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Acoustic Emission Techniques for Evaluating Damage Modes in CFRP Hybrid Joints

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Acoustic Emission Techniques for Evaluating Damage Modes in CFRP Hybrid Joints

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Abstract. The Acoustic Emission (AE) technique is one of the powerful Non-Destructive Evaluation (NDE) tools for predicting and assessing damages in composite structures. In this research work, the energy released during each acoustic event, as a function of the total number of counts, is used for evaluating the damage modes in CFRP hybrid joints. The damage modes identified using the AE parameter, Energy per Count (E_{AE}^{n}) is compared with the waveforms of the acoustic events. Generally, the type of damage mode can be identified by postprocessing the acoustic waveforms. By comparing the waveforms with the E_{AE}^{n}, the damage mode has been evaluated. The technique introduced in this work will reduce the data storage and computation time for analyzing the waveforms. The damage modes can be identified during loading using this technique. In addition to that, the location of the generated acoustic events is used for identifying the critical failure areas in the CFRP hybrid joints. The attenuation of the AE events due to the distance between the sensors and the AE source is also considered for this study. From the observed results, the AE technique proves to be one of the formidable techniques for evaluating damage modes in composite structures.

1. Introduction

Acoustic Emission (AE) technique is one of the most powerful evaluation techniques used for damage characterization and health monitoring. This technique records transient elastic signals generated by a material under straining. This nondestructive technique is categorized under passive technique since the acoustic wave is internally generated by the material itself, unlike the ultrasounds technique, which relies on an external source. AE stands out from other nondestructive tools due to its high sensitivity. Over the years, several parameters from the recorded AE signals have been used for damage characterization and health monitoring. AE signal data, used for characterization, can be categorized into two different types: signal-based data and parameter-based data. A popular signal-based data is the peak frequency of the signal, while popular parameter-based data are acoustic energy and the total number of counts of the recorded signal [1,2].

In this research work, an attempt has been made to use both the signal-based data (waveforms) and a new parameter from the parameter-based data (Energy per Count) for identifying the damage modes in Fiber Reinforced Polymers (FRP). As both the signal-based and parameter-based data are the representatives of an acoustic signal generated during damage propagation in a material, the efficiency of the technique can be increased by utilizing both of them contemporarily. The acoustic waveforms, which are the signal-based data, are analyzed using the Wavelet Packet Transform (WPT), which can measure the percentage of spectral energy distribution in each frequency domain of the waveform. For analyzing the parameter-based data, a new parameter called Energy per Count (E_{AE}^{n}) has been used. For characterizing the damage modes, Carbon Fiber Reinforced Polymers (CFRP) hybrid joint specimens are tested. The acoustic data is recorded during the test and is analyzed for the re-sults. The aim of this research is to select acoustic waveforms from the recorded signal during the test, based on their E_{AE}^{n} and analyze them using WPT.

2. Materials and Methods

2.1. Materials

The specimens tested for this study are CFRP hybrid joints, bonded with strong epoxy adhesive and aluminium rivets. The CFRP prepreg laminate is prepared by impregnating high strength carbon fibers in the ER450 epoxy matrix. The carbon fibers are in stitched configuration. The prepreg has a nominal ply thickness of 0.244 mm. The details about the dimension of the adherends, the number of plies and other details are presented in Table 1. The adherends are bonded using high strength epoxy adhesive with a shear strength of 25 MPa and a peel strength of 65 MPa. A hole of 1.6 mm radius is drilled in the midspan of the adhesive overlapping region. An aluminium flat-headed rivet of length 14 mm is inserted to configure the hybrid joint.

Table 1. CFRP Hybrid Joint Specimen Geometry and Configuration.

Upper Adherend				
Length (mm)	Width (mm)	Thickness (mm)	No. of. Plies	Stacking Sequence
101.6	25.34	1.3	5	+45/+45/+45/-45/+45
Lower Adherend				
Length (mm)	Width (mm)	Thickness (mm)	No. of. Plies	Stacking Sequence
101.6	25.32	6.4	26	+45/[+45/-45]$_{12}$/+45
Overlapping Region				
Length (mm)	Width (mm)	Thickness (mm)		
25.40	23.32	8.27		

2.2. Testing Methods

The CFRP Hybrid Joint specimen is tested under the standard testing procedure of ASTM D5868 - Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding. The tensile load is applied to the specimen at a displacement rate of 13 mm/min. The high crosshead displacement rate is recommended by the ASTM standard for the adhesively bonded specimens [3]. The test is carried out in an INSTRON servo-hydraulic testing machine with a load capacity of 100 kN.

2.3. Acoustic Emission Testing

To record the acoustic activity during the loading, two piezoelectric sensors with an operating frequency range of 150 kHz – 400 kHz (R30α, Physical Acoustics, MISTRAS Group, NJ, USA) are mounted on the specimen. The surface between the sensors and the specimen is separated by a very thin layer of silicone grease to improve the coupling and reduce the reverberation signal. The sensors are calibrated for the signal attenuation with the distance between the source and the signal using a pencil lead break test. Typically, a pencil lead break test creates a signal with a nominal amplitude of 98 dB – 99 dB. For calibration of the signal attenuation, the amplitudes are recorded by breaking the pencil lead in different positions at various distances from the sensor. The data is fed to the Data Acquisition System (DAQ). During the mechanical loading, the recorded acoustic signals are amplified by 40 dB through a 2/4/6-

AE Preamplifier. The threshold amplitude for recording is selected at 35 dB and all the waveforms are recorded at a sampling rate of 1 mega sample per second (1 MSps).

2.3.1. Testing procedure

The AE signals are recorded during the entire loading history and are analyzed in two modes: parameter-based data and signal-based data. For the parameter-based data, a new parameter is introduced in this work. The parameter, named Energy per Count (E_{AE}^{n}) is the ratio of the acoustic energy recorded per count during an acoustic event. The term acoustic event refers to the local material change under loading giving rise to acoustic emission. The number of counts in an acoustic event is the number of times the acoustic signal crosses the detection threshold. The acoustic energy is the total elastic energy in the signal generated by the said acoustic event.

In simple words, the total energy E_{AE}, recorded during an acoustic event i, to the total number of counts N can be defined as the Energy per Count.

$$E_{AE}^{n} = \frac{E_{AE,i}}{N_i} \tag{1}$$

After calculating the E_{AE}^{n} for the entire loading history using Equation (1)-, multiple waveforms associated with lower values of E_{AE}^{n} and higher values of E_{AE}^{n} are taken for the WPT analysis. The selection criteria of the waveforms for this study are explained in detail in the subsequent sections. The WPT decomposes the acoustic waveform without losing its originality into different levels. Then the frequency band associated with each level and the percentage of spectrum energy of the waveform in each frequency band is calculated. More details about WPT can be found in our previous works [4].

3. Results and Discussions

The test is repeated for three different specimens of the same configuration as indicated in Table 1, however, for the sake of brevity, a complete analysis of the mechanical results and acoustic results of a specimen is taken for this study. The load response of the specimen under loading is plotted over time. Similarly, the E_{AE}^{n} is also plotted over the load response. The results are presented in Figure 1.

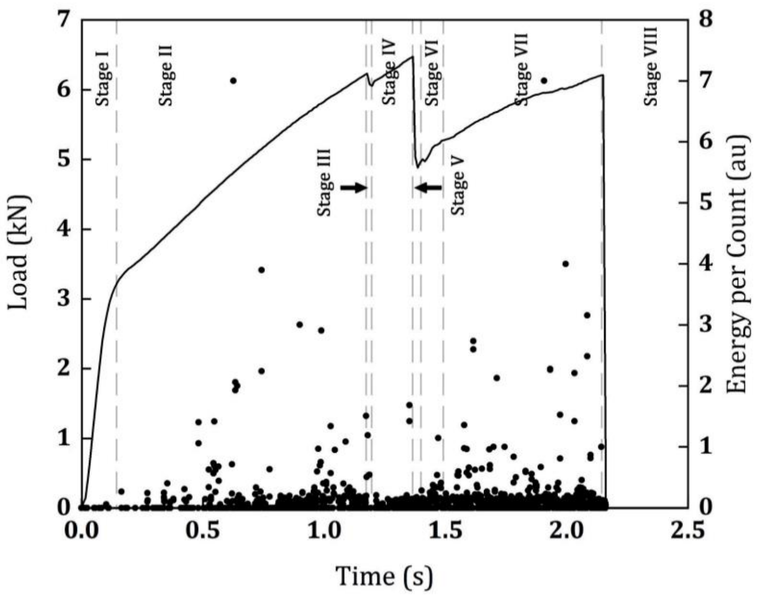

Figure 1. Load vs Time for the CFRP Hybrid Joint Specimen over plotted with Energy per Count calculated from the acoustic results.

The load response of the CFRP Hybrid Joint specimen can be separated into eight different stages and the acoustic emission results are analyzed in each of these stages. The reason for categorizing the load response into different stages is because the stress distribution and corresponding damage propagation in the CFRP Hybrid Joint specimen vary from stage to stage owing to several factors. The larger thickness of the lower adherend, the thickness of the adhesive and the aluminium rivet are some of the reasons for the complex stress distribution in the specimen. Based on that, the load response is classified into stages: i) Linear elastic response – 1 ii) Linear elastic response – 2 iii) Sudden load drop – 1 iv) Linear plastic response – 3 v) Sudden load drop – 2 vi) Nonlinear plastic response vii) Linear response – 4 viii) Final fracture.

From each stage (except Stages i, iv and viii), two acoustic events are selected for the WPT analysis. The selection is based on the E_{AE}^{n}. In each stage, the E_{AE}^{n} value ranges from close to 0 to 7 au, with the majority of the AE events distributed below E_{AE}^{n} value of 1. For this reason, two acoustic events, one between $0 < E_{AE}^{n} < 1$ (level 1) and another $E_{AE}^{n} > 1$ (level 2) is taken for this study. Since the stages i, iv and viii do not have any AE events with $E_{AE}^{n} > 1$, only one acoustic event is taken from this stage.

From the WPT, the energy percentage distributed in each frequency band is calculated for all the signals taken from the eight stages. The results are presented in Table 2.

Table 2. Spectral Energy distributed in each frequency band from WPT results for all AE events.

Stages	Levels	Frequency *(kHz)*							
		437.5-500	375-437.5	312.5-375	250-312.5	187.5-250	125-187.5	62.5-125	0-62.5
I	1	3.31	0.22	18.50	29.31	10.76	9.08	28.80	0.03
II	1	0.92	0.34	39.30	26.94	13.11	7.63	11.70	0.05
	2	0.83	0.93	7.09	7.13	10.56	54.46	17.97	1.03
III	1	3.29	1.46	37.82	25.25	8.85	10.67	12.13	0.52
	2	2.96	1.10	43.37	19.10	7.81	16.10	9.18	0.38
IV	1	0.84	0.22	44.16	21.05	8.92	15.18	7.18	2.45
	2	0.91	0.66	19.34	9.77	5.74	39.50	23.49	0.60
V	1	0.95	4.73	45.34	17.79	11.53	14.48	4.80	0.38
VI	1	0.26	0.38	21.27	29.20	13.65	28.18	6.88	0.19
	2	1.48	2.06	51.84	8.56	8.35	8.64	18.74	0.32
VII	1	0.63	0.63	12.44	14.82	4.54	24.88	41.90	0.16
	2	1.99	1.91	38.33	21.25	9.01	10.97	15.77	0.76
VIII	1	0.68	0.50	35.78	29.81	16.08	9.57	7.42	0.16

The waveform and the WPT results of the low E_{AE}^{n} signal recorded during stage i is presented in Figure 2. First of all, the stage i lasts only for 0.16 s duration in the entire test. This suggests that it is a very short stage and consequently very few AE events are recorded during this stage. The AE event selected from this stage has a relatively high amplitude and count so that any noise signals can be avoided in the analysis. In Figure 2(a), it is evident that the maximum amplitude of the waveform is 0.7 µV. Comparing the results from Table 2 and Figure 2(b), the spectral energy is distributed in all frequency bands between 62.5 kHz and 437.5 kHz. There is no frequency band which has specifically carried any significant amount of energy. Moreover, while testing lap-shear specimens with wedge-shaped grips, during the initial loading, the specimen aligns itself to the axis of loading [5]. That is why there are two linear elastic stages in the load response with the first region is very short (0 s – 0.16 s). Since there is no signal with any significant E_{AE}^{n}, a conclusion can be drawn. During this region, the

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specimen aligns itself to the axis and the AE signals generated during this stage are a result of the friction between the specimen and the end grips of the loading setup.

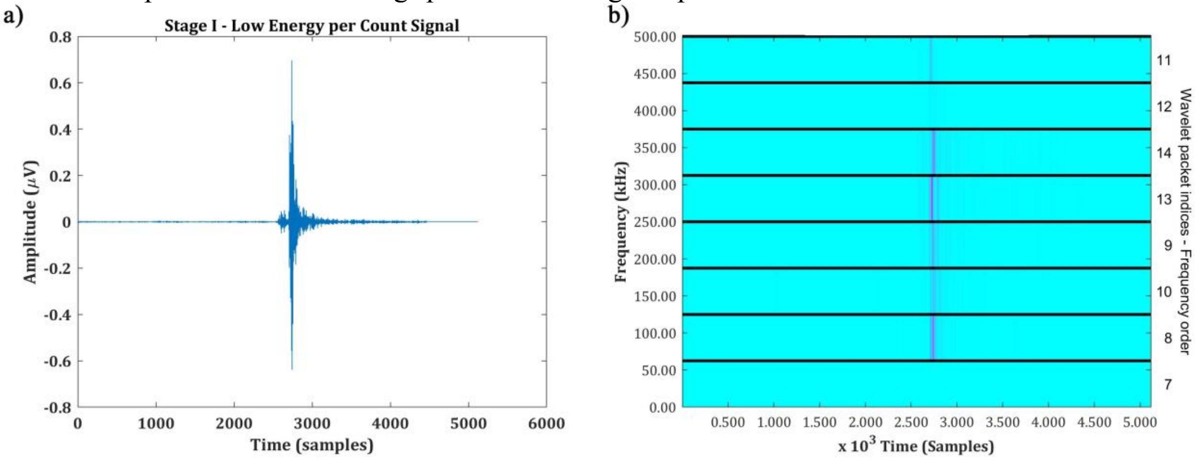

Figure 2. Low E_{AE}^{n} signal recorded at Stage i a) Waveform Result b) WPT Result

The waveform and the WPT results of the low E_{AE}^{n} signal in stage ii are presented in Figure 3. By comparing Figure 3(a) and 3(b), it can be seen that the waveform between time 2500 samples and 3000 samples in Figures 3(a) and 3(b) do not carry the majority of the spectral energy. So the actual signal is shifted to the right in the time domain, indicating the delay in the acquisition. The maximum amplitude is around 0.85 μV and the maximum spectral energy is distributed in two bands: 26.94% in 250 kHz – 312.5 kHz and 39.30% in 312.5 kHz – 375 kHz. The delay in the acquisition, low amplitude and the energy distributed in high-frequency band suggests that the signal is generated due to the microcracking in the specimen or the friction between the specimen and the end grips. However, the results are inconclusive without any secondary damage monitoring capability for this stage.

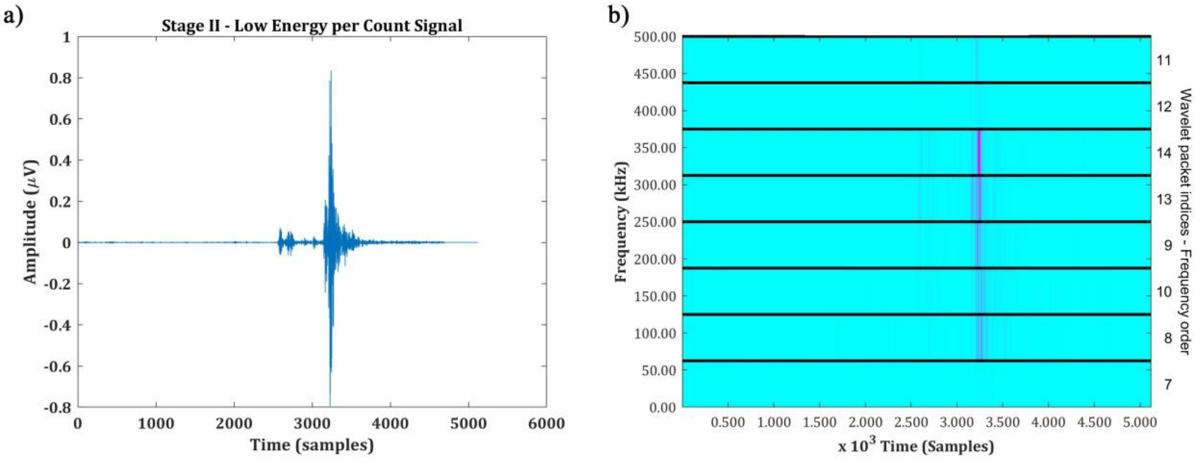

Figure 3. Low E_{AE}^{n} signal recorded at Stage ii a) Waveform Result b) WPT Result

The waveform and the WPT results of the high E_{AE}^{n} signal in stage ii are presented in Figure 4. The intensity of the signal between the time period 2500 and 3000 samples in Figure 4(b) suggests that the small decaying waveform at that time period is significant. In addition to that another similar signal with a very high amplitude of 8 μV can be observed in Figure 4(a). From Table 2, the maximum spectral energy is found to be centered around 125 kHz – 187.5 kHz with 54.46%. In this stage, the high E_{AE}^{n} signal clearly distinguishes the signal generated from damage from the spurious signal associated with the friction in low E_{AE}^{n} signal. Some shreds of evidence from other researchers can suggest that the low frequency can represent matrix cracking in FRP composites, however, the evidence are still inconclusive [6,7].

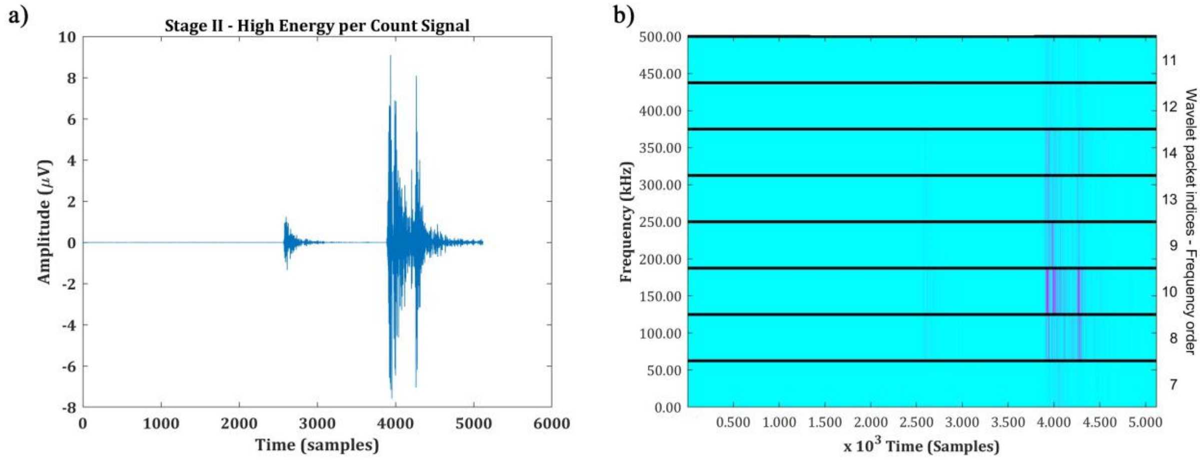

Figure 4. High E_{AE}^{n} signal recorded at Stage ii a) Waveform Result b) WPT Result

The low E_{AE}^{n} AE signal during stage iii – load drop is presented in Figure 5. It can be seen that the maximum amplitude of the signal is merely 0.07 μV and spectral energy is distributed in all frequency bands randomly (Table 2). Moreover, the spectral energy is spread out also in the time domain. This is a clear indication that this recorded signal is noise and does not represent any damage mode. It must be understood that this stage is also very short (1.17 s – 1.19 s) and very few AE signals can be found during this stage. Various signals with low E_{AE}^{n} value are analyzed and repeatedly similar waveform and frequency spread is observed. This compels the authors to come to the conclusion that the low amplitude signals in stage iii are noise.

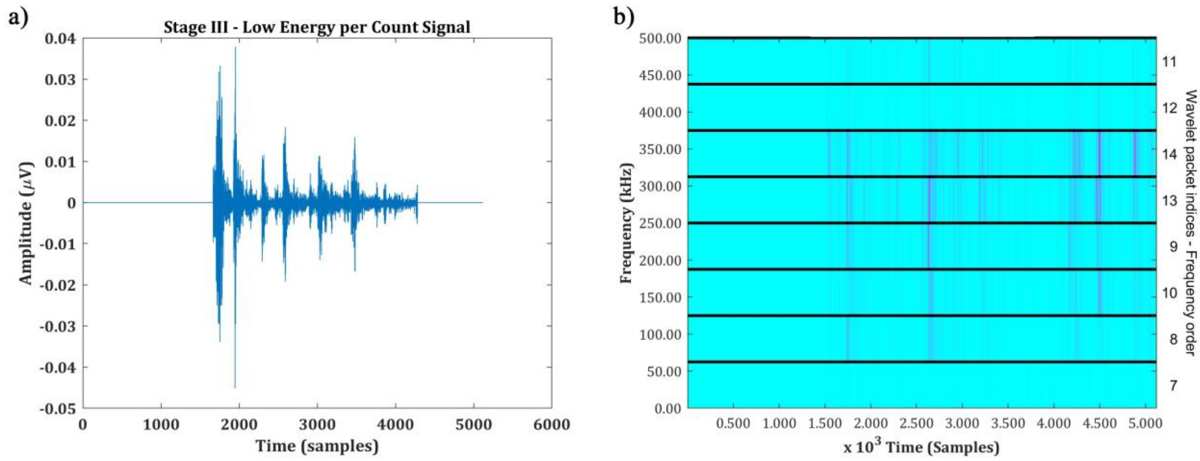

Figure 5. Low E_{AE}^{n} signal recorded at Stage iii a) Waveform Result b) WPT Result

However, the high amplitude signal in stage iii is very peculiar. The signal is very narrow with a very short signal length and is shifted to the right in the time domain (Figure 6(a) and 6(b)). Moreover, the maximum spectral energy of this signal is distributed (about 43.37%) in the high-frequency band of 312.5 kHz – 375 kHz. This represents the lower order asymmetric AE signal, which carries high-frequency signal with a short duration and travels slowly before reaching the sensor [8]. The lower order asymmetric signals are due to the interlaminar crack growth or delamination in the specimen. The load drop in Figure 1 also corroborates that significant damage occurred at this stage is the consequence of the load drop. However, the load drop is less than 0.25 kN (Figure 1). This means that the crack had initiated at one of the weakest plies but it could not propagate further. The material retains its load-bearing capability and moved to the linear elastic regime in stage iv.

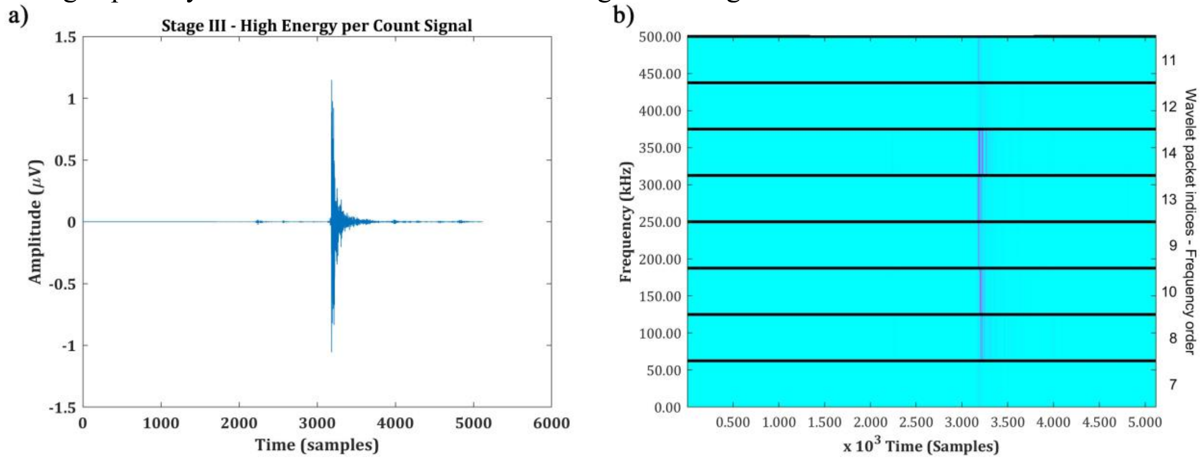

Figure 6. High E_{AE}^{n} signal recorded at Stage iii a) Waveform Result b) WPT Result

The low E_{AE}^{n} signal in stage iv – Linear plastic response is presented in Figure 7. The maximum amplitude of the signal in Figure 7(a) is very low, displaying a peak at 0.07 μV. The small decaying signals in the time domain before 2500 samples are all noise signals as they are insignificant due to their low amplitude. The spectral energy, however, is about 44.16% in the high-frequency band 312.5 kHz – 375 kHz. Once again, the signal recorded at low E_{AE}^{n} turns out to be inconclusive as this frequency band and the low amplitude cannot be directly related to any of the damage modes.

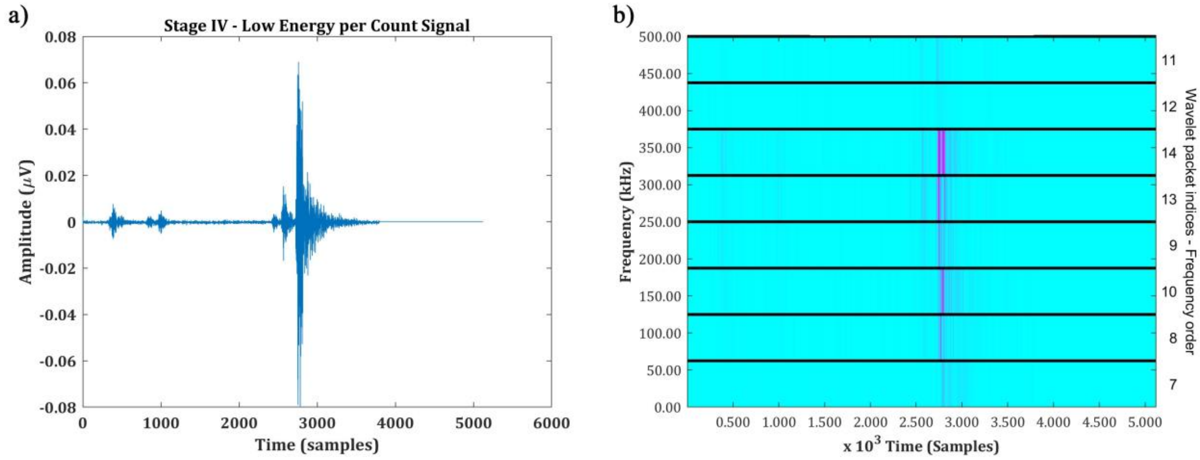

Figure 7. Low E_{AE}^{n} signal recorded at Stage iv a) Waveform Result b) WPT Result

The high amplitude signal in stage iv is very significant in the analysis. The signal is shifted to left in the time domain (Figure 8(a)) and the maximum of the energy content is distributed around 62.5 kHz – 135 kHz (Figure 8(b)). About 39.49% of energy is distributed in this frequency band (from Table 2). This represents the higher-order symmetric AE signal, which is characterized by high speed and low frequency [8]. This mostly is generated due to the consequence of matrix cracking and delamination. After the initial load drop in stage iii, the specimen started to damage through local matrix cracking and delamination, which can be characterized through this signal.

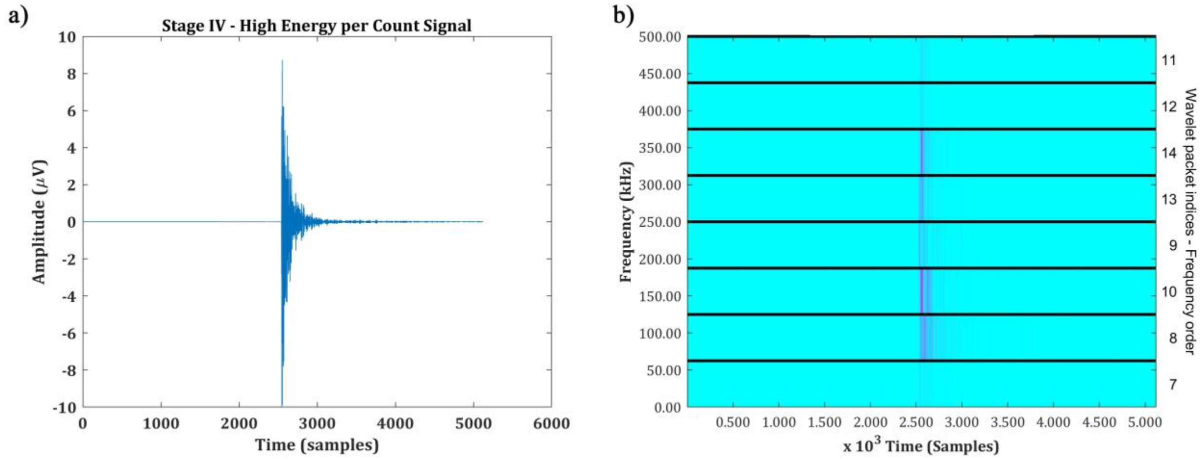

Figure 8. High E_{AE}^{n} signal recorded at Stage iv a) Waveform Result b) WPT Result

In stage v, there is a major load drop, accumulates for about 1.75 kN drop in the load before the material withheld its load-bearing capability. Only low E_{AE}^{n} signals can be found in this region and are presented in Figure 9. The amplitude of the signal in Figure 9(a) is low, with the peak only at 0.125 µV. The narrow frequency band is associated with noise and has a maximum energy of about 45.34% centered around 312.5 kHz – 375 kHz (Figure 9(b) and Table 2). This signal represents the interlaminar crack growth during this load drop. Once again, very few signals can be found at this short stage which extends only for a time period of 1.36 s – 1.38 s and the presented waveform is the representative of most of the AE signals recorded at this stage.

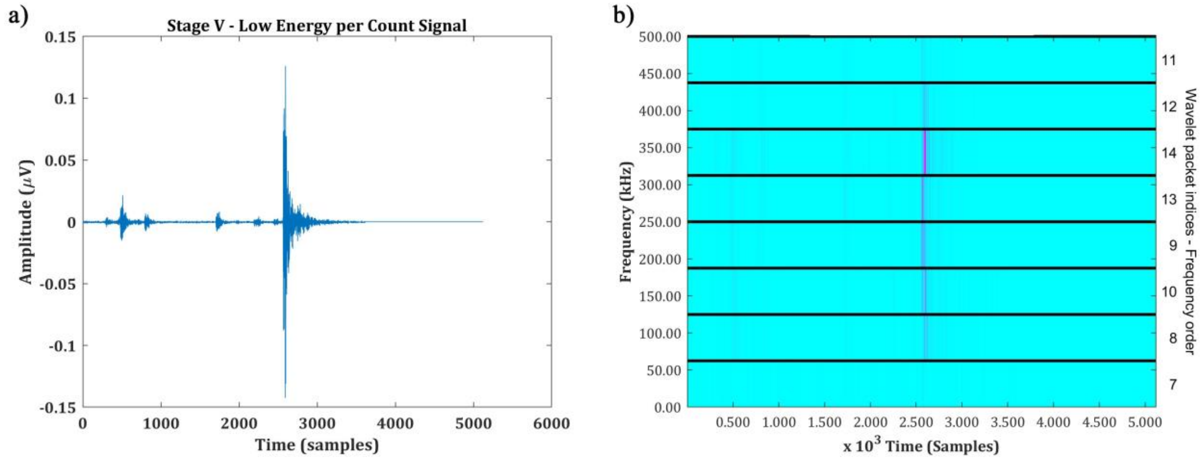

Figure 9. Low E_{AE}^{n} signal recorded at Stage v a) Waveform Result b) WPT Result

Following this stage, the material shows a nonlinear response to the loading in stage vi for a period of 0.10 s (1.38 s to 1.48 s). Some researchers have reported that in riveted joints, sometimes, there will be the yielding of the rivets under loading before the crack starts to progress. The waveforms for the low E_{AE}^{n} signal is presented in Figure 10. The signal is shifted to the left in the time domain and has a maximum amplitude of 0.225 µV in Figure 10(a). The spectral energy is distributed in all the bands except 0 – 132.5 kHz and 375 kHz – 500 kHz frequency bands (Figure 10(b) and Table 2). Once again, the low amplitude, random distribution of the frequency spectrum indicates that the signal with low E_{AE}^{n} is inconclusive. Moreover, the reverberated signals can be found in Figure 10(a) after the initial waveform.

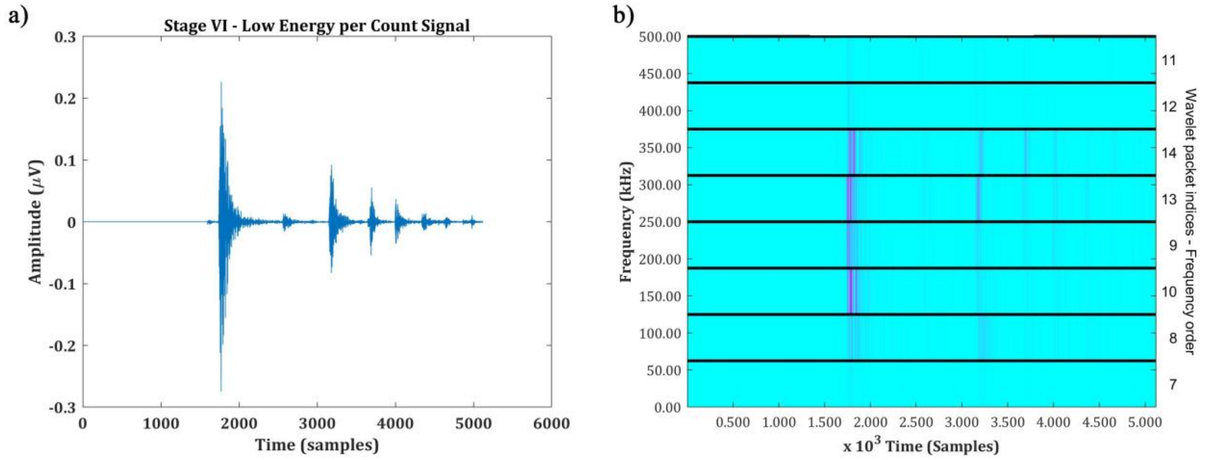

Figure 10. Low E_{AE}^{n} signal recorded at Stage vi a) Waveform Result b) WPT Result

The high E_{AE}^{n} signal in stage vi is presented in Figure 11. The signal is very short in its length and has a maximum amplitude of 10 μV (Figure 11(a)). From Figure 11(b), it can be seen that the frequency band is centered in the band 312.5 kHz – 375 kHz of about 51.84% (Table 2). The signal has high frequency and high amplitude indicating that this could possibly be the representative of the acoustic events generated by the rubbing of the rivet with the matrix and fiber bundles of the CFRP. However, conclusive evidence can be provided only by analyzing the damage mode using some other characterizing tool. Though a conclusion can be made from these results that the specimen had suffered some major damage in stage vi but owing to the presence of the rivet, it carries the load for a period of time before fracture.

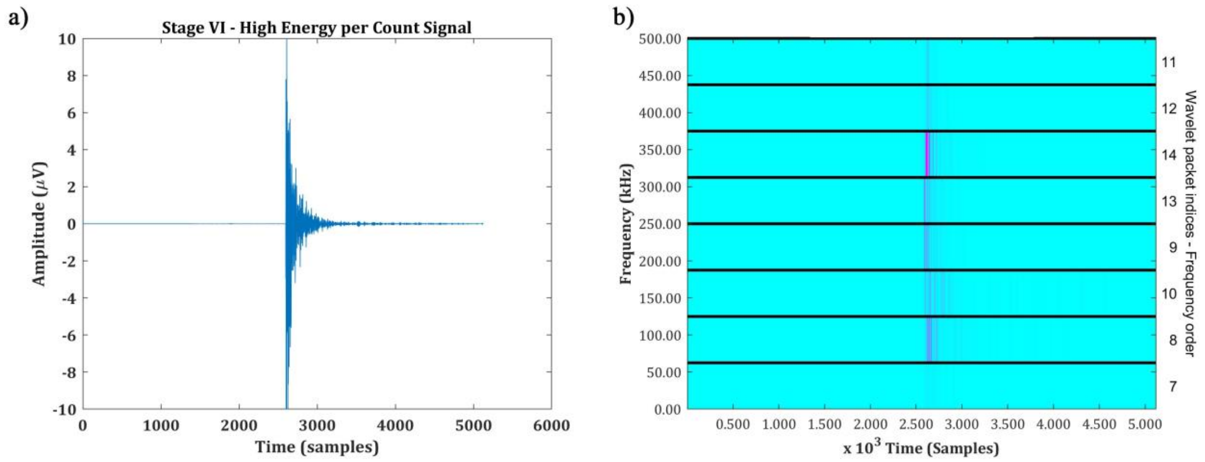

Figure 11. High E_{AE}^{n} signal recorded at Stage vi a) Waveform Result b) WPT Result

In stage vii, the material shows a linear load response before failure. Thus, the signals must be the representations of the damage accumulation before failure. The low E_{AE}^{n} signal is presented in Figure 12. The maximum amplitude is only 0.65 μV in Figure 12(a). The spectral energy in Figure 12(b) is distributed in two frequency bands: 41.90% of energy in 62.5 kHz – 135 kHz and 24.88% of energy in 125 kHz – 187.5 kHz (Table 2).

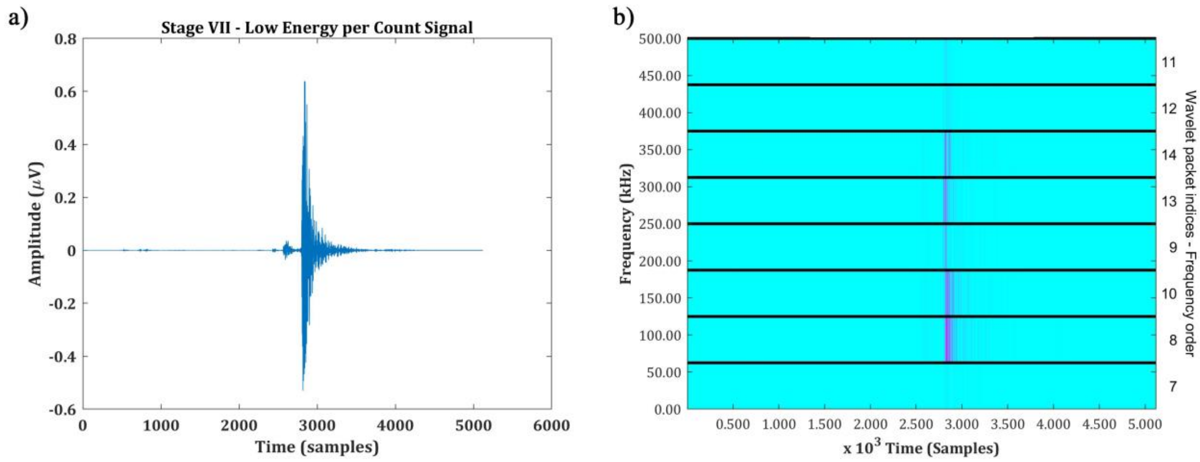

Figure 12. Low E_{AE}^{n} signal recorded at Stage vii a) Waveform Result b) WPT Result

Similarly, the high E_{AE}^{n} signal from stage vii shows two amplitude peaks in Figure 13(a) with one at 9.5 µV and another at 7.5 µV. In Figure 13(b), the maximum frequency band is also distributed in two frequency bands: 38.33% in 312.5 kHz – 375 kHz and 21.25% in 250 kHz – 312.5 kHz. Both these signals have one similarity that they have multiple load peaks in the amplitude of the waveform and the energy is distributed in two different frequency spectrums, although the frequency bands are different. The damage mode cannot be conclusively identified, however, a definite difference can be drawn between the linear responses in stage ii, stage iv and stage vii. The damage mode certainly did not generate lower-order asymmetric AE signal, which means that the damage mode is not matrix cracking [8]. The material responded to several accumulated damage modes in stage vii before failure.

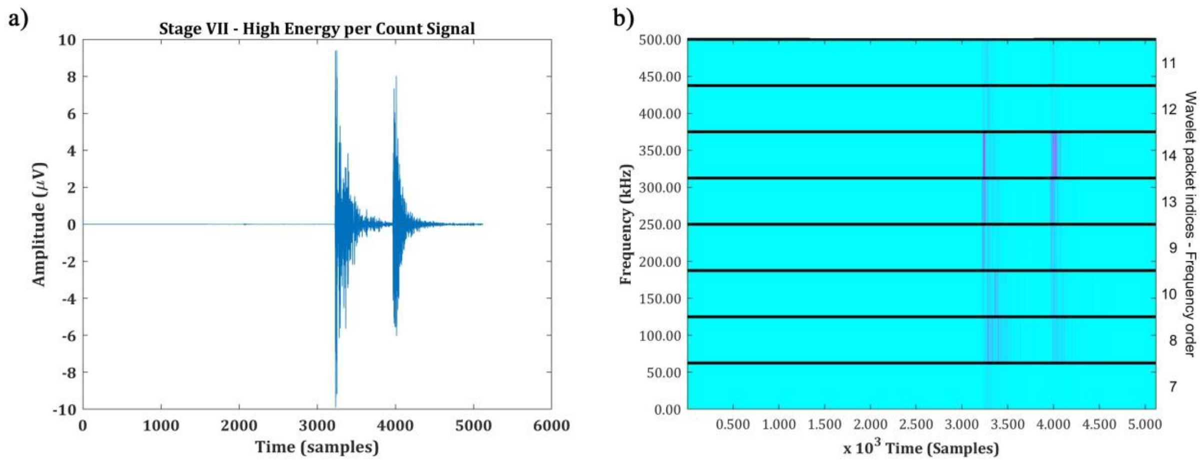

Figure 13. High E_{AE}^{n} signal recorded at Stage vii a) Waveform Result b) WPT Result

During the final fracture stage at stage viii, only low amplitude signals can be found. The waveforms and the WPT results of the signal recorded from this stage are presented in Figure 14(a) and 14(b), respectively. During the fracture, two amplitude peaks can be observed in the two time domains and most of the spectral energy is distributed in the high-frequency band 250 kHz – 375 kHz. The signal observed from this load drop is entirely different from the signal observed from the load drops in stage iii and stage v.

The following conclusions can be drawn from the observed results of all the waveforms and WPT results from different stages. The signals with low E_{AE}^{n} always turn out to have inconclusive results. During a loading, a large number of AE signals are generated, each carrying their own distinct waveform. It is difficult to analyze all the waveforms in the time-frequency domain using WPT, due to the large time consumption and excessive data storage. Only a few signals can be chosen and they can act the representative of that stage during loading. In that regard, the E_{AE}^{n} serves the purpose that the signals selected from $E_{AE}^{n} > 1$ always draw definite conclusions about the damage mode. This value is relative in the sense that it can vary from tests to tests. Nonetheless, signals with a considerably high value of E_{AE}^{n} must be taken for the analysis. Through that, the damage modes can be assessed through the waveforms and wavelet transforms. More concrete evidence to support the damage modes characterized by the signal-based results using other characterizing tools can be of added advantage.

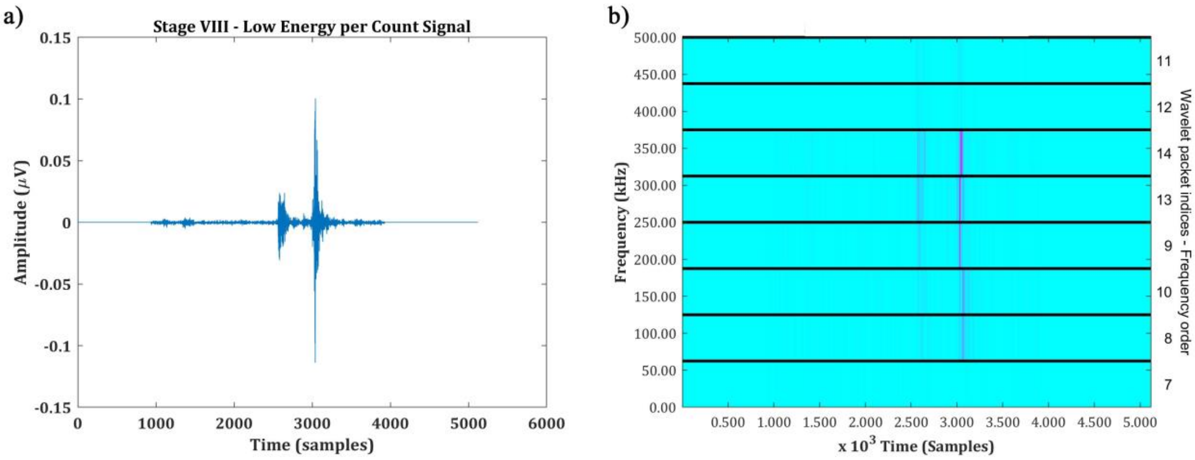

Figure 14. Low E_{AE}^{n} signal recorded at Stage viii a) Waveform Result b) WPT Result

4. Conclusion

The acoustic emission signal-based and parameter-based data are utilized for the characterization of the CFRP Hybrid Joint specimen. A new parameter-based data named as Energy per Count is used as a selection criterion of the signal-based waveforms to be analyzed. The waveforms are analyzed using wavelet packet transform (WPT), which decomposes the signal into different levels and measures the energy associated with different frequency bands. The results conclude that the signals selected from the AE events with low E_{AE}^{n} values are mostly inconclusive and the signals with high E_{AE}^{n} values can categorize the damage modes. This selection criterion will be more useful in analyzing a large set of data by allowing the user to select a representative signal for the entire loading or damage processing region.

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