Estimation of Impact Damage Threshold to Cause Internal Damage in CFRP Laminates by Means of Acoustic Emission*

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Abstract
The impact damage threshold to cause internal damage in cross-ply CFRP laminates has been determined, by monitoring dynamic surface strain and Lamb-wave AE (Acoustic Emission) along with the impact force history in SACMA-type impact tests. Four types of cross-ply CFRP plates ([0°/90°]sym., n = 4,6,8,10) are impacted with a spherical steel tup, 16 mm diameter, at 0.8 and 1 m/s. Surface strain of a test laminate is measured using a strain gauge and Lamb-wave AE signals are monitored by small AE sensors on both surfaces. The time history of surface strain matches with the impact force history when no damage occurs as predicted by theory of impact dynamics. Here, only impact-induced AE (or Impact AE) is obtained when the impact tup contacts the specimen. When internal fracture occurs, measured strain history deviated from that expected from the dynamic force and both Impact AE and fracture-induced AE (Fracture AE) are detected. Fracture AE is detected when the dynamic force and strain history indicates the initiation of internal CFRP damage. Impact damage threshold values for the four types of cross-ply CFRPs are measured by comparing the impact force, strain and Fracture AE. Initial AE signals monitored simultaneously on both sample surfaces are symmetric Lamb waves. Wave simulation analysis has revealed the nature of the onset of fracture to be the matrix cracking of the center plies. Complex AE signals following the initial fracture for a few ms are expected to be from delamination damage, which was confirmed with an ultrasonic C-scan study.

Key words: CFRP Laminates, Impact Damage Threshold, Acoustic Emission

1. Introduction

Carbon-fiber reinforced plastics (CFRPs) are widely used in transportation equipment due to their high specific strength and stiffness. Upon impact of even modest energy, however, CFRPs are likely to suffer complicated internal damages [1]. Therefore, impact fractures of CFRPs are evaluated by standardized method before CFRPs are applied to aerospace structures. SACMA-type impact test is widely used for investigating impact fractures of CFRPs [2]. However, only load history and tup velocity are measured during the test. Therefore, only limited data (max. impact load, impact duration, impact energy) can be observed.

In order to measure detailed impact-frature characteristics of bars and plates, several papers added instrumentation to the impact apparatus. In 1982, Ochiai et al. [3] mounted an AE sensor on the surface of FRP plate (100mm × 406mm × 2.5mm) and conducted impact

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testing. The load level that produced incipient damage was determined by AE activities. It was reported AE counts to be always zero for elastic low-energy impacts on good materials, and non-zero counts for similar impacts on defective materials. This paper focuses on damage detection of structural FRPs by low level impact with AE monitoring. In 1996, Ogawa [4] put AE sensor on the surface of carbon fiber-reinforced silicon nitride and conducted impact bending test by a split Hopkinson pressure bar method. AE data showed that micro-cracking during high velocity deformation testing occurred at an early stage compared to the quasi-static testing. Detail AE analysis was not conducted in this paper. In 1999, Richter [5] put AE sensor on the striker (tup) and conducted pendulum impact tests and three point bending tests. AE is successfully used for determining the ductile crack initiation and the beginning of yield. Liu [6] affixed a broadband AE sensor on the surface of T300 and T800 CFRP plates (100mm × 150mm × 3.8mm) and conducted impact testing. Damage area was estimated by both traditional AE parameters (AE energy and count) and means square errors (MSE) between AE outputs and simulated AE by neural network. He reported that the MSE values obtained from the neural networks appears to be a better correlation to damage area than traditional AE parameters in T300 CFRP, while a poorer correlation was observed for T800 CFRP. It seems farther modification will be required for this method to predict damage area.

In this study, in order to determine the impact threshold or critical impact force to cause internal damage in cross-ply CFRP laminates, dynamic surface strain and Lamb-wave AE along with the impact force history is measured during SACMA-type impact tests. Mode-type of AE signals are also determined for investigating the progression of fracture. Damages of impacted plates are investigated by an ultrasonic C-scan after the impact test and compared to AE results.

2. Specimen and experimental setup

A large-size plate of CFRP ([0°/90°]sym, n = 4,6,8,10) was prepared by laminating pre-preg sheets. Carbon fibers were XN-50 from Nippon Graphite Fiber, pitch-based with the nominal modulus of 490 GPa. Rectangular specimens with 150mm × 100mm were cut with the fiber directions (0°) on the top surface along the longitudinal (or X-) direction. The left side of Fig. 1 shows an impact test machine used for this experiment. The machine is Dynatup 8250 from Instron Corp., which satisfied SACMA SRM 2R-94 standard. The specimen shown by painted rectangle in the figure was set at bottom position of the apparatus. The impactor is dropped to the specimen along guide rails. The right of Fig. 1 represents schematically the impact test method. Impact load was applied at the center of the specimen via a hemispherical steel tup of 16 mm diameter. The weight of the impactor is 3.61 kg. The edges of the specimen were clamped all around by steel flanges. Small AE sensors (Physical Acoustic Corp.: Type PICO) were mounted on both surfaces at 32-mm from the impact point. Polarity of AE signals detected by the two sensors are compared for Lamb wave mode determination. (Top AE sensor is also used for determining damage initiation.) Outputs of the AE sensors were amplified 40 dB and filtered by a band-pass filter of 200 kHz to 1200 kHz for eliminating large amplitude low frequency AE signals due to impact. Extracted signals were digitized at an interval of 500ns with 20480 points, and fed to a computer. The strain gauge was attached on the top surface at 32-mm from the impact point. Outputs of both the strain gauge and the load cell on the impact tup were digitized at the interval of 1 μs with 60000 points. The strain gauge data is used for deciding impact damage threshold and timing.

Impact tests for four types of cross-ply CFRP plates were conducted as shown in Table 1. Impact velocity was controlled by the height of the impactor. Impact test for the 40-ply plate at 0.8 m/s was not conducted, because no damage was observed at 1.0 m/s impact test.
and no damage was expected for lower velocity impact tests.

Fig.1 The picture of impact machine (left) and schematic illustration of experimental setup (right). AE sensors were mounted on both surfaces of the plate. Strain gauge was attached on the impact surface for estimating impact damage threshold.

<table>
<thead>
<tr>
<th>Table 1 The list of conducted impact test</th>
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<tbody>
<tr>
<td>16-ply (2.0mm)</td>
</tr>
<tr>
<td>24-ply (2.5mm)</td>
</tr>
<tr>
<td>32-ply (4.3mm)</td>
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<tr>
<td>40-ply (5.2mm)</td>
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</tbody>
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<table>
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<tr>
<th>0.8 m/s – impact test</th>
<th>1.0 m/s – impact test</th>
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</thead>
<tbody>
<tr>
<td>16-ply (2.0mm)</td>
<td>○</td>
</tr>
<tr>
<td>24-ply (2.5mm)</td>
<td>○</td>
</tr>
<tr>
<td>32-ply (4.3mm)</td>
<td>○</td>
</tr>
<tr>
<td>40-ply (5.2mm)</td>
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</tbody>
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3. Impact history and impact damage threshold

Measured impact force histories are shown in Fig. 2. As the thickness of plates became thinner, impact duration increased, but the maximum impact force decreased. It is noted that impact duration is unchanged due to impact velocity but is greatly affected to the thickness of plates.

Fig. 2 Overlapping of load histories during 0.8 and 1.0 m/s impact to the four types of CFRP plates. Only 1.0 m/s-impact was conducted for 40ply-CFRP.

Figure 3 shows relationship between the maximum impact force and impact velocity. Maximum impact force of thick plates is much higher than thinner plates. Duration of the impact is shown against impact velocity in Fig. 4. Impact velocity has no effect on impact duration.
Figure 5 shows the superposition of impact force history and normalized surface strain upon CFRP plates. The time history of strain was normalized as they fit to the load history at the low force ranges. The vertical lines shown in 16-ply at 0.8 m/s and 32-ply at 0.8 m/s are electrical noises. The time history of surface strain matches to the impact force history when no damage occurred; 32-ply at 0.8 m/s and 40-ply at 1 m/s. However, the time history of surface strain deviated from the impact force history due to plate-stiffness changing when damage occurred; 32-ply at 1 m/s and 16- and 24-ply cases (Impact damage were investigated by ultrasonic C-scan after the impact test (Fig.11). Details of ultrasonic
C-scan are described later.). Therefore, impact damage threshold could be determined by reading an impact force at the deviating point, as marked by arrows in Fig. 5.

![Graph showing impact velocity vs. fracture force for 16, 24, and 32 ply CFRPs](image)

Fig. 6 Measured impact damage thresholds by comparing impact load history and normalized surface strain.

Figure 6 represents relationship between impact velocity and damage threshold value. When impact velocity was raised, impact damage threshold was nearly constant for 16-ply and 24-ply CFRPs, while the maximum impact force increased. For 32-ply testing, the maximum impact force of 1666 N at 0.8 m/s was below the damage threshold of 1843 N found for 1 m/s impact.

Figure 7 to 10 shows superposition of impact force history and normalized surface strain (top) and detected AE signals (bottom). The time scale of these two figures is synchronized. When no damage occurs, only impact-induced AE (IAE) is obtained when the impact tup contacts the specimen. Large amplitude fracture-induced AE signals (FAE) are detected when the dynamic load and strain history indicates the initiation of internal CFRP damage. Therefore FAE can also be utilized for measuring the impact damage threshold values along with surface strain gauge data. For the 16-ply at 0.8 m/s case, we will discuss later with C-scan image data.

![Graph showing superposition of impact force history and normalized surface strain](image)

Fig. 7 Superposition of impact force history and normalized surface strain upon 16ply-CFRP (top). Detected impact induced AE (IAE) and fracture induced AE (FAE) (bottom)
Fig. 8  Superposition of impact force history and normalized surface strain upon 24ply-CFRP (top). Detected impact induced AE (IAE) and fracture induced AE (FAE) (bottom)

Fig. 9  Superposition of impact force history and normalized surface strain upon 32ply-CFRP (top). Detected impact induced AE (IAE) and fracture induced AE (FAE) (bottom)

Fig. 10  Superposition of impact force history and normalized surface strain upon 40ply-CFRP (top). Detected impact induced AE (IAE) and fracture induced AE (FAE) (bottom)
Fig. 11  C-scan images of internal damages at [90°/0°] in cross-ply CFRP plate.

Figure 11 shows C-scan images of impacted CFRPs. Double tree-shape internal damages at [90°/0°] are revealed for four specimens as shown in the figure. No damage is detected for 16-ply CFRP plate at 0.8 m/s impact, which is identified as damaged by impact load and strain data. Then, AE signals detected after IAE may be reflected wave. Because of the strain data is noisy and difficult for fitting to the load history for some data, AE data is more useful and reliable for determining impact damage threshold value.

4. Modal analysis of lamb-AE for monitoring damage progression

Polarity of AE signals detected by both sensors are utilized for investigating the progression of fracture. Our previous result shows that AE signals from mid-plane of plates induce symmetric mode Lamb AE; on the other hand, AE signals from the surfaces of plates induce anti-symmetric mode Lamb AE.[7]

Fig. 12 (a) Impact induced AE. Fracture occurred discontinuously. Blue signal indicate AE detected by lower AE sensor. IAE was A0-mode. Initial part of FAE was So-mode. This indicates that fracture start from middle of the specimen.

Figure 12(a) shows AE monitored for 16-ply CFRP at 1.0 m/s impact by top AE sensor. Small amplitude IAE arrived followed by large amplitude FAE. (b) is enlarged view of IAE circled by dotted line in (a). AE signal detected by bottom AE sensor is
superposed. As wavelength of AE is larger than plate thickness (2.0mm), AE propagates as Lamb wave in the plate. \(A_0\)-mode Lamb AE signals with the opposite polarity are observed for IAE. This means that the source location of IAE was on the surface and corresponding to an impact source. (d) and (e) is enlarged view of initial parts of FAE. Initial FAE signals are symmetric Lamb waves and revealed the nature of the onset of fracture to be the matrix cracking of the center plies. Complex AE signals following the initial fracture for a few ms are expected to be from delamination damage in conjunction with an ultrasonic C-scan study.

5. Conclusion

The impact damage threshold for CFRP plates has been determined by monitoring dynamic surface strain and Lamb-wave AE along with the impact force history in SACMA-type impact tests. Results are summarized below:

1. Large amplitude of fracture-induced AE signals (FAE) are detected when the dynamic load and strain history indicates the initiation of internal CFRP damage. AE monitoring during SACMA-type impact test could be used for determining impact damage threshold values
2. Initial FAE signals are symmetric-mode Lamb waves and revealed the nature of the onset of fracture to be the matrix cracking of the center plies. Complex AE signals following the initial fracture for a few ms are expected to be from delamination damage in conjunction with an ultrasonic C-scan study.

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