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Research Article

Fatigue Damage Evolution and Monitoring of Carbon Fiber Reinforced Polymer Bridge Cable by Acoustic Emission Technique

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Desirable properties of carbon fiber-reinforced plastic (CFRP) composites include their high strength, high rigidity, light weight, corrosion free, and fatigue resistance. CFRP composites are popularly applied in bridge engineering structures, but the causes of fatigue damage in CFRP bridges have not been thoroughly investigated. We adopt acoustic emission (AE) technology to monitor fatigue damage and failure of CFRP bridge cables. The relationship between AE signal characteristics and CFRP cable fatigue damage, as well as the pattern of AE signals during a fatigue test, is investigated. Results show that the failure models exhibit matrix and fiber-matrix interface failures at the initial stage of fatigue testing, followed by delamination and fiber rupture. The b value, Kurtosis index, and RA value based on AE characteristic parameters are proposed to describe the different damage stage failure modes. Finally, the failure types of AE waveform are extracted and analyzed using wavelet transformation. The AE technique proved to be a potential means for evaluating the fatigue damage characteristics of CFRP cables.

1. Introduction

The stay cable, a high-strength steel wire, is an important component of stayed bridge construction. A large sample survey has shown that the corrosion of stayed cable steel wires is the main cause of failure mode. Many cables in China are prematurely replaced because of corrosion, even if the cables have only been in service for a period of ten years. The cost of cable replacement has reached 3 to 4 times more than the cost of a new cable. Thus, the durability of stayed cable should be improved. There are currently two methods of enhancing the durability of a stay cable, namely, by applying protective measures to improve corrosion resistance and the use of corrosion-resistant materials. The latter has a wide range of applications based on theoretical analysis, experimentation, and results of field implementation [1]. Structural health monitoring technique has been widely developed in recent years. For example, Yi and Li proposed some optimal methods to identify and evaluate civil engineering structure [2–4].

The carbon fiber-reinforced polymer (CFRP) has many remarkable advantages. This material is advantageous for cables because it is lightweight, rigid and has high strength-to-weight ratio. However, damage to cables is not visible and can be generated in the manufacturing or service processes, and these damages can seriously affect the durability of structures. Hence, the study of the failure process and breakage mechanism has emerged as a major issue for the structural development, design, and quality inspection of composite materials. To date, various testing methods, such as X-ray detection, ultrasound detection, acoustic emission (AE), and so on, are used to evaluate the damage of composite materials. The AE technique provides damage information and is an effective nondestructive method for examining dynamic failure [5]. The AE source is generated from a range of deformation and fracture mechanisms of materials produced under stress. For example, the failure mechanisms for matrix cracking, interface of fiber and matrix debonding, interface separation, and fiber fracture of composite material are important AE sources. The main key in the study of damage and failure of composite materials is to distinguish the relationship between material failure modes and AE signal characteristics.

AE analysis relies on conventional AE features. An amplitude distribution-based criterion has been applied in distinguishing fiber composite failure modes. High amplitude signals have been correlated with the fiber failure mode, and lower amplitude signals with the matrix cracking mode [6, 7]. The frequency-peak magnitude distribution, event and energy versus duration, has shown clear differences in different damage stages and could explain different damage type mechanisms [8–10]. The average frequency shift from high to low values indicates the shift of the cracking mode from tensile to shear [11]. The coefficient denoted by R_{AE} and the cumulative Benioff law can predict residual fatigue life [12]. Sometimes, however, the simple AE parameter analysis method becomes invalid because of the overlapping of different failure modes. The simultaneous study of various AE features has permitted researchers to obtain more reliable information for the identification of AE source mechanisms, especially when associated with pattern recognition algorithms [13]. The b value is used to evaluate seismic activity and predict earthquake in earthquake engineering. The lower b values in AE application are usually associated with discontinuous crack growth, and the high values can be caused by the plastic zone growth prior to crack propagation. Pattern recognition and neural networks represent a more advanced data analysis methodology that can be applied to AE data. The methods have been verified to identify composite damage sequence and types [13]. Wavelet analysis of AE waveform has undergone rapid development. The wavelet decomposition result shows that different frequency levels reveal different potential failure modes, for example, 300 kHz for fiber failure, 250 kHz for fiber-matrix debonding, and 110 kHz for matrix cracking [14].

The CFRP bridge cable fatigue damage was monitored in this study using the AE technique, and its evolution process was analyzed, as well as described, based on the AE monitoring data. The failure modes of the CFRP bridge cable such as matrix cracking, debonding, and fiber breakage were identified using the kurtosis and the b values. Different damage type waveforms were obtained based on the analysis of the abrupt change points in the kurtosis and the b value curves. The frequencies of AE signals were obtained using wavelet transformation and were used to identify various failure modes.

2. Experimental Procedure

We made two 2 m long cables, each cable inner including seven parallel CFRPs with a diameter of 7 mm. The CFRP cable model was fixed to the MTS fatigue testing machine. The load control mode was used to perform the fatigue test. The fatigue cycle was sinusoidal with a frequency of 5 Hz. The minimum load was 30 N, and the maximum load was 0.45 times the cable breaking force. Three R15 AE transducers with resonant frequency 150 KHz were employed. The AE transducers are made by American Physical Acoustics Corp. Two of which were installed on the anchor as alarm transducers to filter the signals generated from the friction of the anchor and clamp. The AE transducers were fixed using a magnetic mechanical clamp. The third AE transducer was installed in the middle of the specimen and was designed for receiving the signal generated by the cable fatigue damage of the cable. A ferrule was attached to the middle of the cable to fix the AE transducer, which was mounted on the ferrule. We performed the broken pencil experiment prior to the fatigue experiment to test the sensitivity of AE transducers and to ensure that the three transducers have the same sensitivity. Acoustic signals were monitored during the fatigue test by an AE measuring system (MISTRAS-2001, Physical Acoustic Corporation). The monitoring data were collected via the AEwin software. Instrument settings were set at a fixed threshold level of 45 dB, preamplifier gain of 40 dB, main amplifier gain of 20 dB, sampling rate of 5 MHz, and filter frequency range from 100 kHz to 1 MHz. The experimental device used during the test is illustrated in Figure 1.

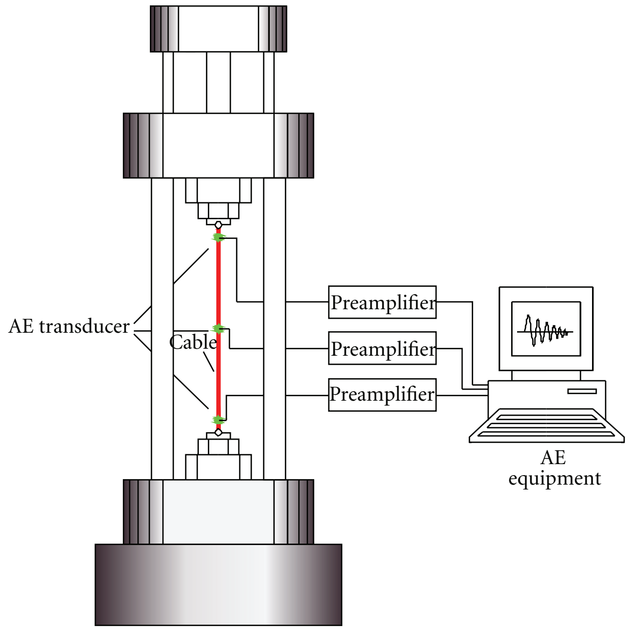
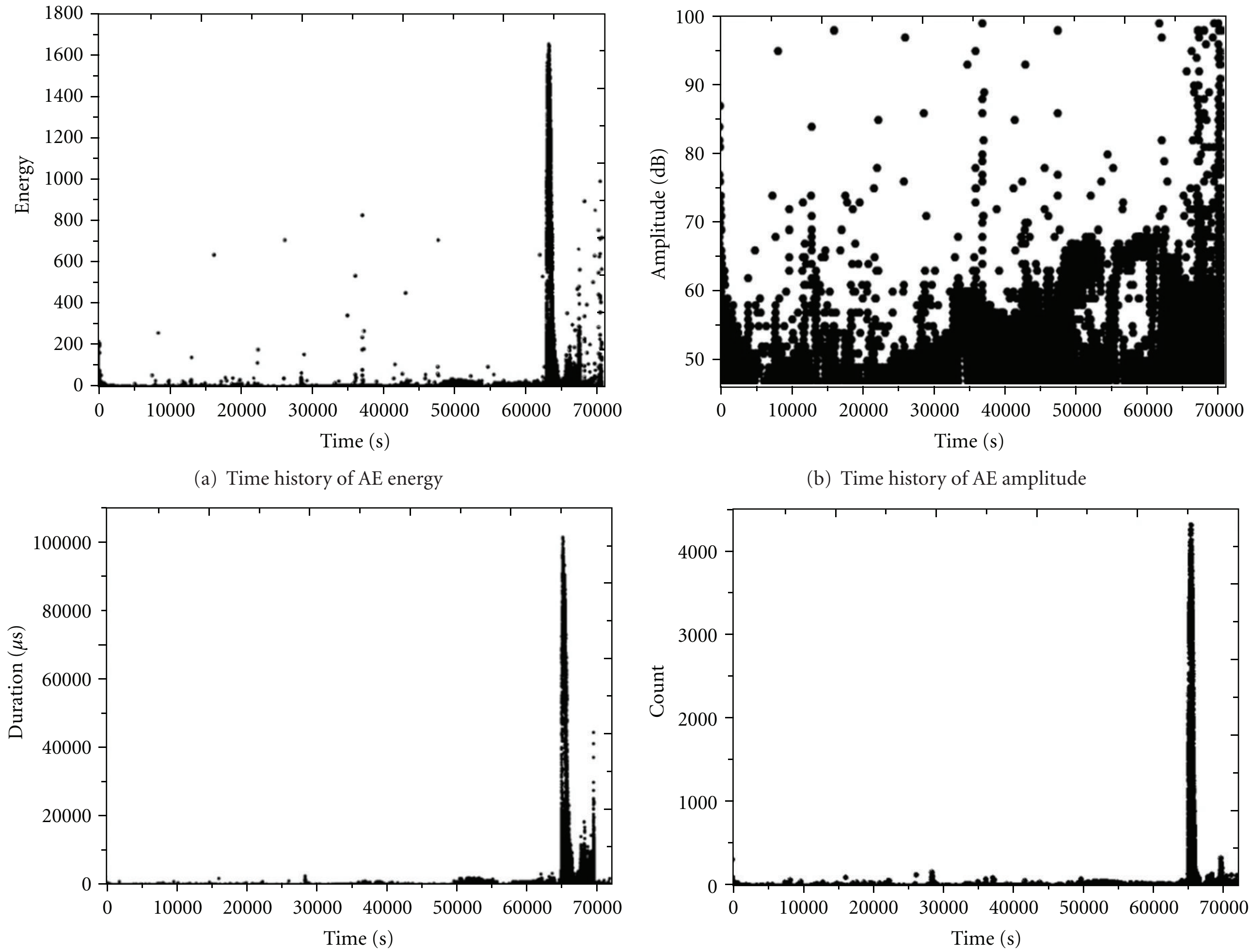


Figure 1: Schematic representation of the experimental setup for the AE.

3. Test Results and Discussion

3.1. Total AE Activity of the CFRP Bridge Cable Fatigue Damage. The AE parameter correlation method is simple, intuitive, and practical, making it the most widely used in practical projects. The entire fatigue damage process can be visually represented by the relationship of AE parameters.

Combining the description of AE signals for fiber composites in literature [15] with the characteristic signal of AE signals and SEM photograph shown in Figures 2 and 3, we conclude that AE signals were of low energy, low amplitude, and short duration in the initial stage of the fatigue test of CFRP bridges, although some high-energy and high-amplitude signals were occasionally recorded. The main sources of these irregular signals are the internal fraction of the CFRP cable and some defects possibly generated during the production process. Stress is concentrated in the pre-existing defects, leading to the cracking of the carbon fiber. The damage accumulates as the fatigue test continues. The interfaces between the fiber bundles, as well as fiber bundles and the base, begin to break and lead to crack propagation



(a) Time history of AE energy

(b) Time history of AE amplitude

(c) Time history of AE Duration

(d) Time history of AE count

Figure 2: CFRP bridge cable fatigue damage AE characteristic parameters.

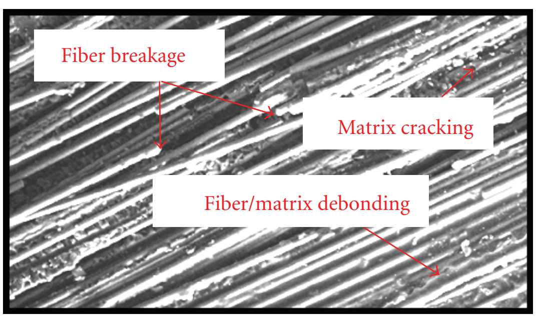


Figure 3: The FRP breakage SEM photograph [15].

because the base materials and reinforcing materials exhibit different properties during elongation and fatigue. Moreover, the cracked fibers at the base have relatively high stress. The fiber breaks when the stress reaches the fatigue limit of the fiber, and higher amplitudes can be obtained from 55 dB to 80 dB. In addition, the energy signal generates a higher value and a longer duration compared with the initial stage of the fatigue test. A considerable amount of high-amplitude and high-energy signals are generated after the test, and the peak value of these signals reaches 100 dB. The damage that occurs at this stage results from the fracture of the fibers after reaching their limit, and many fibers are pulled out from the anchor.

We qualitatively assess the condition of the carbon fiber cables during the whole process of the fatigue test and evaluate the failure modes based on Figure 3. We also reach the conclusion that different types of damage always occur simultaneously, resulting in the superposition of AE signals. However, we cannot effectively evaluate the types of damage solely based on the characteristic parameters of the AE test.

3.2. CFRP Bridge Cable Failure Analysis

3.2.1. CFRP Bridge Cable Fatigue Damage Evaluation with AE Parameters. Aside from the direct analysis of AE parameters and their relationship using the AE signal time-domain analysis method, the statistical time indicators of AE parameters can be calculated to analyze comprehensively the evolution of

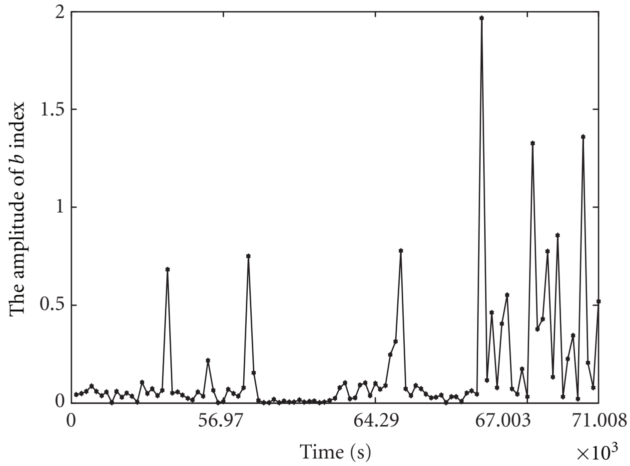


FIGURE 4: B value distribution over time.

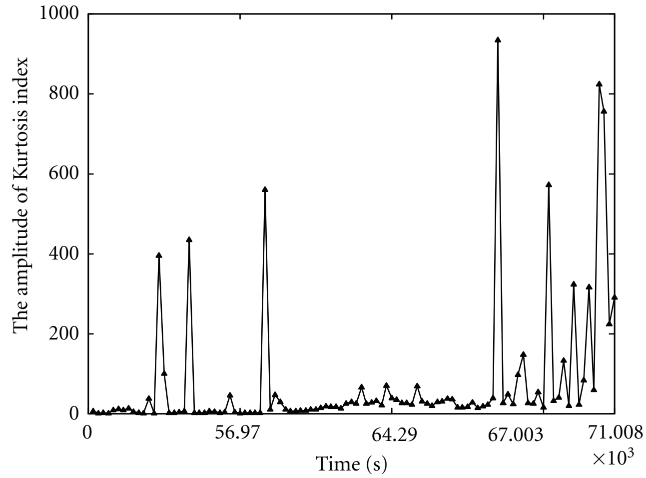


FIGURE 5: Kurtosis index distribution over time.

fatigue damage of carbon fiber cable and identify accurately the various stages of fatigue damage process. Two AE evaluation methods are proposed to determine the ability of these indicators to assess the damage levels in the evolution of CFRP bridge cable fatigue damage.

The b value is proven to be an effective method in studying fracture mechanism. The b values for different materials also show different ranges of values. This value is calculated in the AE technique as follows [16]:

$$\log_{10} N = a - b \times A_{\mathrm{dB}}, \tag{1}$$

where N is an AE event, and A_{dB} is the peak amplitude of the AE event in decibels. a and b are empirical constants. The b value is obtained by the least squares method.

Kurtosis is a measure of the impulsive nature of the signal. Thus, this condition can be used to evaluate potential defects and the service capabilities of the carbon fiber cable. Kurtosis is calculated as follows [17]:

$$\text{Kurtosis} = \frac{(1/N)\sum_{n=1}^{N}\left(x(n) - (1/N)\sum_{n=1}^{N} x(n)\right)^4}{\left[(1/N)\sum_{n=1}^{N}\left(x(n) - (1/N)\sum_{n=1}^{N} x(n)\right)^2\right]^2}, \tag{2}$$

where N is the length of each group AE characteristic parameter (energy) $x(n)$.

The AE characteristic parameters of the entire fatigue process are equally divided into 100 subintervals to simplify the calculations. The calculated results of the kurtosis index and the b value are shown in Figures 4 and 5.

The kurtosis and the b values have the same variation. The peak values in these figures show the failure generated, and the different amplitude values show the degree of fatigue damage.

The activity of the AE source is weak at the start of the test, and the main type of AE signal at this stage is a low-amplitude continuous pulse. The AE waveforms are generated by the rupture of the internal bubble of the CFRP as well as the friction between the anchor and specimens. Damage is accumulated during the fatigue test. The interface of the fiber and matrix begins to break, and a macrocrack is propagated. A few bursts with high amplitude are also generated in the range of 28485 s to 56970 s. The high-amplitude signals show that the activity of AE source is enhanced, and that the cable defects increase with each loading cycle, resulting in matrix separation from the fibers along the area leading to edge of the crack. The process eventually leads to interfacial debonding. The values exhibit substantial changes when the cable enters the stage during which the crack is propagated rapidly. The waveform generated by the interface of the carbon and matrix is damaged, and the carbon fiber is pulled out from the matrix. The essence of carbon fiber and matrix recombination is to form a complete interface upon the fiber surface to transfer stress, and fatigue load is transferred from the matrix to the reinforcement through this interface. Therefore, the structural integrity of the interface plays an important role in the overall performance of the material. The severe damage sustained by the interface will hasten the rate of damage of the carbon fiber cable. Therefore, microcracks expand in an unstable manner during this stage. The fiber pulls out from the fiber bundles, and a high-amplitude pulse waveform is generated.

3.2.2. CFRP Bridge Cable Fatigue Damage Fracture Mode. Different fracture modes produce different AE signals. For example, plastic deformation appears as a continuous waveform, whereas fracture appears as a burst waveform. Aggelis [18] found that a crack in a tensile mode has a short rise time and high-frequency AE waveforms. By contrast, shear-type cracks usually result in longer waveforms with lower frequency and longer rise time. The rise time/amplitude (RA, Figure 6) values are proposed to describe different fracture modes. Aggelis concluded that lower RA is exhibited during the early damage stage, but this value increases as the material approaches total failure. Thus, lower RA expresses tensile crack, and higher RA expresses shear crack.

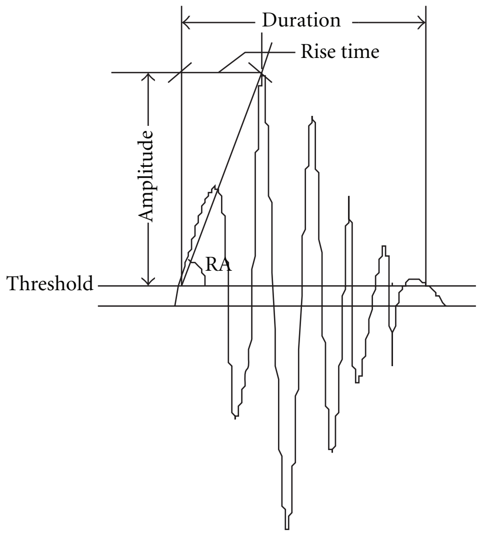


Figure 6: Typical AE waveform.

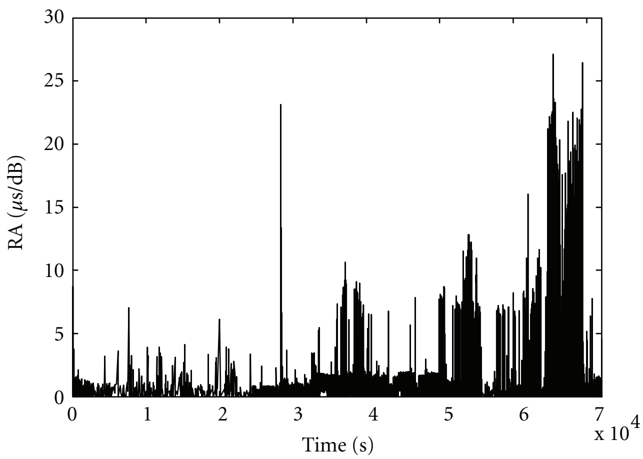


Figure 7: Time history of CFRP bridge cable fatigue damage RA value.

RA value is defined as

$$\mathrm{RA} = \frac{\text{Rise time}}{\text{Amplitude}}. \quad (3)$$

The RA value is defined as the angle where the AE signal crosses the threshold to the maximum amplitude for the first time. The RA value of the entire fatigue damage process is shown in Figure 7.

The RA value gradually increases until the end of the experiment. The activity of the AE source is enhanced during the damage initiation stage, and the cable defects increase with each loading cycle. This phenomenon eventually leads to interfacial debonding. Furthermore, matrix material is easily damaged under fatigue load because of its low ductility. The cracking is due to the tensile load. Delamination occurs within the loading cycle, and large quantities of fiber are pulled out from the fiber bundles because of the interface separation during the late stage of fatigue damage, resulting in eventual carbon fiber fracture. These events resemble shear-type failure caused by the friction between the fibers and the surrounding matrix. The RA shift to higher values indicates that shear stresses gradually dominate the failure process although the cracks are initiated by tension. The same case has also been reported recently for vinyl fiber and steel fiber concrete as well as metal plate tensile fatigue fracture [18–20].

4. Failure Modes Classified by AE Waveforms

The damage waveforms were extracted based on the location of each high burst point presented in Figures 4 and 5, and the time-frequency method was used to analyze the waveforms. Wavelet functions are localized both in frequency (or scale) and time via dilations as well as translations of the mother wavelet. Wavelet transform offers a self-adjusted and localized method that automatically adjusts the time-frequency window to analyze different signals in the frequency domain, thus fulfilling our demand for practical analysis. The wavelet transformation theory has been reported in a number of documents [21, 22]. The equation corresponding to the wavelet transformation theory was not shown in this paper.

In this paper, the CFRP cable fatigue damage type was analyzed by AE waveform, that is, only a preliminary investigation and qualitative differentiation method. The waveforms and the time-frequency spectra for matrix cracking, interface separation, and fiber fracture are shown in Figure 8 to reveal the distribution features in the time-frequency spectrum for different fatigue damage waveforms.

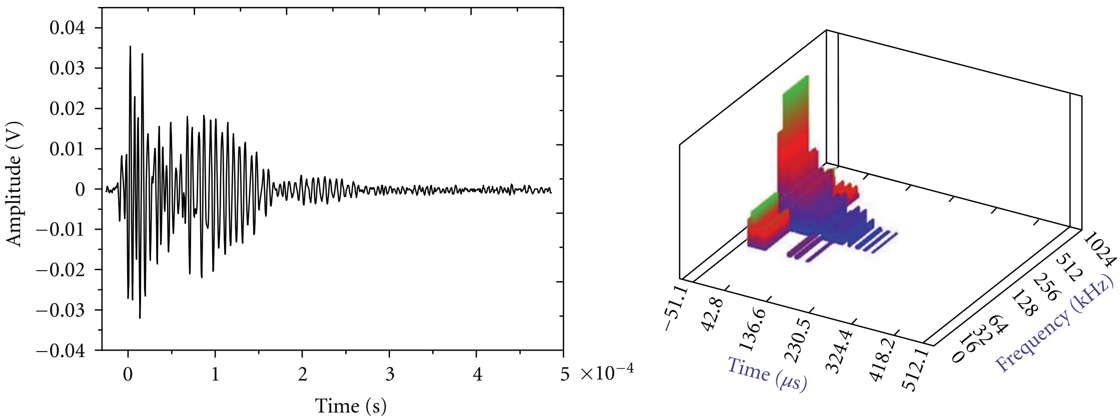
The different damage mechanisms of the AE signal have different characteristics of waveform and frequency scale (Figure 8). The waveform of matrix fracture may be described as a low-amplitude, wide pulse and has a wide frequency range from 64 kHz to 512 kHz, mostly concentrated at 128 kHz. The frequency range of delamination ranges from 64 kHz to 1024 kHz, mostly concentrated at 256 kHz. The frequency scale of a fiber fracture is wide, with a minimum frequency less than 64 KHz and crest amplitude of frequency reaching over 1024 KHz, mostly concentrated from 256 kHz to 512 kHz.

5. Conclusions

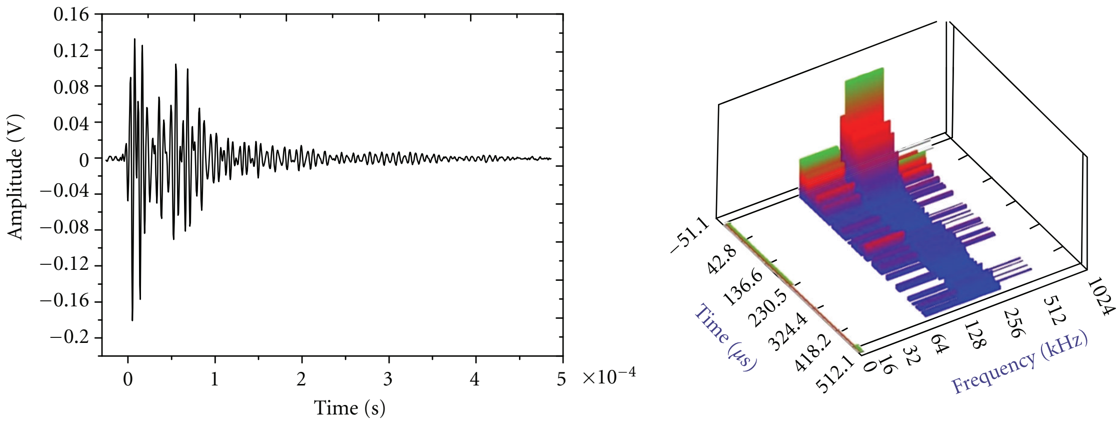
The AE technique was used to monitor the damage process in CFRP cable, and the AE data of the entire fatigue test was analyzed to examine the fatigue damage evolution process. The results show what follows.

(1) The entire fatigue damage process in carbon fiber cable can be represented visually by the AE parameter correlation diagram. The stage of steady crack propagation has a long duration and takes up 88% of the total fatigue life. The AE parameters are fluctuating within a small range in this phase. However, the AE signal shows the features of high-amplitude and wide frequency once the crack reaches the unstable micro-crack growth phase.

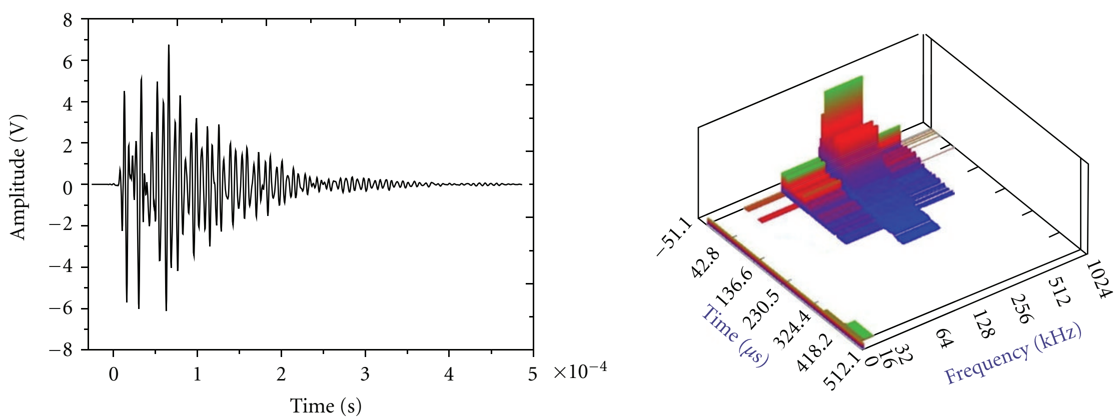
(2) The breakage evolution process in carbon fiber cable was analyzed using the kurtosis index, and b and



(a) The AE waveform of matrix fracture



(b) The AE waveform of delamination



(c) The AE waveform of fiber fracture

Figure 8: The time-frequency analysis of CFRP cable fatigue damage AE signal.

RA values. The location and extent of fatigue failure in the entire process were reflected clearly from the changes in the indicators.

(3) The matrix fracture, delamination, and fiber fracture waveforms were extracted from large transformations of diagnostic criteria. These are the major damage types of a CFRP cable. Different waveforms have different frequency distributions according to the wavelet transformation time-frequency analysis. High-amplitude signals have been correlated with the fiber failure mode and lower amplitude signals with the matrix cracking mode.

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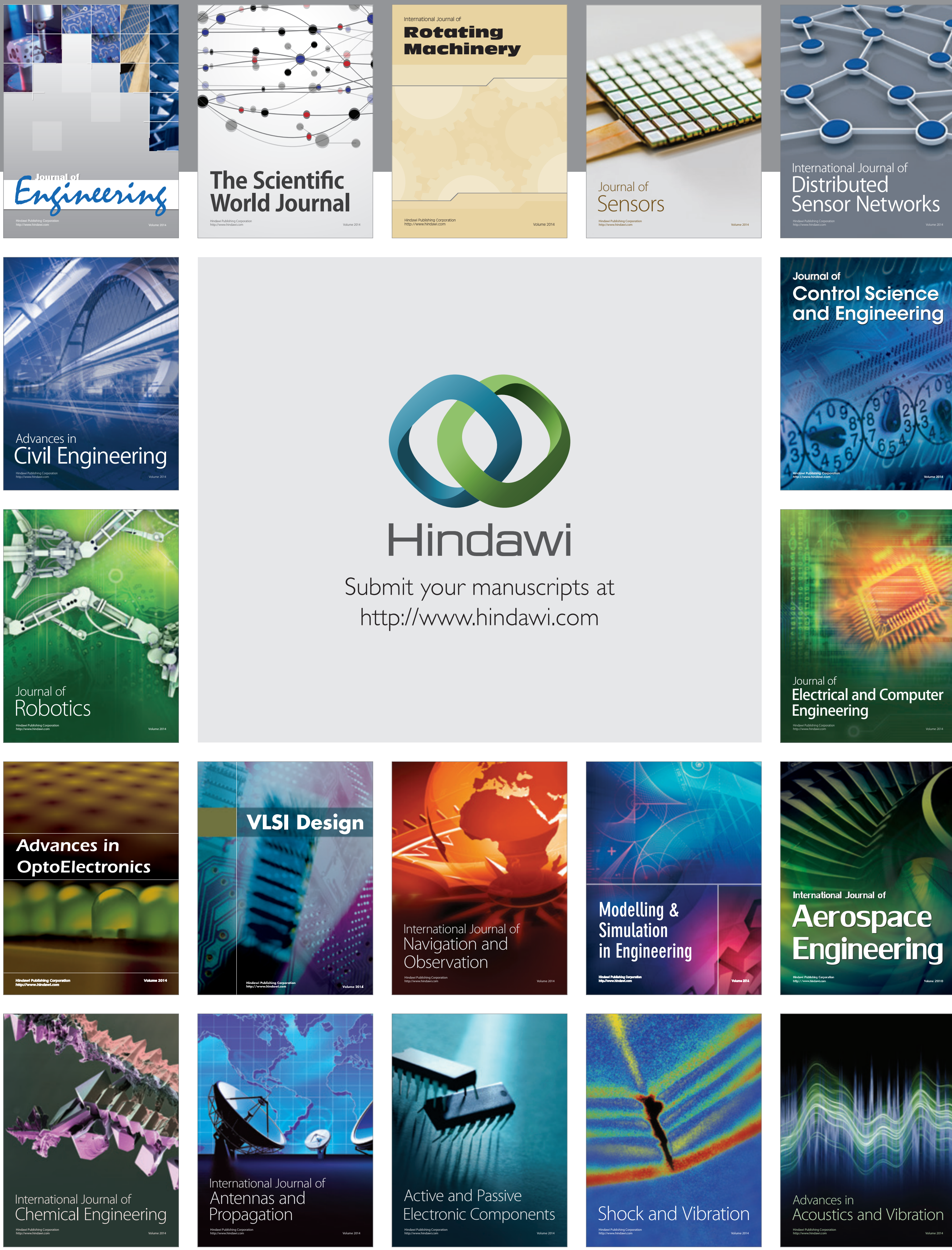

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