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Barely visible impact damage assessment in laminated composites using acoustic emission

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ABSTRACT

Despite the key advantages of Fiber Reinforced Polymer (FRP) composites, they are susceptible to Barely Visible Impact Damage (BVID) under transverse loadings. This study investigates BVID in two quasi-isotropic carbon/epoxy laminates under quasi-static indentation and Low-Velocity Impact (LVI) loadings using Acoustic Emission (AE). First, the evolution of interlaminar and intralaminar damages is studied by analyzing the AE signals of the indentation test using b-value and sentry function methods. Then, the specimens are subjected to the LVI loading and the induced damages are compared with the indentation test and the percentage of each damage mechanism is calculated using Wavelet Packet Transform (WPT). In consistent with the mechanical data, ultrasonic C-scan and digital camera images of the specimens, the AE results show a considerable similarity between the induced BVID under quasi-static indentation and LVI tests. Finally, the obtained results show that AE is a powerful tool to study BVID in laminated composites under quasi-static and dynamic transverse loadings.

1. Introduction

Fiber Reinforced Polymer (FRP) composites have key advantages such as high specific strength and stiffness, high corrosion resistance, and high fatigue life [1,2]. Despite these advantages, they are susceptible to Barely Visible Impact Damage (BVID) under transverse loadings [3,4]. Low-Velocity Impact (LVI) is a common transverse load that may be applied to a composite structure during its service life, such as dropping a tool on the laminate surface during maintenance process, bird strike phenomenon during airplane landing or takeoff, and impact of hailstones to the composite structures during a hailstorm [5]. The LVI-induced damages in a FRP laminate are generally divided into two groups; interlaminar damages such as delamination and intralaminar damages such as matrix cracking and fiber breakage. These damages usually occur inside the material without any significant evidence on the structure surface which are usually named BVID [6]. The damage detection process also gets more difficult for dark FRP composites such as carbon/epoxy in comparison to transparent FRP composites such as glass/epoxy. In this situation, Non-Destructive Evaluation (NDE) techniques are capable tools to detect BVID in the material.

Many researches have been conducted to detect BVID in laminated composites using different NDE techniques [7–11]. Polimeno et al. [12] used the Nonlinear Elastic Wave Spectroscopy (NEWS) to detect BVID in carbon fiber composite plates. The results showed that NEWS is able not only to detect the presence of delamination at the plies interfaces but also indicates the damage severity. Klepka et al. [13] detected the presence of delamination in impacted carbon/epoxy composites using the modal and nonlinear vibro-acoustic modulation tests. Sun et al. [6] used the X-ray Computed Tomography (CT) scanning and a 3D Finite Element (FE) model for the experimental and numerical detection of BVID in carbon/epoxy laminates, respectively. The obtained results illustrated that the detected delaminations by CT scan are in accordance with the predicted delaminations by the FE model. Dziendzikowski et al. [14] detected and located impact-induced delamination in glass/epoxy laminates using an array of piezoelectric (PZT) transducers. They compared the performance of the embedded and attached PZT transducers to detect BVID and also proposed an algorithm based on a correlation analysis technique called RAPID (reconstruction algorithm for probabilistic inspection of defects) to localize the damages. Katunin et al. [15] identified BVID in three different composite structures

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consisting of a glass/epoxy composite plate, a GLARE plate, and finally, a CFRP composite structure reinforced with stiffeners that was extracted from a vertical stabilizer of an aircraft using PZT sensing, ultrasonic, thermography, and vibration-based inspection methods. The results showed that the application of PZT is limited to the rough condition monitoring and its results are dependent on the arrangement of the PZT transducers. Also, the sensitivity of the ultrasonic C-scan was higher than thermography, but the inspection process by thermography was faster than ultrasonic C-scan. Finally, although the vibration-based inspection presented acceptable results, its resolution was less than C-scan and thermography methods. Mustapha et al. [16] used the ultrasonic guided waves to detect BVID in CF/EP sandwich composites. They defined a damage index based on the change in the peak magnitude and time reversal method and then used this index to locate the damage position. All the mentioned researches have only focused on the detecting and localizing of impact-induced delamination by the active NDE techniques such as ultrasonic C-scan, CT scan, modal analysis, ultrasonic guided waves, thermography, etc. and they have not investigated other impact-induced intralaminar damages such as matrix cracking and fiber breakage and also the evolution behavior of these damages.

Acoustic Emission (AE) as a passive NDE technique has the capability for the online monitoring of the induced damages in laminated composites [17–22]. Pashmforoush et al. [23] classified four different damage mechanisms in sandwich composites using AE and k-Means genetic algorithm. Mohammadi et al. [24], quantified damage mechanisms in Open Hole Tensile (OHT) glass/epoxy laminates using AE and wavelet analysis. The quantity of the clustered damages was in accordance with the results of the proposed continuum damage-based FE model.

Literature review shows that many studies have been conducted on the experimental, analytical, and numerical analysis of the impact-induced damages in laminated composites [25–30], but there is a lack in the case of AE-based study of BVID in these materials. Boominathan et al. [31] employed AE to characterize the effect of temperature on the impact-induced damages in carbon/epoxy composites. They did not directly monitor the impact process by AE and used the AE to monitor the quasi-static Compression After Impact (CAI) test on the impacted specimens. Saeedifar et al. [32] studied the performance of six different clustering methods containing k-Means, Genetic k-Means, Fuzzy C-Means, Self-Organizing Map (SOM), Gaussian Mixture Model (GMM), and hierarchical model to classify AE signals of the interlaminar and intralaminar damages in carbon/epoxy laminated composites under quasi-static indentation loading. The results showed the hierarchical model has the best performance to cluster the AE signals of the damage mechanisms. Suresh Kumar et al. [33] monitored the induced damages in hybrid laminated composites under repeated quasi-static indentation loading using AE. The rise angle of the AE signals and also the sentry function method were utilized to track the damage evolution in the specimens without study the evolution behavior of each damage mechanism, individually.

This paper focuses on the study of the evolution of barely visible interlaminar and intralaminar damages in carbon/epoxy laminated composites under quasi-static and LVI loading conditions using AE technique. First, specimens are subjected to the quasi-static indentation loading and the interlaminar and intralaminar damages are clustered based on their AE features. Then, the evolution behavior of each damage mechanism is investigated using b-value and sentry function methods. In order to verify the AE results, ultrasonic C-scan and digital camera images are employed to detect BVID in the specimens. Afterward, the specimens are subjected to LVI loading and the mechanical behavior and their BVID are compared to the quasi-static indentation tests. In order to quantify the interlaminar and intralaminar damages in the impacted specimens, the recorded AE signals during the impact tests are analyzed by Wavelet Packet Transform (WPT) and energy content of each damage mechanism is specified. The C-scan and digital camera images of the LVI specimens are employed to verify the AE results of impact test. The AE-predicted percentages of each damage mechanism for LVI and quasi-static indentation loadings have a good consistency with each other. The obtained results show the applicability of AE to detect and distinguish BVID in laminated composites and also to track the evolution of different damage mechanisms under quasi-static and dynamic transverse loading conditions.

Table 1
The physical and mechanical properties of IM7/8552 [34,35].

Physical properties	
Fiber density (g/cm^3)	1.77
Resin density (g/cm^3)	1.30
Fiber volume (%)	57.70
Laminate density (g/cm^3)	1.57
Mechanical properties	
E_1 (MPa)	161000
E_2 (MPa)	11400
E_3 (MPa)	11400
υ_{12}	0.300
υ_{23}	0.436
G_{12} (MPa)	5170
G_{13} (MPa)	5170
G_{23} (MPa)	3980

2. Experimental procedures

2.1. Description of the materials

The experimental tests were carried out on Hexcel IM7/8552 unidirectional carbon prepregs cured according to the manufacturer's recommended procedure [34]. The physical and mechanical properties of IM7/8552 are represented in Table 1 [34,35].

2.2. Test method

In order to study the effect of stacking sequence on BVID, two quasi-isotropic laminates with the specified configurations in Table 2 were fabricated. The layup of the first specimen is $[60/0/\text{-}60]_{4S}$, which is named dispersed specimen and shown by S_D and the layup of the second specimen is $[60_4/0_4/\text{-}60_4]_S$ which is named blocked specimen and shown by S_B. The quasi-static indentation tests were conducted by pushing a Φ16 mm spherical-head indenter at the center of the rectangular specimen which was simply supported over a 125 × 75 mm^2 hollow window and was held by four clamps at its four corners. The tests were carried out under displacement control mode with the constant rate of 0.5 mm/min by an INSTRON servo-hydraulic testing machine at the temperature of 25 °C. The machine continuously recorded the values of displacement and load during the tests. In order to capture the originated AE signals from the specimens under loading, four AE sensors were placed on the surface of the specimens (see Fig. 1a). Three samples of each specimen type were tested to check the data repeatability.

The LVI tests were done according to ASTM D7136 [36] using an INSTRON Dynatup 9250 H V drop-weight impact tower (see Fig. 1b). The diameter and weight of the impactor are 16 mm and 6.2 kg, respectively. The supporting window and the clamps are the same as the indentation test. The values of acceleration, velocity, deflection, and

Table 2
Configurations of the specimens.

Specimens	Dimensions (mm)	Lay-up	Ply thickness (mm)
S_D	150 × 100 × 3	$[60/0/\text{-}60]_{4S}$	0.125
S_B	150 × 100 × 3	$[60_4/0_4/\text{-}60_4]_S$	0.125