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Damage Analysis for Low Velocity Impacted Composite Laminates using Acoustic Emission Technique

Characterization of dynamic induced damage is one of the most controversial issues in the application of composite structures. To this aim, Acoustic Emission (AE) technique has been qualified as a robust tool for damage sequence analysis due to its high sensitivity to damage mechanisms. First, AE reference map was created using a couple analysis of Fuzzy C-Means (FCM) clustering and Principal Component Analysis (PCA). The low velocity impact tests were then conducted on composite plates. Finally, Impact AE signals were discriminated and the sequence of damage mechanisms during impact process was discovered. As a result, it is concluded that AE method accompanied with the presented method is a new appropriate approach to discriminate damage mechanism sequences in impacted composite specimens.

Keywords: *Acoustic emission, Fuzzy c-means, Low velocity impact, Damage.*

1. INTRODUCTION

One of the main issues of laminated composite usage in industrial applications is their brittle-type behavior under impact damage loading [1], which may cause unexpected failure mechanisms in these materials. The low velocity impact may lead to crucial internal dama–ges [2-4] which can cause catastrophic failures in composite laminates [5-9]. In this case, the damage sequence analysis can be used to reveal the effect of various sequence characteristics on these failures. Non-Destructive Techniques (NDTs) are excellent candidates for real-time damage monitoring of composite speci–mens for this purpose.

Several damage mechanisms, such as matrix cracking, fiber breakage, and matrix/ fiber debonding and delamination, can be created when a composite laminate is subjected to low velocity impact. In this case, acoustic emission, as a non-destructive approach, has the ability to characterize these failure modes [10-20] for in-service monitoring conditions. From the literature review and to the authors' knowledge, studies are lacking in the field of damage sequence analysis using AE technique. Therefore, further study in the field of composite under impact loading and determining damage sequences using processed AE data, are essential and results of such studies can lead to acquire sufficient knowledge in order to increase the reliability of composite specimens.

The main goal of the present study is to investigate the damage sequence of laminated composites under low velocity impact using processed AE data. To this aim, glass/epoxy laminated composites were subjected to low velocity impact tests. First, Fuzzy C-Means (FCM) method was used to characterize damage mec–hanisms during impact loading. Afterwards, the damage sequences were obtained. Finally, it was observed that AE is a capable tool to characterize damage sequence under low velocity impact tests.

Table 1. The characteristics of the specimens with their stacking sequences.

Specimen	Mid-plane	Stacking Sequence	Average Thickness (mm)
S	0-0	[0]8	2.9

2. EXPERIMENTAL PROCEDURE

2.1 Materials

The experimental work was carried out on rectangular plates of glass/epoxy composite materials. Specifica-tions of unidirectional laminate layups are reported in Table 1.

A Vacuum Infusion Process (VIP) method was used to manufacture the specimens. Epoxy resin, EPL1012,

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mixed with EPH112 as a hardener was used for the samples. The weight of unidirectional fibers were 400 g/m2. The specimens were then inserted in the open air for 7 days at 25°C after resin injection. The ultrasonic C-scan method was used to check the quality of the plates. Then, a water jet machine was used to cut the plates and to make the specimens with dimensions of 230×230 mm. The fiber volume fraction was 60 ± 3% for each specimen and the nominal average thickness of each specimen was 2.9 mm.

2.2 Test method and machines

For low-velocity impact tests, a drop-weight with a hemispherical impactor was used to deliver impact to specimens by a standard drop-hammer. The time and acceleration were continuously measured in 13 µs intervals during tests. Different impact energies ranging from 0.84 to 61 J were utilized using different impactor masses for impact tests. The diameter of the hole in the window of the clamp plate was also 150 mm and the diameter of the hemispherical indenter was 16 mm.

2.3 AE sensors

The rough AE signals were recorded using two AE sensors, which were placed in aligned and perpendicular directions to the fibers with a distance of 40 mm from impactor. The threshold of AE signals captured during the tests was adjusted to 30 dB. The resonance frequ–ency of the single-crystal piezoelectric AE sensor was 513.28 kHz. An optimum operating range of these sensors were 100–750 kHz. The 2/4/6-AST preamplifier with a gain selector of 40 dB was utilized to enhance the acoustical signals. The sampling rate of AE data acquisition board was set to 40 MS/s (Mega Samples per Second). To calibrate the AE sensors and to check their reproducibility, the pencil lead break method (see Figure 1) was implemented prior to each test. Vacuum grease was used to cover the contact surface between sensors and specimens to create good acoustical coupling.

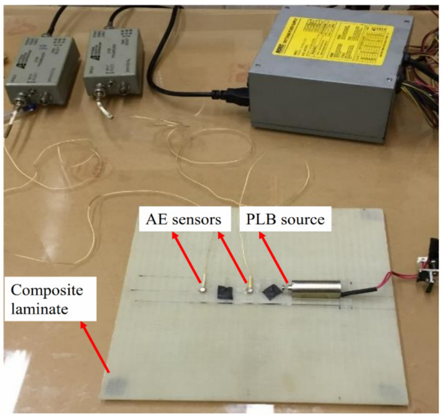

Figure 1. PLB method to calibrate the AE sensors and to check their reproducibility.

3. RESULTS AND DISCUSSION

Based on the literature review, dominant damage mechanisms of composite materials, are matrix cracking, fiber/matrix debonding and fiber breakage [21-23]. A crucial stage in AE-based analysis of damage mechanisms is to correlate AE features with these three types of damage in composite laminates [24]. For this purpose, the quasi-static process was online monitored using AE method.

The signal waveform has a multi-mode characteris–tics. To extract AE features corresponding to each specific mode, HT was applied on rough AE signals to extend them into the complex plane. The envelope of input signal was then obtained through magnitude calculation of the output signal for further mode detection. Also, instantaneous frequency and its average were then computed using instantaneous phase assigned to analytical signal for distinct excited modes. This procedure helps to attain an accurate analysis for multi-mode waveforms.

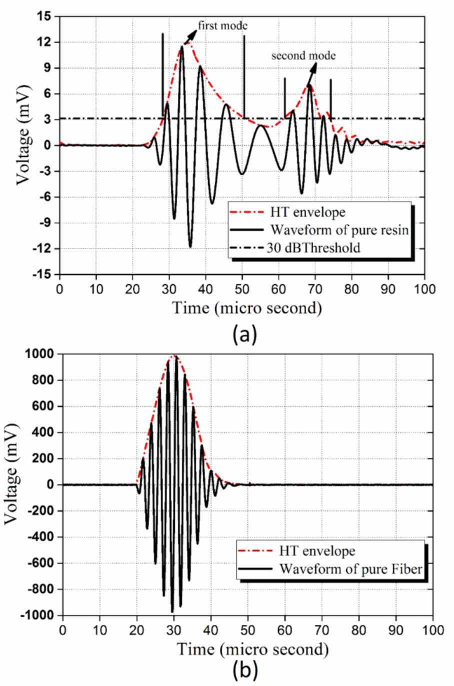

Figure 2. A sample of the obtained signal during quasi-static test.

The frequency content of the signal in Figure 3.a was analyzed using HT concept and was compared to conventional Fast Fourier Transform (FFT) method related to the rough AE signals (see Figure 3.b). As it is clear, HT method gives a more compact frequency content especially for non-stationary waveforms, compared to FFT approach. In conclusion, a mode by mode analysis gives a more accurate result than using global AE parameter for rough signals. This method also eliminates the effect of time window length on output parameters like duration and average frequency.

To map AE features into damage mechanism clusters, an analysis procedure was applied. To start analysis, five AE parameters including amplitude, duration, rise time, counts and average frequency were considered as AE descriptors. Since the variables (AE features) were not in same units, they were firstly standardized using their standard deviation. Afterward, AE reference map was created using a couple analysis of Fuzzy C-Means (FCM) clustering and Principal Component Analysis (PCA). Table 2 shows the variance correlated to each distinct PC. The cumulative sum of the variances of first three PCs was about 96.5 of the total variance. As a consequence, first three PCs were kept for clustering analysis.

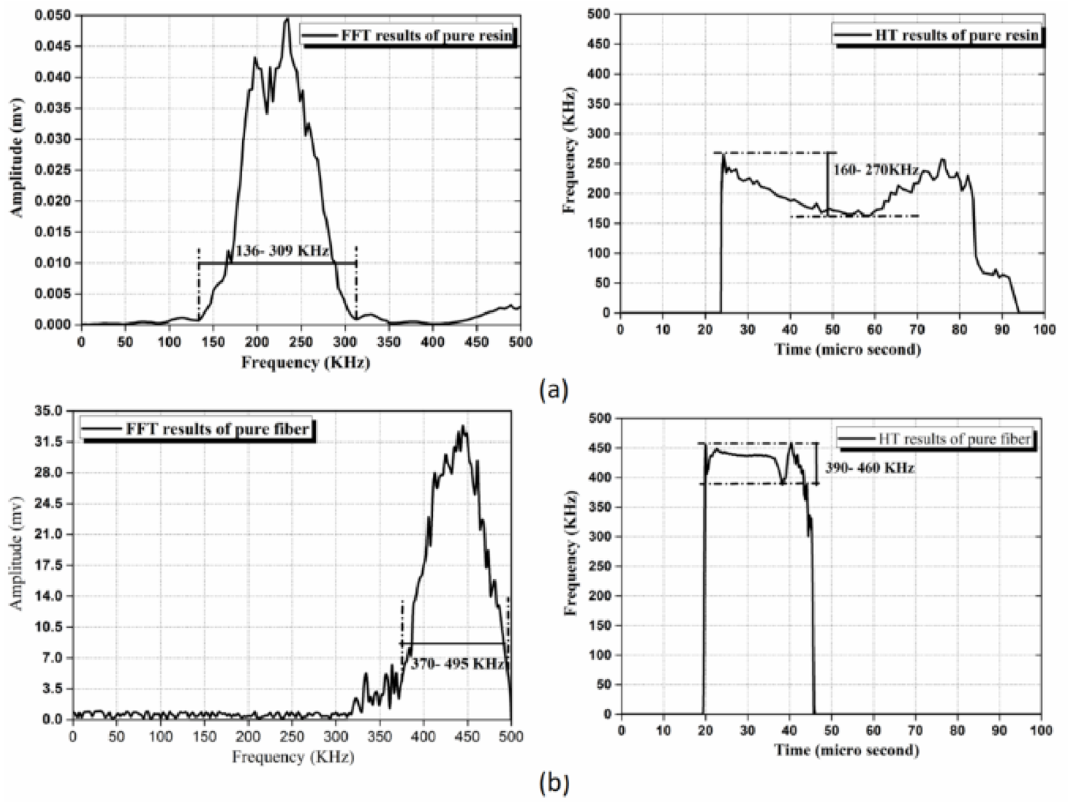

Figure 3. The dominant frequency ranges of a) rough and b) processed AE signals for a sample wave of the quasi static test.

Table 2. The variance correlated to each principal component.

parameter	PCA 1	PCA 2	PCA 3	PCA 4	PCA 5
Variance (%)	48.1	28.7	19.7	1.7	1.8

PCA visualizations of Fuzzy clustering are shown in Figure 4. Since the datasets were labeled, mean acou–stical parameters could be computed for each distinct cluster. In this case, the frequency feature was best distinguished due to its higher variance among other AE parameters. Hence, frequency was used as an efficient AE descriptor for damage characterization.

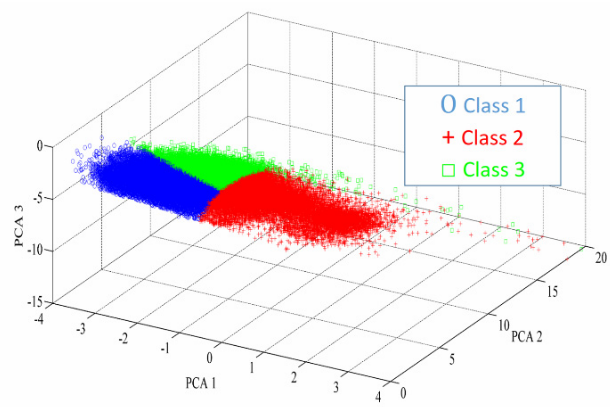

Figure 4. PCA visualizations of Fuzzy clustering of the AE signals in quasi-static test.

The frequency contents of AE signals belonging to different clusters are shown in Figure 5. The results highlight three frequency ranges. Dominant frequency ranges of obtained clusters are summarized in Table 3. According to previous studies [16,17], a same procedure using HT was carried out to obtain frequency ranges of pure matrix and fiber failure mechanisms. It is achieved that the dominant frequency range of matrix cracking is about (160-270 kHz) and dominant frequency range of fiber breakage is about (390-460 kHz).

Consequently, it can be concluded that the AE events of the first and third clusters are representatives of matrix cracking and fiber breakage, respectively. Therefore, the AE signals of remaining cluster are associated with fiber/matrix debonding mechanism. As a final point, the AE pattern is completely achieved through the aforementioned steps.

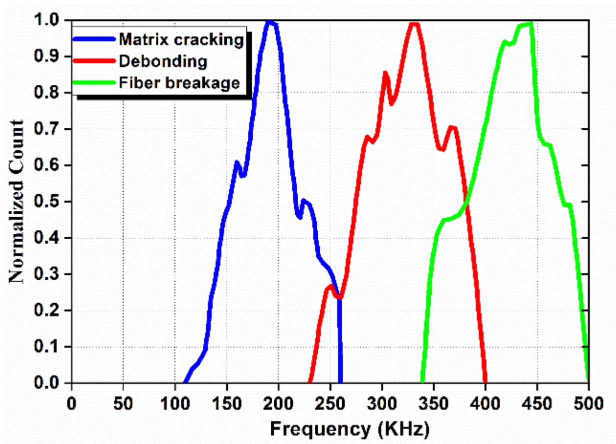

Figure 5. The frequency contents of AE signals belonging to different clusters.

Table 3. Frequency ranges of different damage mechanisms using FCM clustering.

Damage mechanism	Matrix cracking	Fiber/matrix debonding	Fiber Breakage
Frequency range (KHz)	110-260	230-400	340-500

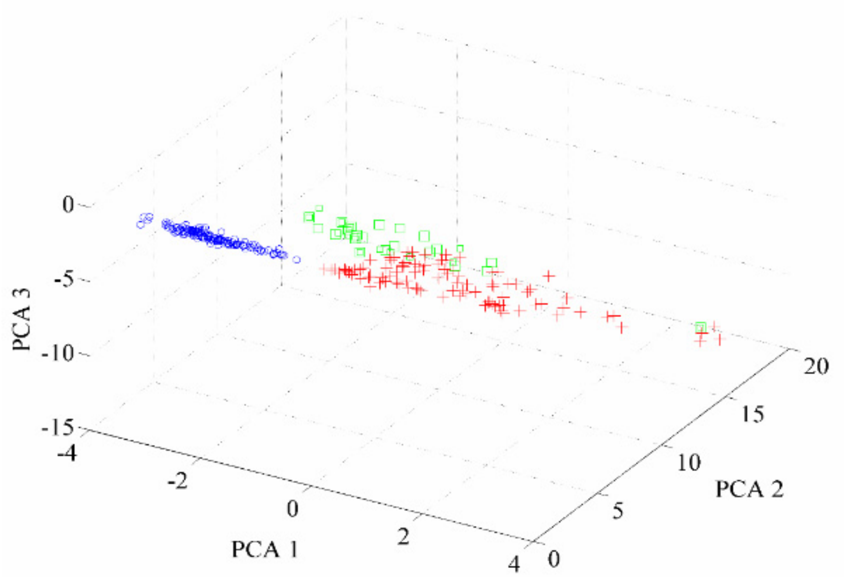

Figure 6. PCA visualization of impact AE data.

To investigate impact-induced damage, impact process was online monitored using AE sensors. Then AE features associated with excited modes were extracted using same procedure described in previous section. AE features were then transformed to the principal component space and clustered according to the reference map using distance criteria. Figure 6 shows a sample of PCA visualizations of clustered AE data relating to 21.2 J impact energy level. In this Fig, classes 1 to 3 are correlated to matrix cracking, matrix/fiber debonding and fiber breakage, respectively.

3.1 Stress wave analysis

One of the fundamental issues in detecting acoustical features is to discriminate between the impactor and damage AE signals in low velocity impact tests. To this aim, a low velocity impact simulation was accomplished using a three dimensional FE model with an 8-node, quadrilateral, first-order interpolation, stress/ displace–ment continuum shell element with reduced integration (SC8R). Meshing of the FE model was chosen based on the accuracy of the FE results and computational time, which is shown in Figure 7. To decrease the time of FE analysis and acquire accurate results, the mesh sen–sitivity analysis was obtained using finer and coarser mesh models. Besides, the impactor was considered as a rigid body because of its higher strength leading to negligible deformation in comparison to the composite laminates.

Figure 8 depicts time-stress curve behavior for a node located in the fiber direction with a 20 mm distance from the impactor. The time period for the explicit FE model was considered 90 microseconds. This selection was because of the fact that no severe damage occurs in the specimens in the mentioned period. Therefore, the unique source of this resultant stress wave (see Figure 7) was the impactor effect. To obtain the acoustical feature of this wave, a frequency analysis was performed by FFT method for this wave. Figure 9 shows the FFT result for the impactor stress wave. As it is obvious, the frequency range of the impactor is lower than 100 KHz. Thus, it is possible to capture only AE signals related to damage mechanisms during impact tests by filtering frequencies lower than 100 KHz. To prove this claim, a low velocity impact test with 2 J energy (in stage I) was conducted using 100-1000 KHz frequency ranges. It was observed that no signals were captured during this elastic impact test.

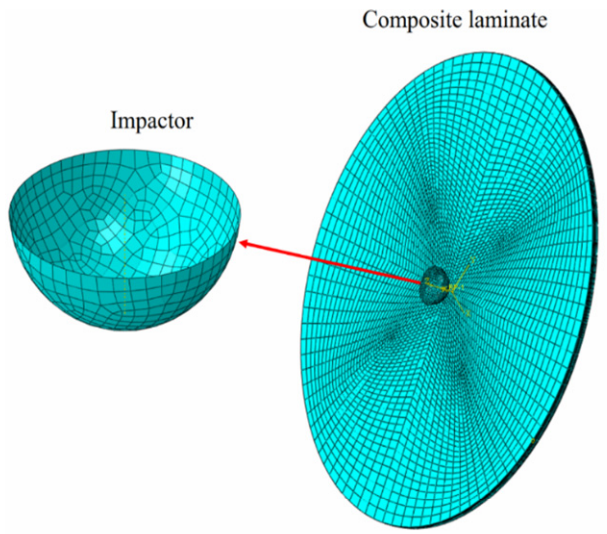

Figure 7. Three dimensional FE model of low velocity impacted laminates.

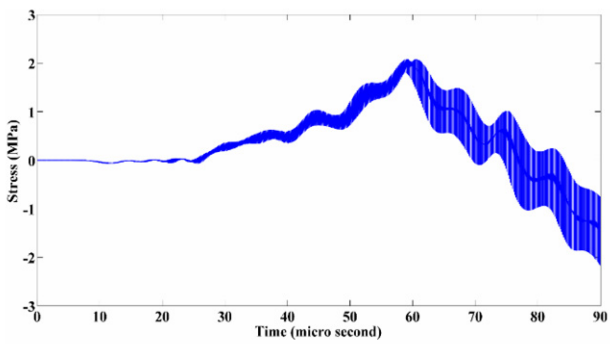

Figure 8. The simulated stress wave using FE model in 90 μs period.

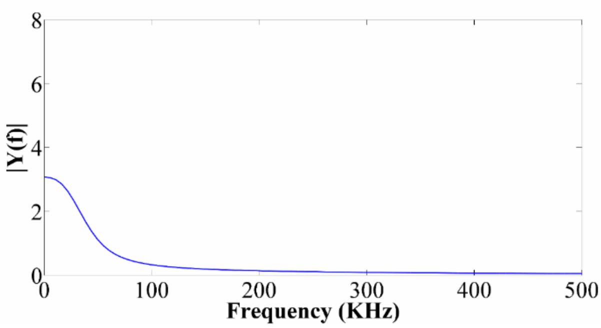

Figure 9. FFT content of the wave related to the impactor effect.

3.1 Impact damage analysis

Figure 10 shows the load vs displacement curves of impact events in 5 stages in comparison to the static load to access the applicability of quasi-static assumption. Each stage is associated with two impact energy levels. For the 1st stage (Figure 10.a), curves are completely placed in the elastic region of the static load (stage I), no apparent damages were observed for these impacted specimens. For this region, loading and unloading behavior is almost the same and consequently, the absorbed energy is too small. E3 and E4 events (Figure 10.b) reach the second region of the static diagram. For these events, the first major load drop (where force reaches to its maximum extent) magnitude, which reflects the released strain energy, is lower than that of the static test.

For impact energy levels, which are placed in the third stage of the quasi-static test (Figure 10.c), the quasi-static curve can yet very well predict the impact trends of these intermediate energy ranges. The 19.1 and 21.2 J energy levels (Figure 10.d) reach the fourth stage of the quasi-static test. The load drop behavior was not obvious in these curves. However, these impact events reach a point that the load history in maximum point loses its smoothness, which can be considered as the minor fiber failure zone.

The impact events existing in the 5th stage of the quasi-static test show an increased resistance to the fiber damage due to the membrane effect, which causes higher maximum load for fiber damage of the impacted laminate. This region can be considered as the major fiber failure zone, which consists of a major load drop. This major load drop causes such an abrupt change in load, exciting higher order natural frequencies of the plate (Figure 10.e). These trends also depict that the total energy absorption capacity is underestimated by the quasi-static test. It can be found that for impact events with low and intermediate energy levels, the quasi-static and impact curve approximately follow the same trend. Therefore, the low and intermediate impact energy events are not mostly strain dependent. However, there is a large difference between quasi-static and impact event trend for the major fiber failure zone, which proves the strain dependency of this damage mechanism.

In the lowest impact energy events (E1& E2), which induced no damage in target composite specimens (detected using ultrasonic C-scan), the energy of all obtained signals is concentrated in the lowest frequency regime (AA part of Figure 11(b)). As a consequence, the AA component of each signal was considered due to some stress waves induced from the impact process itself and friction between impactor and target. So, this component does not correspond to any damage mechanism during contact time, and should be neglected for damage analysis. Additionally, quasi-static results predict these impact events to be damage-free because of no acoustic activity in stage I. As shown in Figure 11, the dominant frequency range of AD part mostly coincides with the frequency interval of matrix cracking mechanism. As a consequence, the cumulative energy of AD part during the impact event was considered due to matrix cracking mechanism (blue component). In the same way, based on the damage excitation frequency intervals obtained in the previous section, the WP components with red and green color (DA and DD component) are correspond to matrix/fiber debonding and fiber breakage, respectively.

As discussed previously, matrix cracking and matrix/fiber debonding initiate in the quasi-static state at stages II and III, respectively. Similar to the quasi-static test, the AD component energy becomes considerable for E3&E4 impact events, which exhibits that matrix cracking is the dominant damage mechanism while no matrix/fiber debonding has occurred. Quasi-static results also predict that matrix/fiber debonding mechanism is activated for E5&E6 events, which is in agreement with WP analysis of impact AE result. The deviation arises when the impact energy reaches stage IV. Although the existence of fiber failure mechanism is evident in AE analysis of impact data in this stage, its activity is not so high in contrast to the quasi-static state due to dynamic factor phenomenon. Therefore, this region is considered as a minor fiber failure zone in this case. Since the total energy absorption capacity is underestimated by the quasi-static test, so E9&E10 event results cannot be compared with equivalent quasi-static ones.

Some researchers consider absorbed energy to be a reliable indicator of damage [5]. In Figure 12, absorbed energy percentage has been plotted as a function of impact energy. As discussed acoustically, the impact events (E1&E2 events in Figure 11) in the elastic region, which have no damage indicate that significant amount of the impact energy returns to the impactor. The second region of this plot is considered as the matrix and fiber/matrix debonding region. This region includes the intermediate level of the absorbed energy. The third and fourth regions are the minor and major fiber failure zone, respectively. In this case, more than 60 percent of the energy transfers to the specimen. It is found that, a threshold impact energy is evident, below which the absorbed energy is quite small and beyond which impact energy is significantly absorbed. This threshold can be considered as the resistance of E/glass composites to impact loads. Based on the discussion, this threshold can be predicted from quasi-static test as the initiation of the minor fiber failure zone. Accordingly, quasi-static test predicts this threshold to be about 15 J, which well matches the absorbed energy results.

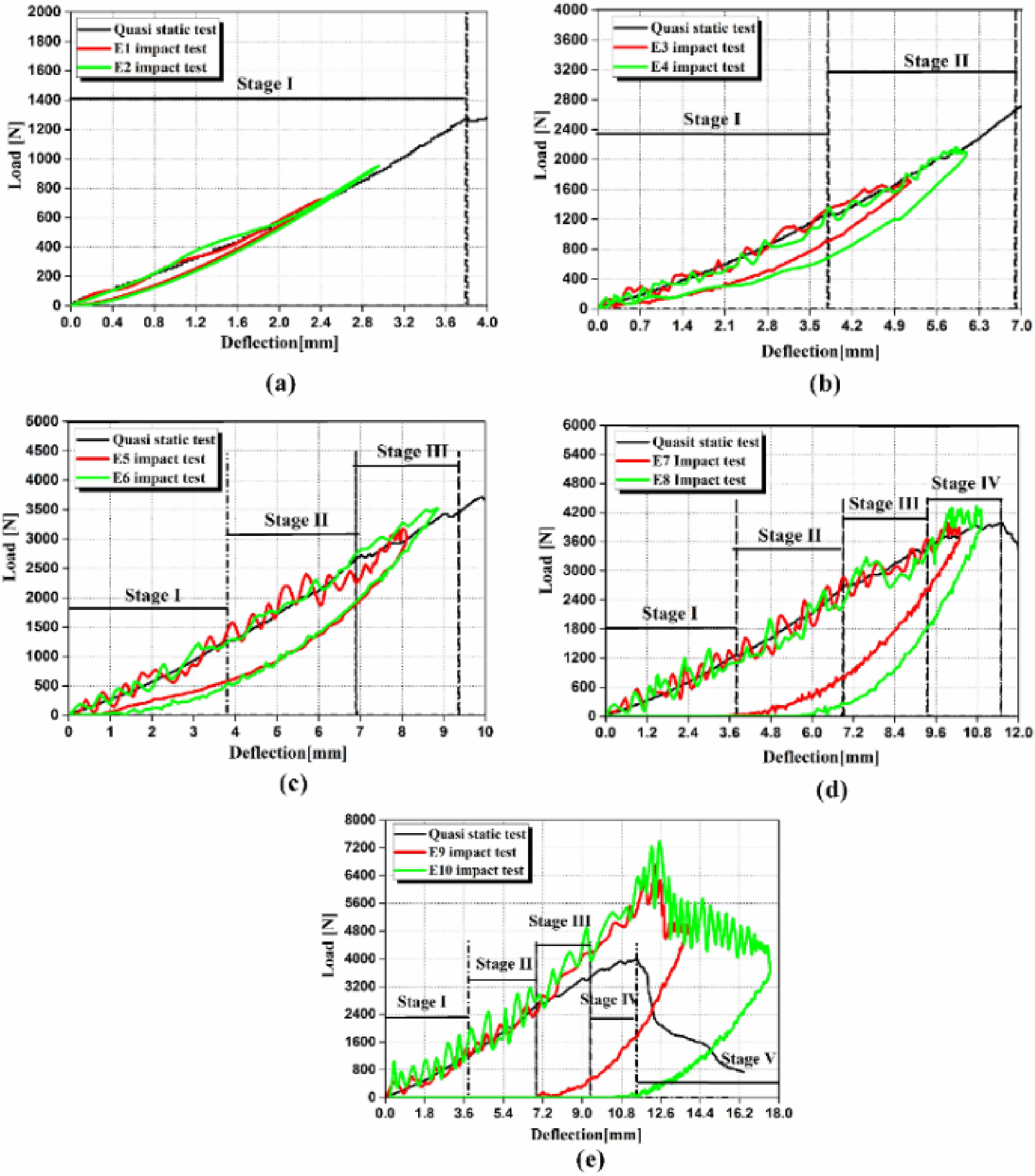

Figure 10. The force-displacement curve of impact events in comparison with quasi-static test in different stages.

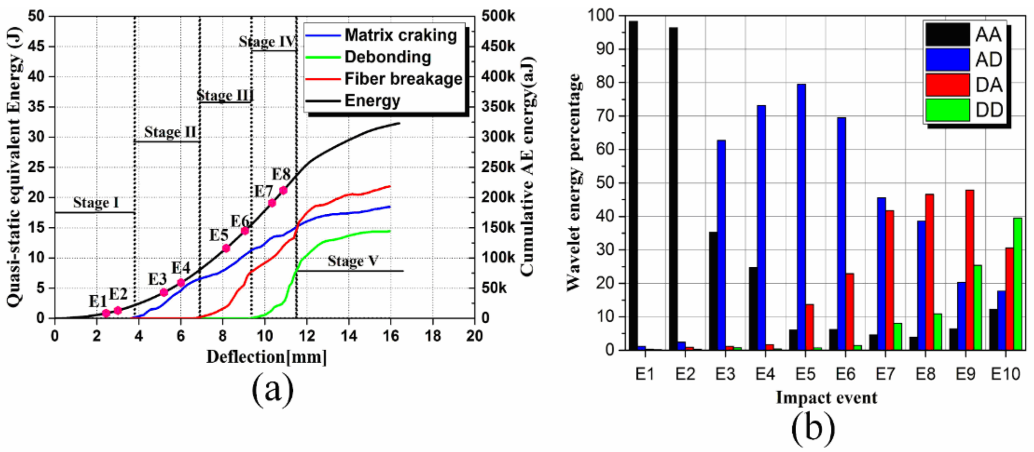

Figure 11. The a) acoustic energy assigned to quasi-static equivalent energy and b) energy percentage distribution of the wavelet decomposition for each impact event.

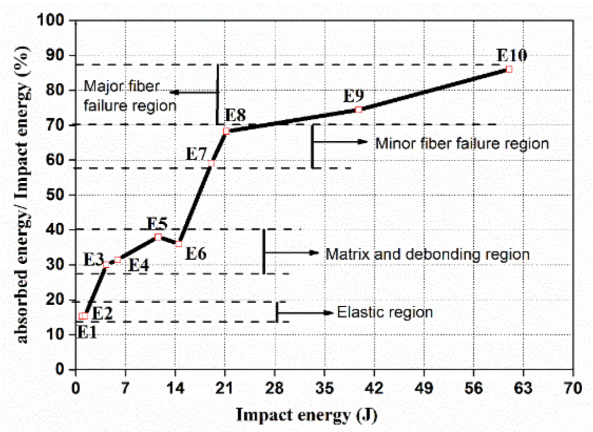

Figure 12. The absorbed energy vs the impact energy of each impact event.

4. CONCLUSIONS

In this study, damages of impacted composite laminates were investigated using a novel AE based approach. It was shown that the load-displacement curve of quasi-static and impact events have the same trends up to the minor fiber failure zone. Also damage of impact tests were analysed using processed AE data. As a final point, the proposed AE methodology can be used as a capable tool for damage evaluation under low velocity impact events. Potential future studies include the validation of the same technique on green composites, given their recent rising interest from industry and literature [25-30].

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АНАЛИЗА ОШТЕЋЕЊА КОМПОЗИТНИХ ЛАМИНАТА ПРИ УДАРУ СА НИСКИМ БРЗИНАМА КОРИШЋЕЊЕМ ЕФЕКТА АКУСТИЧНЕ ЕМИСИЈЕ

J. Јоусефи, А. Махдиан, Н.З. Карими, Х. Хеидару, М. Ахмади, Ђ. Минак

Карактеризација динамичне индуковане штете је једно од најконтраверзнијих проблема у примени композитних структура. У том циљу, техника акустичне емисије (АЕ) је квалификована као робустан алат за анализу секвенци штета због своје високе осјетљивости на механизме оштећења. Прво, АЕ референтна мапа је креирана помоћу пар анализа Fuzzi C-Means (FCM) груписања и анализе главне компоненте (ПЦА). Потом су изведени тестови удара при ниским брзинама на композитним плочама. Коначно, ударни АЕ сигнали су били дискриминисани и откривени су низ механизама оштећења током процеса удара. Као резултат тога, закључује се да је АЕ метода праћена представљеном методом нови одговарајући приступ за дискриминацију секвенци механизама оштећења у композитним узорцима.