UT scans enabled us to characterize the impact damage size, shape and location.

Impact tests conducted on AE instrumented 2-mm composite coupons showed similar impact characteristics despite bonding four PWAS to acquire real-time AE signals. AE signals corresponding to the impact hits were identified clearly and separated from the AE signals that corresponded to internal damage growth in the composite coupons. It was observed that the AE due to impact hit has a stronger low frequency content with high amplitude at a region below 200 kHz. It was also observed that the AE signals due to the irreversible process of damage has a stronger high-frequency content in the range of 300 to 50-0 kHz.

Upon performing the mode separation study on the impact hits, it was observed that the impact hit has a strong A0 mode content depending on the energy of the impact. The mode separation study on the AE hit corresponding to damage growth indicated that it has a strong S0 mode and SH0 mode content where the SH0 mode seems to be the dominant mode and more sensitive to the impact damage.

An invention disclosure [32] covering our novel findings has been prepared and is in the process of becoming a provisional patent.

5.3 Future work
Further controlled impact tests will be conducted on AE instrumented 2-mm composite coupons using the mass, height and energy combinations estimated from the preliminary impact experiments to obtain multiple impact damage sizes for a comparative study. A deviation from the ASTM D7136 standard for drop weight impact testing will be employed to use larger size coupons (12” x 6”) to use non-reflective boundary and receive clean signals from the impact tests which are free from boundary reflections. AE signal analysis will be used to investigate the separation of AE signals from different types of damages processes (matrix crack, fiber break and delamination) that occur during an impact event.

Further work could be performed towards the practical application of the research results presented in this paper by exploring the possibility of using PWAS for real-time AE structural health monitoring of impact events in composites to ascertain if damage has occurred or not. Estimating the size, location, shape and extent of the impact damage by analyzing the AE signals received by a network of PWAS will be of paramount interest. Computer simulations and equipment development could be conducted independently or in collaboration with an industrial partner.

[References]
[32]
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