Damage mode identification of Carbon fiber/Epoxy composites under fatigue process using acoustic emission monitoring

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Abstract. In this paper, the static and fatigue behavior of carbon fiber/Epoxy composites laminate are investigated. The degradation and damage evolution in the composite laminate tests process were monitored using the acoustic emission technique. The acoustic signals collected during the tests were analyzed. The results of the acoustic emission signal accumulated during static and fatigue tests are compared in order to identify the accumulated damage mechanism of carbon fiber/Epoxy composites laminate. The accumulated damage is manifested by matrix cracking, fiber/matrix interface debonding, shear failure, delamination, and fiber break.

1. Introduction
Carbon fiber reinforced resin matrix composites materials are used in aerospace, automotive, and a variety of industrial fields contribute to their high strength, lightness, fatigue resistance, and designability of material performance compared to traditional metallic materials. The customizable laminate structure provides excellently mechanical properties for diverse application scenarios. Ahmadzadeh [1] et al. develop a stiffness-based model to characterize the progressive fatigue damage in quasi-isotropic carbon fiber reinforced polymer (CFRP) [90/±45/0] composite laminates with various stacking sequences. Tae [2] et al. investigated the fatigue characteristics of the [±θ/0]s laminate bolted joint with respect to the angle θ and the bolt clamping pressure and compared with the result of the [02/±45/90]s laminate. Furthermore, the anisotropy, heterogeneity, interface properties between the two components of carbon fiber and resin matrix result in more complex fatigue behavior. The failure of laminate composites during service is mainly fatigue damage accumulation. Composite laminates showed multiple types of failure during fatigue cycle loadings, normally two or more failure modes arise simultaneously which causes the complexity of fatigue failure. Hence, non-destructive inspection techniques are necessary for the detection of fatigue damage of composite laminates [3]. Among the current non-destructive inspection techniques, the acoustic emission (AE) technique detects the transient elastic wave produced by the rapid release of local energy caused by the damage of the material in the service, which is called AE signal and the signal detected by the AE technique is emitted by the material itself. The characteristics of the signal can be used to analyze the type and evolution of damage. The AE technique is one of the extensively used and promising approaches which is almost covered in various applications as structural health monitoring and microcrack detection and location methods. By attaching a small piezoelectric sensor to the surface of the component, the active output
AE signal is detected. The AE technique is able to assess any geometry components and the signal propagation, and the signal received by the receiver can be regarded as a real-time generation of damage. Spectral analysis technology and multiparameter statistical analysis methods are used to identify the modes and degree of internal damage of the components based on the dominant AE signals. Bourchak [4] et al. carried out static and fatigue loading tests with the AE technique on the damage of carbon fiber reinforced plastic composite laminates. AE energy provides a valid and useful damage parameter and effective failure criteria for fatigue life prediction. Xu [5] et al. combined the clustering analysis, the time-domain analysis, and the frequency-domain analysis of AE signal to identify various damage modes and to study the hygrothermal aging effect of the single-lap joint.

The main objective of this study is to investigate and comprehensively analyze the fatigue behavior and the evolution of damage of the carbon fiber reinforced composite laminates. The AE technique was conducted on composite laminate under tensile-compression fatigue cycle loading and the signal results obtained from the AE tests were processed. Combined with the fracture morphology of the composite laminate specimen observed by the scanning electron microscope (SEM) to identify the damage modes and damage mechanism.

2. Material and testing

2.1. Material
Cutting the plates according to the geometry of specimens, the structure schematic of composite laminates is shown in Figure 1. The length, width, and thickness dimensions of specimens are 200mm, 20mm, and 5mm, respectively, and a total of 25 layers of fiber structure are included in the thickness direction which includes 0°, ±45°, 90° layers, and each layer has a thickness of 0.2mm. Among them, the carbon fiber layers are T800 PAN CF unidirectional belt, and the matrix is IS2101 bismaleimide resin. The density of the composite laminate is 1.6-1.8 g/cm³.

![Figure 1 Microstructure and schematic of carbon fiber/epoxy composites laminate specimen.](image)

2.2. Testing
The specimens were performed on MTS hydraulic servo testing machine, subjected to static and fatigue tensile tests until final failure which was numerically controlled by a computerized data acquisition system. Static tensile and compression tests were carried out at a constant rate of 1 mm min⁻¹ under displacement control until failure. The load waveform of fatigue tests is a sinusoidal wave at a stress control with a frequency of 10 Hz. The maximum fatigue loading is selected according to the static test results and the stress ratio (the ratio of minimum to maximum fatigue loading) of -1. The AE testing system was used to detect the fatigue damage behavior and damage evolution in the composite laminates during fatigue loading. The acquisition of the signals was conduct on AEwin software from American Physical Acoustics Corporation (PAC), and for filter noise interference the AE signals detected by sensors are preprocessed by a preamplifier with a threshold value of 45 dB. The micromorphology of the composite laminates after failure was observed by SEM. The typical parameters of the AE signal are...
commonly used for characteristic analysis, as shown in Figure 2. All tests are performed at room temperature.

![Common waveform parameters calculated by the acquisition system for each AE event.](image)

**Figure 2**

3. **Experimental results**

3.1. **Static tests**

Figure 3 shows the composite laminate stress-strain curves at constant displacement rates in the static tensile and compression tests, the acoustic activity is also displayed. It can be seen that the ultimate stress value of tensile and compression tests are 625MPa and 200MPa, respectively. The asymmetry of tension and compression is apparently in composite laminates. We know that the strength of the resin matrix is far lower than carbon fiber. The tensile strength of the composite laminate is between the carbon fiber and resin matrix due to the properties of the two materials are diverse. Monotonic loading in the tensile test revealed a significant reduction in stress caused by delamination of the specimen due to the inability of the substrate to provide stress support after specimen delamination. The subsequent persisted increase in the tensile stress of the specimen is due to the higher tensile resistance of the fiber bundle.

![Evolution of applied load with displacement during static tests](image)

**Figure 3**

Having investigated the tensile and compression behavior of the composite laminate specimens under static loading and identified the max fatigue cycle stress ought not to exceed the ultimate stress of static loading. The static test results tell us that the ultimate stress of compressive is less than the tensile, thus for investigation, 90 percent (180MPa) of the compressive ultimate stress (CUS) is select as the maximum fatigue load. The evolution of applied load combined with acoustic signals activity during tensile and compression tests under 180MPa is displayed in Figure 4. It can be seen that the amplitude
of tensile load focused on 45-80 dB. Compared with the tensile load that the amplitude under compression load varies between 45 dB and 100 dB. The analysis of the results obtained for the amplitude shows that the intensity of AE signals of the tensile load is much smaller than that of compression load under 180 MPa.

![Figure 4 AE amplitude signals composite laminate specimen during static tests](image)

(a) Tensile test  
(b) Compression test  

3.2. Fatigue tests

Constant amplitude fatigue tests were conducted to investigate the fatigue behavior of carbon fiber/epoxy composites at load 180 MPa and the stress ratio of -1. The multiple parameters of the AE signal for composite laminate specimens were acquisition. Figure 5 shows the results of the distribution of amplitude with time during whole fatigue tests. Obviously, there is a clear stratification of the AE signal.

![Figure 5 AE amplitude signals composite laminate specimen during fatigue tests](image)

The static test results of 3.1 revealed that the tensile-compression asymmetry existed in the composite laminate specimens. The AE signals activity of static tests also showed that the AE signals intensity of tensile test less than compression tests. Therefore, the black curves of AE signals are mainly produced by the compression load during the fatigue process, while the red curves are generated by tensile and compression load, and the compression damage is higher than tension at the same stress level. The summit existed in the initial stage are due to the fatigue loading selected in the tests are closed to compression limit and higher than the load-bearing capacity of the resin matrix so that random cracks generated in the matrix, and the fracture of carbon fiber at the internal defects of the composite laminate
[6]. In the subsequent process, the signal strength towards stability, and multiple small summits appeared at different moments in the intermediate phase. However, a major increase in AE activity for composite laminate specimens at the end of tests, which exceeds the initial phase, indicates that momentous damage has occurred in the final failure.

3.3. Microstructure analysis

The micromorphology of the composite laminate specimens after fatigue failure was examined by SEM as shown in Figure 6, used to provide an indication of their failure mechanisms. Carbon fiber is soft and incapable of bearing the load by itself. The resin act as a medium joining the fibers providing a matrix for load distribution between them and protecting the carbon fiber from deterioration. Under 90% CUS, the main failure mechanisms were matrix cracking, fiber/matrix interface debonding, delamination, and fiber fracture. It can be found that the resin matrix micro-cracks are formed on the surface of the specimen (Figure 10 a). Figure 10 b shows the carbon fiber/matrix interface debonding. As demonstrated in Figure 10 c, the dominant failure mechanisms of composite laminates were delamination and occurs between almost all layers. The matrix cracks and fiber/matrix interface debonding would have resulted in the reduction of the adhesive force between layers [7]. After the specimens are delaminated, the individual layer can barely withstand the fatigue load subsequently the fibers break, and the specimen failure rapidly.

![Figure 6 Fracture surface of carbon fiber/epoxy composite laminate specimen.](image)

4. Conclusions

The results obtained show that the acoustic emission method is a very useful technique used to identify the different damage mechanisms that occur in composite laminates during static and cyclic tensile tests.
The conclusions obtained within the tests and SEM observation of this research study are summarized below.

(1) The ultimate stress value of tensile and compression tests are 625Mpa and 200MPa, respectively. Besides, there is a clear stratification of the AE signal during fatigue tests due to the asymmetry of tension and compression in composite laminates.

(2) Five damage mechanisms have been identified using the above-mentioned techniques, namely matrix cracking, fiber/matrix interface debonding, shear, delamination, and fiber break. The delamination of the composite laminate specimens is the dominant damage mechanism.

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