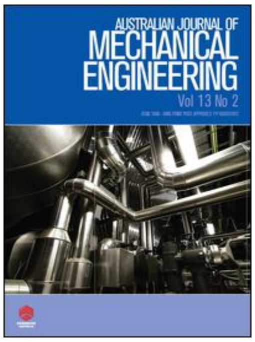

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Acoustic emission analysis for characterisation of damage mechanisms in glass fiber reinforced polyester composite

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ABSTRACT
This study assesses the progression of damage occurring on glass fiber reinforced polyester composite specimens using acoustic emission (AE) parameters. Its aims are to improve understanding of the particular characteristics of AE signals; and also to determine the relationship between AE signals and the failure of the material. Time and frequency domain trends were analysed at four different applied loads (60.97, 67.75, 74.52 and 81.30 MPa) representing 45–60% of the ultimate tensile strength of material. The relevant AE parameters were analysed both in the early stages of the test and as the material neared the fracture zone. The results showed a high degree of correlation between the root mean square and number of hits AE values and the number of cycles to failure, of 92.99 and 92.19%, respectively. This correlation, as well as AE basic parameters, suggests that AE can be a valuable tool to predict the fatigue life and detect the onset of damage in such composite materials.

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KEYWORDS
Acoustic emission; glass fiber reinforced composite; fatigue; failure mode

1. Introduction

The use of acoustic emission (AE) is a relatively new technique in the Non-Destructive Evaluation (NDE) industry. It was introduced to address the limitations of previous NDE technologies and cut the costs of evaluation. The first attempts to evaluate AE's suitability for use in engineering applications were made by researchers from Japan, Europe and the USA in the late 1970s and early 1980s (Barber 2006).

AE can be defined as the energy emitted as a result of changes in the microstructure of a material, which then generates stress waves with transient elasticity (Gholizadeh, Leman, and Baharudin 2015; Mouritz 2003; Wevers 1997). The energy source usually originates within the material's elastic stress field, and is generally caused by mechanical, chemical, pressure or thermal stress on the material in question. These stresses can often lead to fatigue failure in the material – a common phenomenon in many operations or structures. Fatigue failure in composites is a particularly complex phenomenon, as it generally arises from the cumulative effect and interaction of different types of damage, cause dependent on. Three main failure modes – namely matrix cracking, interface debonding and fiber failure – can all play major roles, often in a sequential order, at different stages of damage development. Analysing the AE data obtained from fatigue tests on such composite materials therefore requires considerable attention to detail, and often involves a significant number of material and test parameters as well as consideration of both the nature and quantity of the data. Most studies investigating damage mechanisms in composite materials have used pattern recognition as a multivariable technique for AE event classification (Bar, Bhat, and Murthy 2004; Bhat, Bhat and Murthy 2003; Godin et al. 2004; Huguet et al. 2002; Philippidis, Nikolaidis, and Anastassopoulos 1998; Philippidis, Nikolaidis, and Kolaxis, 1999). Bar, Bhat, and Murthy (2004) conducted research using the AE technique to analyse the mechanisms by which damage arose in multi-layered glass fiber reinforced plastic. The AE signals were captured through a polyvinylidene fluoride film sensor as of composite laminates of three dissimilar sets stacking sequences during monotonically increasing tensile load. Bhat, Bhat and Murthy (2003) meanwhile used artificial neural networks to identify noise suppression in AE data, with the long-term objective of in-flight monitoring on airplanes. In contrast, very few writers have studied damage modes in the usage of AE distributions in glass fiber reinforced composite. Huguet et al. (2002) conducted research on AE signal parameters used to identify a range of real-time damage in the stress applied to glass fiber reinforced polymer composite. Gostautas et al. (2005) studied the structural performance of glass fiber reinforced composite bridge decks in order to determine the nature of the damage when specimens were subjected to static loading (three point bending). The authors also compared the performance of repaired structures with original ones. All

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these authors used the Felicity Ratio to check the Kaiser effect and the Felicity effect, as well as intensity analysis.

The use of AE waveform multiparameters should lead to improve identification of damage modes in composite materials, and hence be a valuable tool for detecting the onset of damage in such materials. In line with this, this study used basic AE parameters to investigate damage modes in glass fiber reinforced polyester composite at different test times, from initiation to the point of near fracture, in order to determine the relationship between AE signal parameters and fatigue cracks.

2. Experimental

Woven reinforced glass fibers were cut into 30 × 30 cm sizes to make glass fiber reinforced composites consisting of 40 wt% (40 per cent by weight) glass fiber, 60 wt% matrix (GP 268 BQT-W) and 2 wt% hardener. Specimens were then cut from a six-layered unidirectional glass fiber reinforced polyester plate for testing in the laboratory, to evaluate the properties of the materials under different loading conditions. A total of 19 specimens, each 5 mm thick, 250 mm length, and 25 mm wide (Figure 1), were cut according to ASTM D3039. Three samples were subjected to a tensile test before carrying out the cyclic fatigue test, in accordance with ASTM D3479.

2.1. Tensile testing techniques

The goal of the prior tensile tests in this study was to determine the ultimate tensile strength (UTS) of the materials. The three specimens were tested on a universal machine testing system type INSTRON 3382, with a 100 kN capacity. An average UTS of 135.5 MPa was obtained from the tensile test, and this UTS was used as the basis for subsequent experiments.

2.2. Fatigue testing with AE sensor attachment

The specimens were installed into the test rig under a one-point test set-up (AE sensor), as shown in Figure 2. They were loaded using a 100 kN hydraulic MTS test machine. The load was applied in a sinusoidal waveform. An AE sensor was attached on the centre of the surface of each specimen, as the position shown in Figure 3.

The MTS 647 Hydraulic Wedge Grip testing machine with a maximum load of 100 kN and maximum pressure of 21 MPa or 3000 psi were used to apply the load to the specimens until the specimens separated. A set of 16 specimens were loaded under tension-tension cyclic loading, at a frequency of 8 Hz with 45–60% of UTS, a maximum load of 10.07 kN and minimum load of 7.33 kN, and at a stress ratio of $R = 0.1$ with 3.5 MPa of pressure. Load data from the testing machine was fed to the parametric channel of the AE data acquisition system. This load data

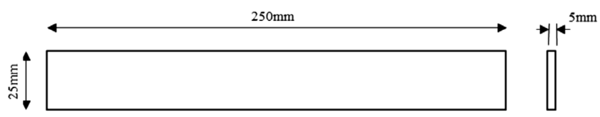

Figure 1. Specimen geometry.

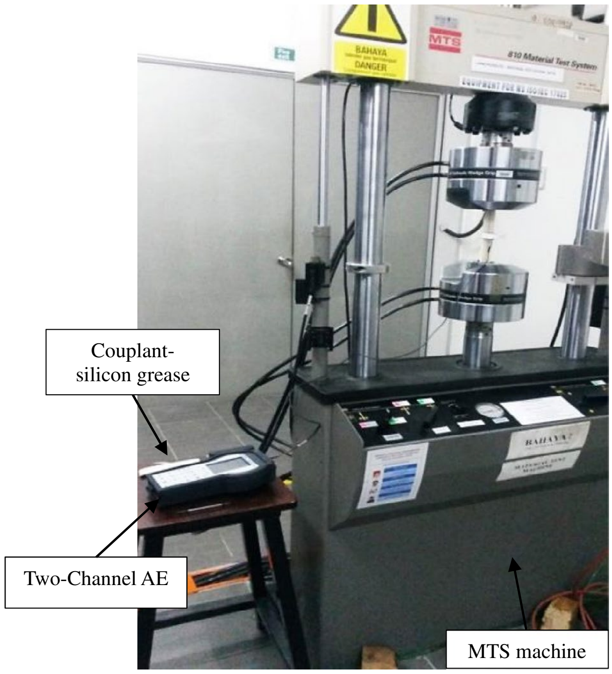

Figure 2. MTS machine and AE equipment.

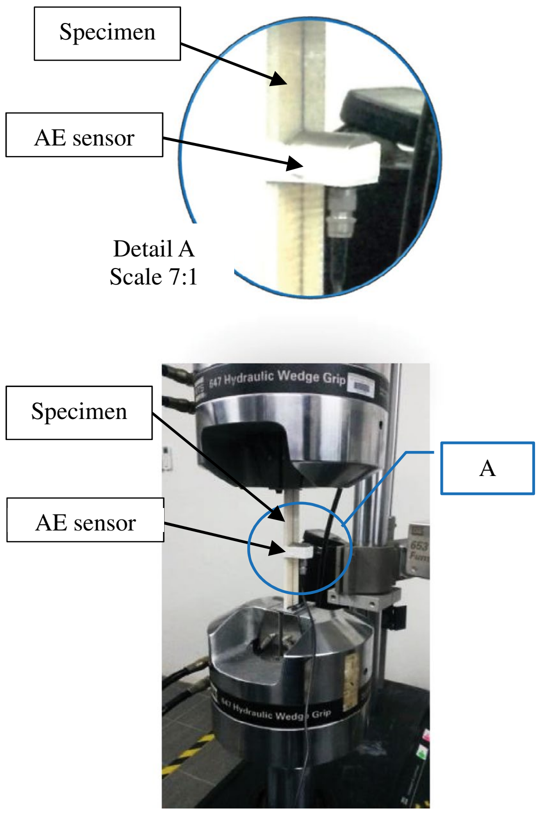

Figure 3. AE sensor position.

Table 1. AE control parameters.

Parameters	Set value
Peak definition time (PDT)	50 µs
Hit definition time (HDT)	150 µs
Hit lockout time (HLT)	300 µs
Sample rate	5 M sample/s

were recorded simultaneously with the transient AE signals detected during the test. Both sets of data were then used to characterise the AE source mechanism by correlating the AE parameters with the load values.

2.3. Acoustic emission

A MISTRAS AE system from the Physical Acoustic Corporation Two-Channel was used to acquire the AE signals released by fatigue crack growth during the tests. One wideband (WSa) AE transducer with a frequency range of 100–1000 kHz was used to detect the AE signals from the fatigue test at the centre of the specimen. This sensor was attached to the specimens and connected to the AE data acquisition system through a coaxial cable. A 40 dB threshold level for AE data acquisition was set to avoid interference from any background environmental noise below this level. The detected events were amplified by a 26 dB pre-amplifier and a 40 dB amplifier. All the recorded signals were stored on the computer for further analysis. AE WinTM software for data acquisition and signal processing was used throughout this study to capture, replay and display stored AE data. To ensure proper AE monitoring, certain parameters of the data acquisition systems need to be adjusted to the specific testing materials and existing noise levels: in particular, Peak Definition Time, Hit Definition Time and Hit Lockout Time. The specific values used for these timing parameters of the signal acquisition process are shown in Table 1.

3. Results and discussion

3.1. Time domain trend

The number of incoming signals is the most basic parameter of AE monitoring, and is a commonly used criterion to assess structural integrity in many types of standardised monitoring. Usually, some AE parameters such as hits, amplitude and root mean square (RMS) increase along with the load increment, because crack propagation increases as the load increases (Loutas and Kostopoulos 2009; Paipetis and Aggelis 2012). In this case, the AE signal patterns were measured in the early stages of testing and as the fracture zone approached, at applied stress levels of 45, 50, 55 and 60% of UTS with a loading of 60.97, 67.75, 74.52 and 81.30 MPa, respectively. The results of these various measurements are shown in Figures 4–8, and are explained in more detail below.

Based on studies the range of 40–55 dB of amplitude is associated to matrix cracking, 55–60 dB is AE indication of interface failure, 60–65 dB related to fiber debonding, 65–85 dB is linked to fiber pull-out and 85–100 dB is related to fiber fracture cracks (Barre and Benzeggagh 1994; Huguet et al. 2002; Kotsikos et al. 2000; Ségard et al. 2003). According to Barre and Benzeggagh (1994) and Huguet et al. (2002), high level of number of hits (AE events) in the range of amplitude between 40 and 55 dB is associated with matrix cracking. It was discovered that the number of hits versus amplitude shows the damage contributed in materials. Figure 4 shows average of AE parameter based on material behaviour at this level. It is apparent that higher level of number of hits (more number of hits) occurred between 40 and 50 dB of amplitude that is related to matrix cracking. Along with this growing matrix cracking, some hits begin to be distinguished between 55 and 65 dB associated with interface failure as well as fiber debonding.

Figure 5 displays the AE signal patterns measured at 45% of UTS with a loading of 54.2 MPa, both in the initial stages of testing and near the fracture zone. Before the main crack occurred, some micro-cracks appeared in the matrix resin and there were also signs of fiber debonding between 40 and 60 dB of amplitude. The composite also showed increased delamination between 50 and 70 dB (Ono 1988). Some larger cracks appeared between 60 and 80 dB, due to fiber pull-out (Barre and Benzeggagh 1994; Kotsikos et al. 2000). In terms of crack propagation, the number of hits and RMS fluctuated between 40 and 80 hits/s and 0 to 0.1V, respectively, reaching around 80 hits/s at the time of delamination. Once the specimens started to divide into two main pieces, the RMS increased to more than 0.15 V, and continued roughly at this level until the fiber broke – at which point the RMS value presumably increased well beyond this level, since it relates to the vibration signal energy in a time series, which could be expected to increase sharply upon breakage.

Number of hits vs. amplitude which is contributed to damage of the composite is shown in Figure 6, at 50% of UTS. It is apparent that higher level of number of hits (more number of hits) occurred between 40 and 55 dB of amplitude that is related to matrix cracking and some hits occurred between 55 and 65 dB associated with interfacial failure as well as fiber debonding. Since the number of hits increased as the loading was increased, at this level the number of hits reached to around 8000 that was more than previous level.

Figure 7 shows the AE distributions illustrating the amplitude, number of hits and RMS at 50% of UTS, with a loading of 67.75 MPa. Both the amplitude and crack propagation were much higher than at the previous level of applied stress, because of the increase in loading. In the early stages of testing, in addition to matrix cracking and fiber debonding, the specimens also experienced

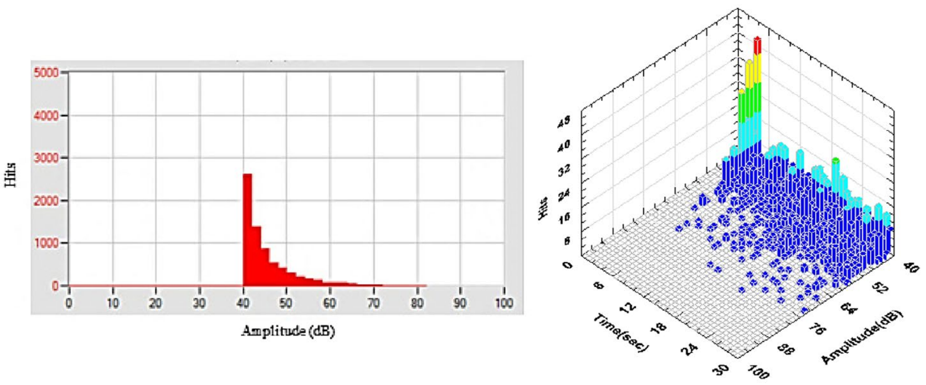

Figure 4. Number of hits vs. amplitude at 45% of UTS.

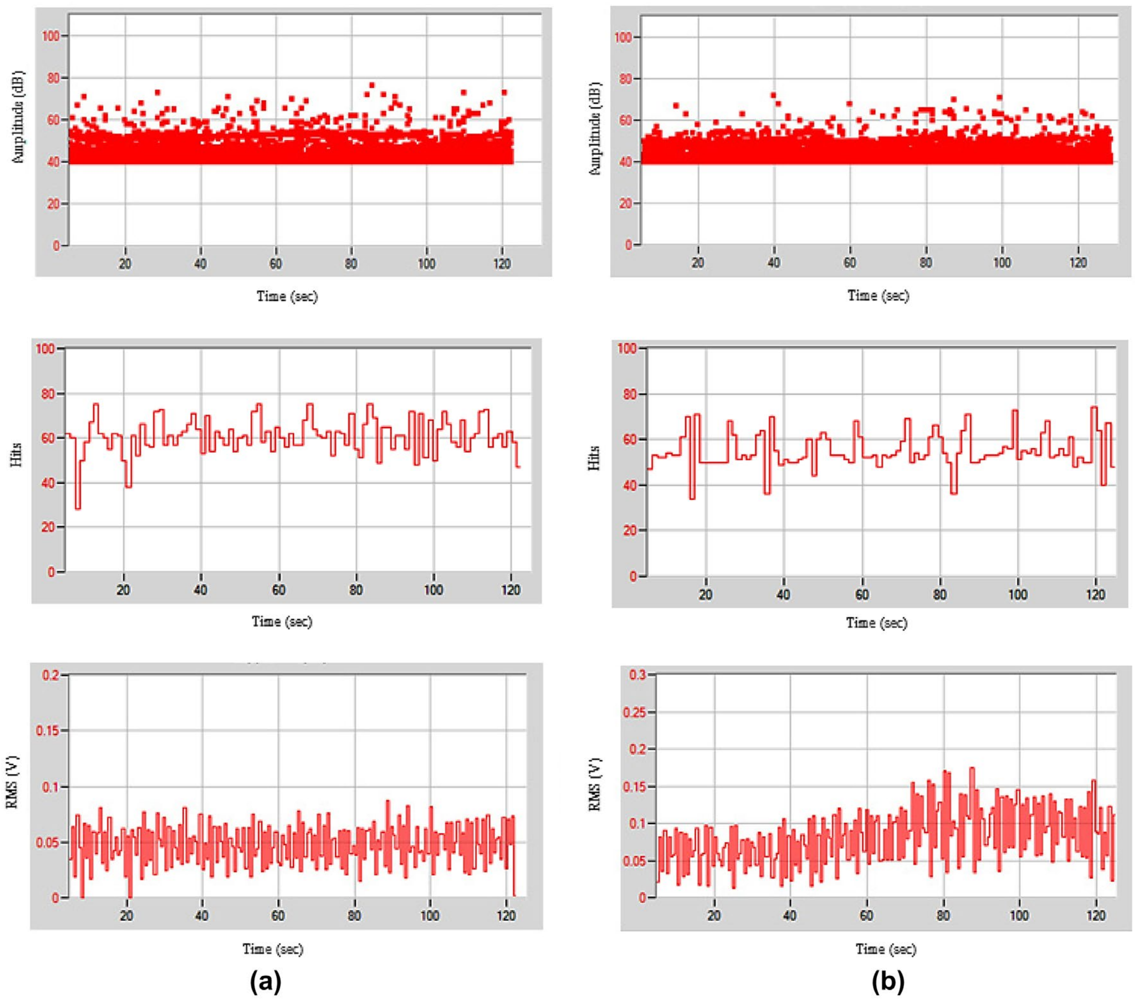

Figure 5. Amplitude, number of hits and RMS at 45% of applied stress level (a) early stage of testing, (b) near fracture zone.

fiber pull-out at amplitude of 90 dB, 70 hits/s and around 2.5 V RMS. At this point, a scattering of micro-cracks became obvious. When the main crack occurred, a high rate of incoming AE signals were recorded (up to 200 hits and 2.5 V RMS); the cracking events were much more extreme and frequent; and visible cracks ruptured the brittle matrix, leading to several side cracks. Furthermore, when the specimens split causing fiber pull-out, both the RMS and number of hits went up substantially. Towards the end, the matrix continued to rupture slowly and fiber pull-out also continued until the point of fiber breakage, at 100 dB amplitude and around 4 V RMS.

Figure 8 shows the number of hits which was lower than the previous levels; however matrix cracking occurred between 40 and 50 dB of amplitude and thereafter, fiber debonding and crack growth were observed. At 100 dB of amplitude fiber breakage was recorded.

Figure 9 shows the AE signal patterns at 55% of UTS (74.52 MPa), again measured both in the early stages of testing and near the fracture zone. Based on the behaviour of the material at the previous levels, it was expected that the specimens would break faster. Therefore, recordings were made every 30 s to track the behaviour of the material. In the event, because of the shorter recording time, the fact that AE activity is related to fracture events and crack behaviour (every hit represents the acoustic activity that occurs in the material during the crack mechanism process), and finally because higher loads lead to shorter failure times, the acoustic activity experienced in the specimens was not as strong as at lower loads (Mohammad et al. 2014). Thus, the AE parameters, both in the early stages and towards the fracture zone, came out lower than at the previous levels. However, when the point of delamination and fiber breakage was reached, high levels of RMS became visible.

As mentioned in previous level with regard to the cracks zone, at 60% of UTS, after a common matrix cracking between 40 and 50 dB, many interface fractures

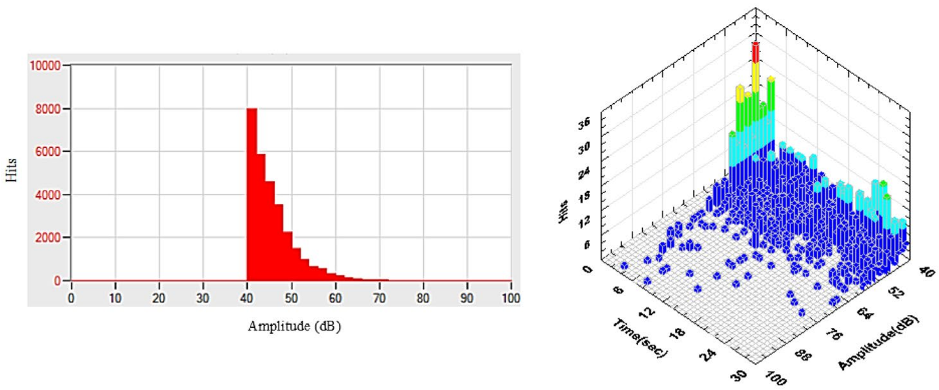

Figure 6. Number of hits vs. amplitude at 50% of UTS.

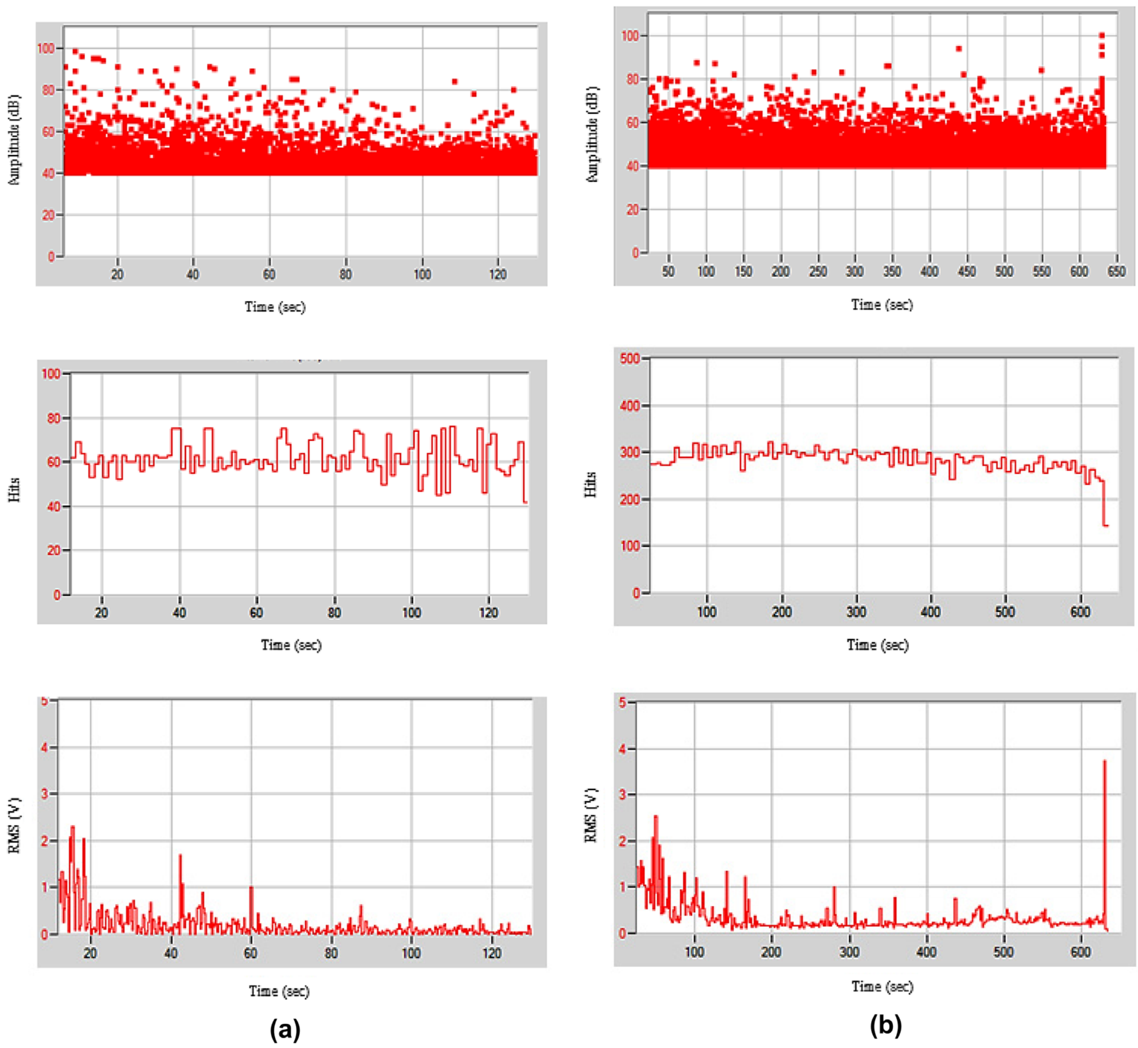

Figure 7. Amplitude, number of hits and RMS at 50% of applied stress level (a) early stage of testing, (b) near fracture zone.

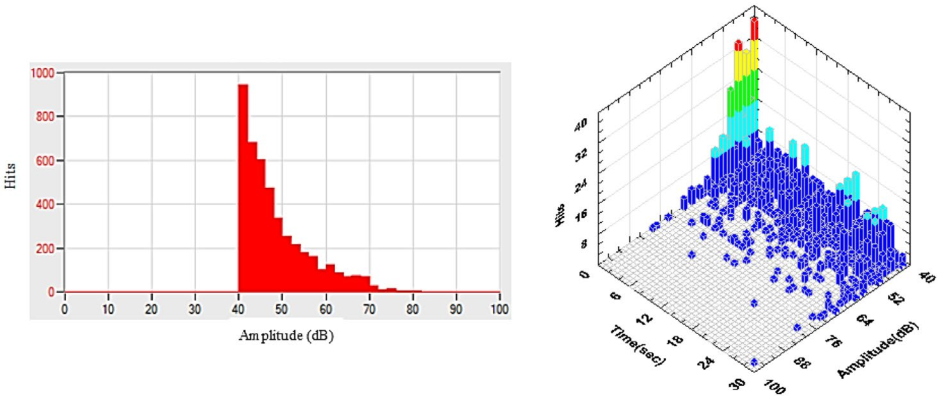

Figure 8. Number of hits vs. amplitude at 55% of UTS.

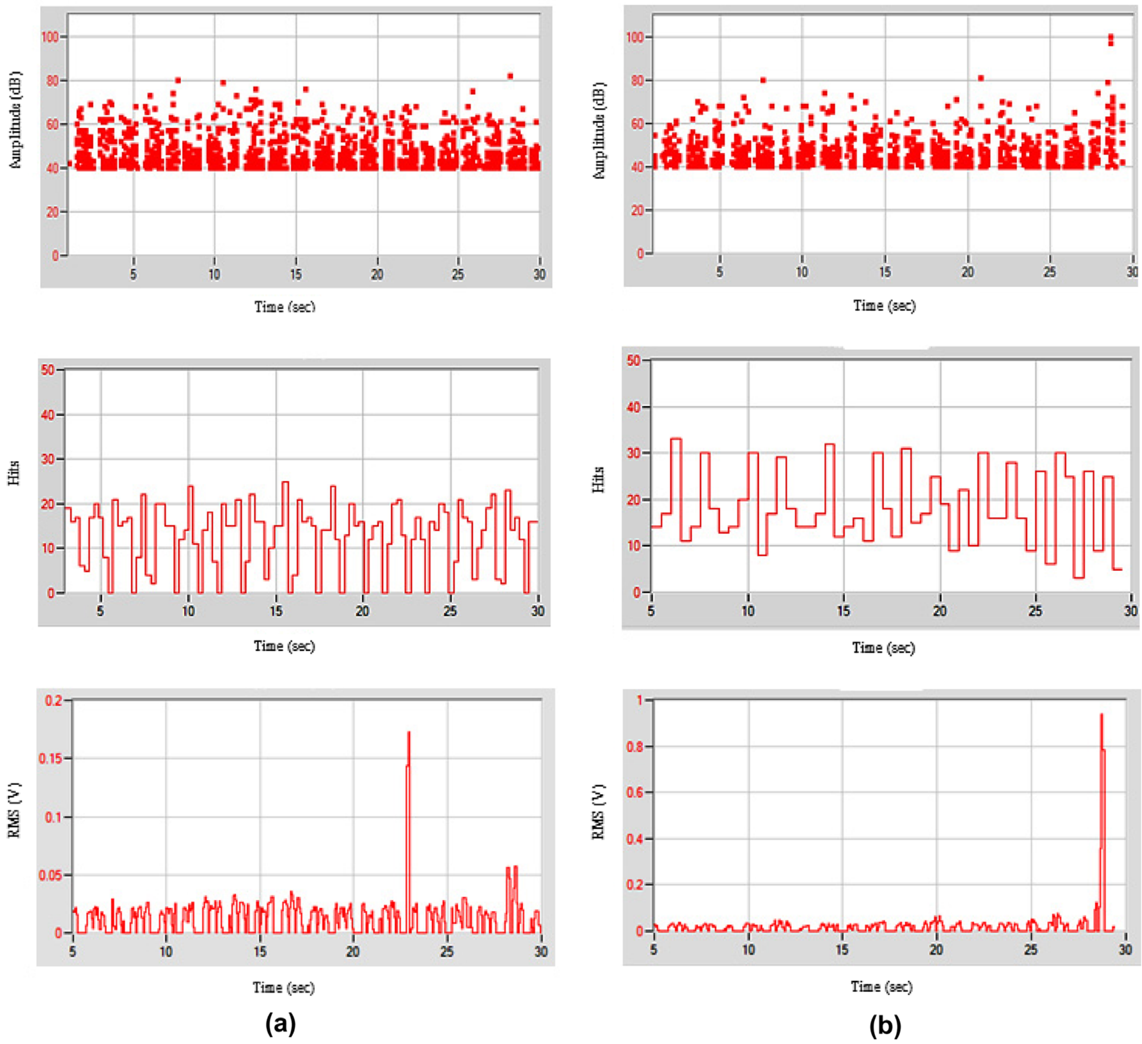

Figure 9. Amplitude, number of hits and RMS at 55% of applied stress level (a) early stage of testing, (b) near fracture zone.

occurred which were immediately followed by fiber pull-out. With this growing matrix cracking, some high-amplitude events began to be distinguished between 55 and 65 dB (Figure 10).

The final level of testing, at 60% of UTS and 81.30 MPa of stress, is shown in Figure 11. At this level, it was anticipated that the specimens would break even more quickly. Therefore, all the test times were recorded from the start until breakage. Although the AE parameters rose compared to the previous level, they were still lower than at the earlier (lower) levels of applied stress. Much more extensive amplitude became clear at this level compared with the others. This is logical because, as the load increases, not only is there much more extensive matrix cracking but also many more delaminations occur than at the previous loading steps. Micro-cracking

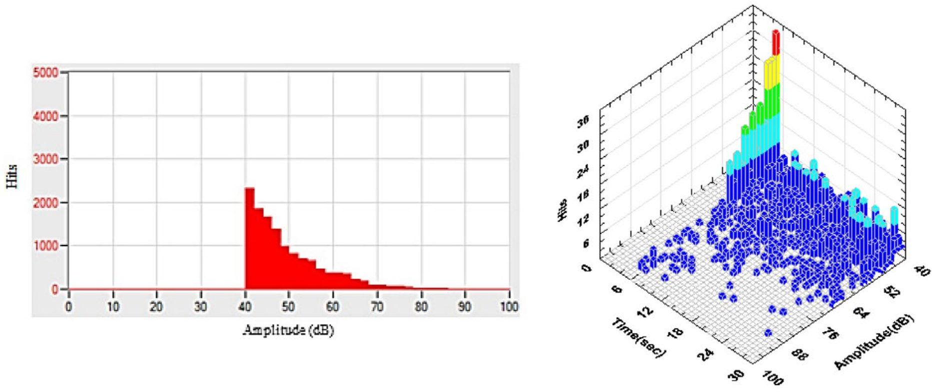

Figure 10. Number of hits vs. amplitude at 60% of UTS.

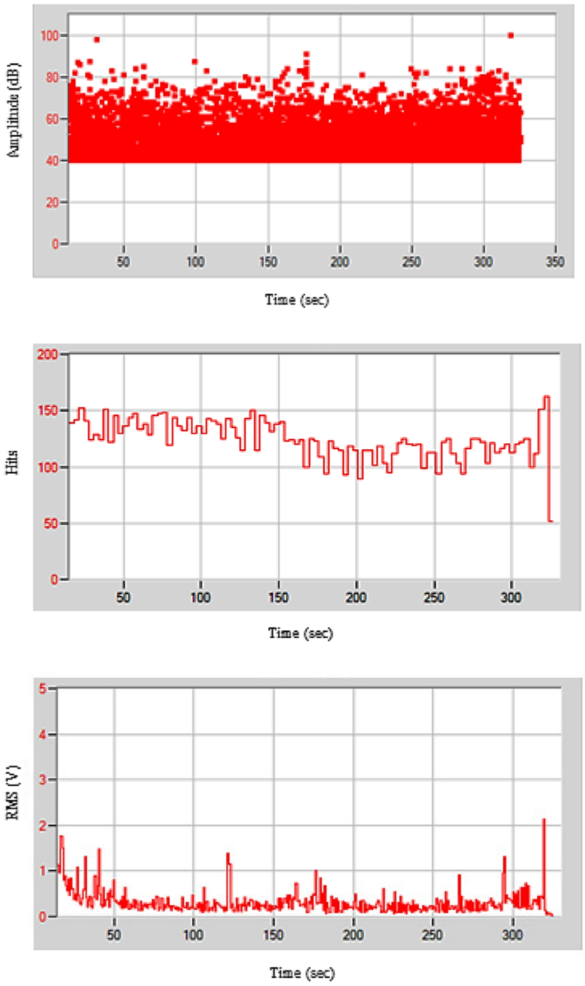

Figure 11. Amplitude, number of hits and RMS at 60% of applied stress level.

developed initially, after the strength limits of the material were reached, followed by a macroscopic crack and then suddenly a large amount of cracking and a high level of RMS was therefore recorded (Figure 11). As the loading continued, the crack propagation spread to the top, rupturing of the rest of the material, while fiber pull-out gradually occurred. At this stage, the AE hit rate was generally lower than at previous stages and was falling, mainly because the number of fibers left to be pulled out was also continuously decreasing. At the point of fiber breakage, all the parameters increased dramatically.

3.2. Frequency domain

Studies of glass fiber polyester composite systems have shown that fiber breakages tend to generate extensional wave signals within the frequency range of 420–520 kHz, while matrix cracks provide flexural wave signals in frequency ranges from 30 to 150 kHz, and fiber debonding at frequencies of less than 350 kHz (Bohse 2000; Huguet et al. 2002; Ramirez-Jimenez et al. 2004). Figure 6 displays the frequency signature for different breakages at the fracture zone for different levels of applied stress, along with further details of different damage signatures. It is clear from Figure 12, at 60.97 and 67.75 MPa applied stresses, the frequency showed same crack from 30 to 350 kHz. At the last two levels of stress, fiber breakage occurred at the 500 kHz frequency at a high level of power. In fact, the patterns of cracking at different levels of applied stress in the frequency domain waveform were very similar to those described earlier for the time domain waveform.

Figure 10 shows that, on average under different loadings, 95% of total AE hits were recorded between the amplitude bands of 40 and 60 dB. Based on previous studies (Godin et al. 2004; Huguet et al. 2002), fiber breakage is generally the primary damage mechanism. This predominance of AE hits occurring at an amplitude response of less than 60 dB possibly correlates with fiber breakage. According to the tests on this material across the whole range of different levels of applied stress, most fiber breakage occurred at between 85 dB and 100 dB – a level of amplitude which differs from those produced by previous AE studies. Earlier studies have reported various ranges of amplitude for carbon and glass fiber breakage, such as 60–75 dB (Bohse 2000), and 95–100 dB (Siron and Tsuda 2000).

Table 2 shows the number of RMS at different stress level from 45 to 60% of UTS. It is evident that with continuous loading RMS continued increasingly,

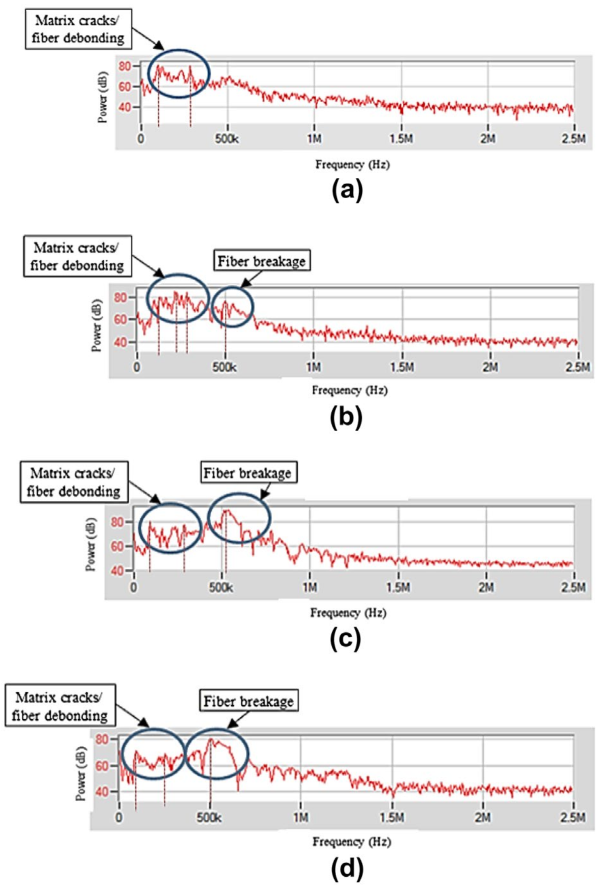

Figure 12. Power spectrum analysis of glass fiber polyester composite at different applied stress (a) 60.97 MPa, (b) 67.75 MPa, (c) 74.52 MPa and (d) 81.3 MPa.

Table 2. Number of RMS (v) at different stress level.

Stress level (% of UTS)		Minimum	Maximum	Average
45%	Early time of testing	0.0014	0.0036	0.0017
	Near fracture zone	0.0022	0.0042	0.0031
50%	Early time of testing	0.0019	0.0045	0.0030
	Near fracture zone	0.0018	0.0766	0.0062
55%	Early time of testing	0.0024	0.0042	0.0032
	Near fracture zone	0.0054	0.0114	0.0084
60%	Overall	0.0024	0.052	0.0124

starting with maximum number of 0.0036–0.000.52 v that occurred near fracture zone.

The linear correlation between the RMS of the AE and the number of cycles until failure, as well as the number of AE hits and applied stress, are shown is Figures 13 and 14 respectively. The number of cycles increased as the RMS value decreased, and the number of hits increased when the applied stress increased. The correlation coefficients $R^2 = 92.99\%$ and $R^2 = 92.19\%$ indicate that there is a good correlation to predict specimen life.

The use of AE technique for detecting and monitoring damages and the progress on damages in different structures is widely used and has earned a reputation

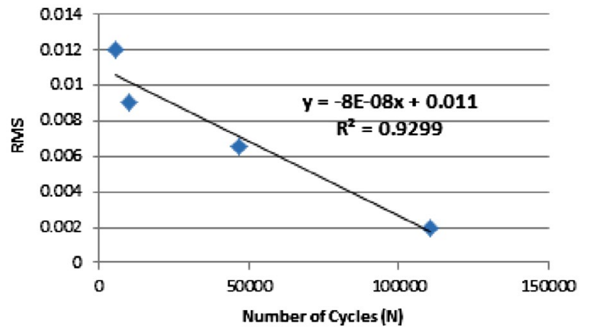

Figure 13. Correlation between RMS of AE and number of cycles to failure.

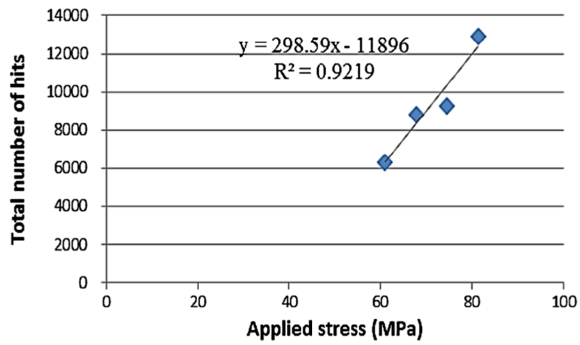

Figure 14. Correlation between total number of AE hits and applied stress.

Table 3. Comparison of AE characteristics with other methods (Kaphle 2012).

Acoustic emission	Other methods
Detects movement of defects	Detect geometric form of defects
Requires stress	Do not require stress
Each loading is unique	Inspection is directly repeatable
More material sensitive	Less material sensitive
Less geometry sensitive	More geometry sensitive
Less intrusive on plant/process	More intrusive on plant / process
Requires access only at sensors	Require access to whole area of inspection
Main problem is noise related	Main problem is geometry related

as one of the most reliable and well-established techniques in non-destructive testing (NDT). This technique has been used in many industries as a structural health monitoring technique for an early warning detection of structural damage associated with cracks, impacts, fracture, and delaminations in advanced materials. Table 3 shows a comparison between AE characteristics and other methods.

AE technique employs single or multiple sensors in listening to the large variety of activities that are likely to occur within a solid material. It can be applied in three different application domains based on the high frequency sound source (Awerbuch et al. 2016; Mohammed et al. 2013; Nicolas, Sullivan, and Richards 2016). The condition monitoring and life prediction of aircraft main structures have received great concern because it has significance in maintaining high flight safety. The early detection of fatigue crack initiation and growth is in general beyond the capability of various conventional NDT means. AE however, is more suitable to undertake the task. The application of AE took centre stage after it was employed in developing reinforced glass–fiber composite rocket motorcases that were used in 1962 for Polaris A3. It was also used to test Apollo lunar module propellant tanks and various aerospace applications (Gholizadeh, Leman, and Baharudin 2015). Several recent studies on AE in aircraft manufacturing can also be found in (Awerbuch et al. 2016; Mendoza et al. 2013, 2014; Ullmann et al. 2010).

According to AE characteristics in this study the following conclusions were reached:

- AE can be a tool for fatigue crack monitoring in composite materials for detecting the onset of damage as AE signals can be recorded from initial cracks and also crack propagation at different time of service which can be obtained according to AE data.
- AE basic parameter can be useful tools for finding damage assessment at real time and by actual AE data.
- According to the results, the fatigue crack growth was located at different applied stress levels using actual AE data since AE signals record the material behaviour under different loading.

4. Conclusion

This study looked at the capability of the AE technique to assess the onset of damage in glass fiber reinforced polyester composite material. Three common AE parameters, namely amplitude, number of hits and RMS, were analysed to determine the behavior of fatigue cracks in the course of a cyclic fatigue test. The number of hits indicated that the level of acoustic activity in the material during the crack mechanism process was directly related to the level of stress being applied. Moreover, 95% of the total AE hits took place within the amplitude bands of 40–60 dB. According to the results, most fiber breakage occurred at between 85 and 100 dB. Higher power percentage values were observed for both fiber breakage and matrix cracks in the extensional and flexural frequency bands. There was a satisfactory level of agreement between the different power spectrum results for fiber breakage and matrix cracks in the material. This suggests that the power spectrum method, which analyses the whole waveform, is a reliable way of identifying different types of damage in composite materials. It was found that the AE parameters in fact decreased at the point of onset of damage in the specimen at higher levels of applied stress, because of the faster failure rate. Finally, the linear correlation between the AE parameters and the number of cycles to failure and applied stress produced R^2 coefficients of 92.99 and 92.19%, respectively. All the AE parameters thus had a direct relationship with the applied stress values, suggesting that these correlation coefficients are reliable means of predicting fatigue life in a composite material.

Disclosure statement

No potential conflict of interest was reported by the authors.

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S. Gholizadeh is a postgraduate student, and the author's research area includes Mechanical Engineering, Damage mechanics, Failure analyses, Materials characterisation, Condition monitoring (Acoustic emission) and Mechanical behavior of materials.

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References

Awerbuch, Jonathan, Frank A. Leone, Didem Ozevin, and Tein-Min Tan. 2016. "On the Applicability of Acoustic Emission to Identify Modes of Damage in Full-scale Composite Fuselage Structures." *Journal of Composite Materials* 50 (4): 447–469.

Bar, H. N., M. R. Bhat, and C. R. L. Murthy. 2004. "Identification of Failure Modes in GFRP Using PVDF Sensors: ANN Approach." *Composite Structures* 65 (2): 231–237.

Barber, Gary. 2006. "An Overview of NDT Technologies and Systems." In *Asia-Pacific Conference on NDT, 5th*. Auckland, New Zealand.

Barre, S., and M. L. Benzeggagh. 1994. "On the Use of Acoustic Emission to Investigate Damage Mechanisms in Glass-fiber-reinforced Polypropylene." *Composites Science and Technology* 52 (3): 369–376.

Bhat, C., M. M. Bhat, and C. Murthy. 2003. "Acoustic Emission Characterization of Failure Modes in Composites with ANN." *Composite Structures* 61 (3): 213–220.

Bohse, J. 2000. "Acoustic Emission Characteristics of Micro-failure Processes in Polymer Blends and Composites." *Composites Science and Technology* 60 (8): 1213–1226.

Gholizadeh, S., Z. Leman, and B. T. H. T. Baharudin. 2015. "A Review of the Application of Acoustic Emission Technique in Engineering." *Structural Engineering and Mechanics* 54 (6): 1075.

Godin, Nathalie, Stéphane Huguet, Roger Gaertner, and L. Salmon. 2004. "Clustering of Acoustic Emission Signals

Collected during Tensile Tests on Unidirectional Glass/Polyester Composite Using Supervised and Unsupervised Classifiers." *NDT & E International* 37 (4): 253–264.

Gostautas, R., G. Ramirez, R. Peterman, and D. Meggers. 2005. "Acoustic Emission Monitoring and Analysis of Glass Fiber-reinforced Composites Bridge Decks." *Journal of Bridge Engineering* 10 (6): 713–721.

Huguet, Stéphane, Nathalie Godin, Roger Gaertner, L. Salmon, and D. Villard. 2002. "Use of Acoustic Emission to Identify Damage Modes in Glass Fiber Reinforced Polyester." *Composites Science and Technology* 62 (10): 1433–1444.

Kaphle, Manindra R. 2012. "Analysis of Acoustic Emission Data for Accurate Damage Assessment for Structural Health Monitoring Applications." PhD Thesis, Queensland University of Technology.

Kotsikos, G., J. T. Evans, A. G. Gibson, and J. M. Hale. 2000. "Environmentally Enhanced Fatigue Damage in Glass Fiber Reinforced Composites Characterised by Acoustic Emission." *Composites Part A: Applied Science and Manufacturing* 31 (9): 969–977.

Loutas, T. H., and V. Kostopoulos. 2009. "Health Monitoring of Carbon/Carbon, Woven Reinforced Composites. Damage Assessment by Using Advanced Signal Processing Techniques. Part I: Acoustic Emission Monitoring and Damage Mechanisms Evolution." *Composites Science and Technology* 69 (2): 265–272.

Mendoza, Edgar, John Prohaska, Connie Kempen, Yan Esterkin, and Sunjian Sun. 2013. "In-flight Fiber Optic Acoustic Emission Sensor (FAESense) System for the Real Time Detection, Localization, and Classification of Damage in Composite Aircraft Structures." Proceeding SPIE 8720, Photonic Applications for Aerospace, Commercial, and Harsh Environments IV, 87200K (May 31, 2013); doi:10.1117/12.2018155.

Mendoza, Edgar, John Prohaska, Connie Kempen, Yan Esterkin, Sunjian Sun, and Sridhar Krishnaswamy. 2014. "Fiber Optic System for the Real Time Detection, Localization, and Classification of Damage in Composite Aircraft Structures." 23rd International Conference on Optical Fiber Sensors - Santander, Spain, ISBN (Print) 9781628411751, Vol. 9157, 6/2014.

Mohammad, M., S. Abdullah, N. Jamaludin, and O. Innayatullah. 2014. "Predicting the Fatigue Life of the SAE 1045 Steel Using an Empirical Weibull-based Model Associated to Acoustic Emission Parameters." *Materials & Design* 54: 1039–1048. doi:10.1016/j.matdes.2013.09.021.

Mohammed, Bizuayehu Y., Chee K. Tan, Steven J. Wilcox, and Alex Z. S. Chong. 2013. "Damage Characterisation of Carbon Fiber Reinforced Composite Plate Using Acoustic Emission." Key Engineering Materials 558:184–194, Trans Tech Publication Switzerland, June 2013, doi: 10.4028/www.scientific.net/KEM.558.184

Mouritz, AP. 2003. "Non-destructive Evaluation of Damage Accumulation." In *Fatigue in Composites* edited by Bryan Harris, 242–266. Cambridge: Woodhead Publishing Ltd.

Nicolas, Matthew, Rani Sullivan, and W. Richards. 2016. "Large Scale Applications Using FBG Sensors: Determination of In-flight Loads and Shape of a Composite Aircraft Wing." *Aerospace* 3 (3): 18; doi:10.3390/aerospace3030018

Ono, Kanji. 1988. "Acoustic Emission Behavior of Flawed Unidirectional Carbon Fiber-epoxy Composites." *Journal of Reinforced Plastics and Composites* 7 (1): 90–105.

Paipetis, A. S., and D. G. Aggelis. 2012. *Damage Assessment in Fibrous Composites Using Acoustic Emission*. InTech. Open Access Publisher, ISBN: 9535100564, 9789535100560.

Philippidis, T. P., V. N. Nikolaidis, and A. A. Anastassopoulos. 1998. "Damage Characterization of Carbon/Carbon Laminates Using Neural Network Techniques on AE Signals." *NDT & E International* 31 (5): 329–340.

Philippidis, T. P., V. N. Nikolaidis, and J. G. Kolaxis. 1999. "Unsupervised Pattern Recognition Techniques for the Prediction of Composite Failure." *Journal of Acoustic Emission* 17 (1–2): 69–81.

Ramirez-Jimenez, C. R., N. Papadakis, N. Reynolds, T. H. Gan, P. Purnell, and M. Pharaoh. 2004. "Identification of Failure Modes in Glass/Polypropylene Composites by Means of the Primary Frequency Content of the Acoustic Emission Event." *Composites Science and Technology* 64 (12): 1819–1827. doi:10.1016/j.compscitech.2004.01.008.

Ségard, E., S. Benmedakhene, A. Laksimi, and D Laï. 2003. "Damage Analysis and the Fiber–Matrix Effect in Polypropylene Reinforced by Short Glass Fibers above Glass Transition Temperature." *Composite Structures* 60 (1): 67–72.

Siron, Olivier, and Hiroshi Tsuda. 2000. "Acoustic Emission in Carbon Fiber-reinforced Plastic Materials." Paper read at Annales de Chimie Science des Materiaux 25 (7): 533–537. Japan.

Ullmann, Thomas, Thomas Schmidt, Severin Hofmann, and Raouf Jemmali. 2010. "In-Line Quality Assurance for the Manufacturing of Carbon Fiber Reinforced Aircraft Structures." DGZfP-Proceedings BB 124-CD, 124. DGZfP. 2nd International Symposium on NDT in Aerospace, Hamburg. ISBN 978-3-940283-28-3.

Wevers, M. 1997. "Listening to the Sound of Materials: Acoustic Emission for the Analysis of Material Behaviour." *NDT & E International* 30 (2): 99–106. doi:10.1016/S0963-8695(96)00051-5.