Acoustic emission-based real-time monitoring of fatigue damage evolution of T800 carbon fiber/bismaleimide composites

X F Qi\textsuperscript{1,2}, Y Yang\textsuperscript{1}, W P Kang\textsuperscript{1}, Q Wang\textsuperscript{1} and G Zhao\textsuperscript{1}

\textsuperscript{1}Aircraft Strength Research Institute of China, Xi'an 710065, China

E-mail: 741612110@qq.com

Abstract. For the damage mode recognition in the fatigue coupon test of T800 carbon fiber/bismaleimide, the acoustic emission is employed. However, the latter application is hindered by noises produced by various environmental factors, which may suppress damage-induced ones. In this study, external noises are effectively reduced by the absorbing adhesive. For damage mode recognition, an integrated strategy is proposed, which features a combination of a characteristic signal extraction and damage mechanism analysis via piezoelectric and fiber Bragg grating sensors. The final verification shows that the different damage modes of the composite specimen can be clearly distinguished based on this method.

1. Introduction

Bismaleimide (BMI) resin matrix composites surpass epoxy resin matrix ones by thermal stability, fatigue resistance under high humidity, and have lower linear expansion coefficients [1]. In addition, the processing properties of BMI are also more lucrative [2]. For these reasons, carbon fiber/BMI composites have attracted much attention from researchers in recent years and get rapid development.

The fatigue behavior of most materials is commonly detected by non-destructive testing (NDT) techniques [3], such as ultrasonic testing, radiographic testing, magnetic particle testing, penetrant testing, and eddy current testing. However, in some cases, these conventional techniques have unavoidable limitations and shortcomings. For example, they have no capability of identifying the damage type and micro-damage. Especially, in case of composite materials, there are mainly four different kinds of damage mechanisms including matrix cracking, fiber-matrix debonding, delamination, and fiber breaking, according to the related damage theory [4]. Consequently, it is quite problematic to adopt the above methods to identify the damage mechanism and follow the damage evolution of composite materials. Fortunately, among others, the acoustic emission (AE) is supposed to be a feasible way to monitor damage behavior of composite materials [5], since it possesses the ability of achieving early damage recognition, allowing real-time monitoring of damage process and identifying different kinds of damage mechanisms attributed to its high sensitivity, passivity and dynamic nature [6].

In the case of composite materials, many AE-based studies have been carried out, attempting to relate the AE response with the corresponding damage mechanism. Masmoudi et al. [5] analyzed the acoustic signals by using the classification $k$-means method to identify different damage mechanisms and follow the evolution of these mechanisms for composite materials. In studies of Gutkin [7] and Sause [8], the highest frequency signals have been considered to be related to fiber breakage, while the lower frequency signals were related to such mechanisms as matrix fracture or fiber pull-out. Moreover, Godin
et al. [9] used AE features and combined two kinds of classifiers, a supervised classifier and an unsupervised one (Kohonen’s map), to discriminate different types of damages occurring in a constrained composite. However, in general, the above investigation achieving good results in laboratory could encounter some new challenges and difficulties, while used in high ambient noise environments and other practical field conditions, and yield poor results. In the context, it is necessary to present a strong anti-noise, convenient, real-time and reliable AE working method available to practical engineering, such as fatigue field condition with high-noise and real-time requirement.

2. Experimental
2.1. Material and specimen geometry
The [45/0/-45/90]s composite laminate of T800 carbon fiber reinforced BMI resin was used for this work. The specimen was cut out from the commercially available laminated plates of 300x400mm² and its geometry is shown in figure 1, where the circle with diameter Φ in the middle section represents prefabricated hole-shaped defect used to define the locations of initial fatigue damage inside the specimen to allow more focused observation during in-situ monitoring. Dimensions of the specimen are L=300mm, W=38mm, T=2mm, and Φ=7mm, where L, W, T and Φ are the length, width, thickness and diameter, respectively.

2.2. Experimental set-up
At ambient temperature, the specimen was subjected to tension-tension fatigue test until the delamination was large enough to be perceived by the unaided eye. The test was performed on an INSTRON 8801 standard hydraulic machine, the cyclic loading had a load spectrum of sinusoidal waveform at a constant frequency rate of 10Hz and had a maximum of 29.417kN with the stress ratio R=0.1, indicating a minimum load of 2.9417kN. Particularly, prior to testing, sandpaper should be pasted on either end of the specimen in order to prevent the specimen from slipping during loading.

Figure 1 shows the experimental system in this article. As can be seen from Figure 1, on the front side of the specimen, two AE sensors are attached on either end around the prefabricated hole respectively. On the back side of the specimen (figure 1), other NDT techniques, including piezoelectric (PZT) and fiber Bragg grating sensors (FBG) are surface mounted on the plate to conduct measuring synchronously during loading to allow for cross-validating with the AE technique in the further analysis. In addition, since the hydraulic cylinder of the testing machine is located on the side of the lower fixture, the AE noise caused by vibrations of the hydraulic cylinder has always been there after the specimen is clamped by the lower fixture. In order to remove this noise, it is necessary to paste some absorbing adhesive between the lower fixture and 2# AE sensor to absorb the surface noise waves resulting from vibrations of the hydraulic cylinder.
In this experiment, AE signals were sensed by an AE sensor R15α from Physical Acoustics Corporation (PAC) with a frequency range 50 kHz-200 kHz and a resonant frequency of 150 kH. The AE signals detected by the sensor were amplified by the preamplifier provided by PAC with a 40dB uniform gain across all frequencies, and the acquisition of AE signals was carried out by the master computer that utilizes SAMOS PCI-8 data acquisition board with 8 channels.

3. Experimental analysis and results

The entire test took nearly 90 minutes, spanning 56,000 cycles and was ultimately terminated due to the visible damage form (the delamination with a length of 2 mm). In the following section, the following will only take 1# channel as an example for analysis and explanation, considering the consistency of the data distribution of 1# and 2# channels.

3.1. AE response before loading

Prior to loading, during which the fixtures of the test machine were clamped but the load was not started, the amplitude versus time history of the acoustic emission signals was generated as shown in figure 2, in which the acoustic emission signals with amplitude of about 40dB between 0 and 143s were caused by vibrations of the hydraulic cylinder after tightening fixtures and AE signals between 143 and 208 s came from pasting the absorbing glue. The results of using the absorbing glue are observed when comparing the recorded signals of 0 ~ 143 s to the signals after 208 s. It can be obviously seen that the vibration noise is successfully removed after the adhesives are pasted between 143 and 208 s.

3.2. AE signals analysis workflow

To attempt a quick, reliable and real-time damage identification for the composite materials in field condition, this article presented a workflow for the AE signal real-time analysis.

First of all, the AE activity diagrams should be analyzed in an effort to find the trend of the number of AE source with the test time to obtain the overall development trend of the specimen damage. Subsequently, the AE intensity diagrams should be investigated, which are indicative of damage mechanism and therefore identified as useful for the recognition of damage types. Finally, related with the damage theory of composite materials, the real-time identification of the composite specimen in field cyclic loading condition can be implemented by a combination of the comprehensive analysis of the features behavior in intensity and activity diagrams and the cross-validation conclusions from FBG and PZT.

3.3. Analysis during 0~17000 cycles

As shown in figure 3, the fatigue test started from 234s and then was interrupted 6 times at 450~550 s, 750~850 s, 1050~1130 s, 1380~1460 s, 1720~1800 s, and 2420~2450 s, respectively by the PZT detecting, during which high-amplitude acoustic emission signals were correspondingly generated, which should be ignored in the subsequent analysis.

Figure 4 is the activity diagram of AE signals during 0~17000 cycles described by the number of AE hit per unit time, illustrating the development trend of AE sources activity. The figure indicates that AE hits increase with time and the envelope of the figure increases slowly before 1800s, and rapidly after
1800s. These implies that more and more acoustic emission sources start to emerge in the specimen with time. However, the identification of the specific damage mechanism can not be achieved by analyzing the activity diagram alone. Hence, it is necessary to analyze the intensity diagrams of AE signals. In order to recognize the damage mechanism.

From figure 3 (one of AE intensity diagrams), it can be observed that the amplitude of AE signals between 255 and 285 s is much higher than that of other periods. Furthermore, the associated AE waveforms with these signals have such burst nature as shown in figure 5. Meanwhile, other features during this period (figure 6), including count, energy, rising time, and duration, also stand out. Extrapolating from these findings, as well as considering AE signals with these natures never appeared after 285s, the AE signals of 255 ~285s were reckoned to be caused by the breakage of defective fibers generated in the manufacturing process of the specimen.

After a small amount of defective fibers breaking and releasing energy, it can be seen from figure 3 that after 310 s, the amplitude of most AE signals remains below 85 dB, and the signals of 65-85 dB are in a discrete distribution, not in a continuous distribution like friction noise signals. Therefore, it is argued that the damage was generated from the beginning of the test, resulting in the occurrence of scattered signals of 65-85 dB. This damage can be attributed to the matrix cracking, which is validated by the damage theory [4] of composite that matrix damage first occurs during loading because of its low strength, and it will continue in the course of the composite test.
Figure 6. AE different characteristic parameters vs. time during 0-17000 cycles.

A set of AE intensity diagrams is illustrated in Figure 7 where the duration, the energy and the rise time all display rapidly increasing trends after 2380s. However, the amplitude (Figure 3) has the similar value range to one before 2380s. Based on the fact that the AE signals related to delamination are characterized by long duration, high energy, long rise time and no obvious change in amplitude [5], the conclusions can be drawn that the damage of delamination occurs in the specimen after 2380s. According to the damage theory of composite, delamination is a kind of damage occurring in laminates and when a matrix crack propagates through a laminate, it may be blocked if its tip meets the fibers of adjacent laminates. However, due to the high shear stress in the matrix adjacent to the crack tip, the crack may branch and then grows in parallel to the laminate, resulting in delamination.

Figure 7. AE intensity during 0-17000 cycles in fatigue test.

In addition, the intensity diagrams (Figures 3 and 8) imply that the number of AE signals with amplitude of over 60 dB (Figure 3) and absolute energy of over 2000 increases significantly between
1500 and 1700 s. According to other studies [10-11], high amplitude and high energy are the characteristics of AE signals related to fiber-matrix debonding. Hence, it is concluded that the AE signals of 1500–1700 s should correlate with the damage mechanism of fiber-matrix debonding, which is consistent with the damage theory of composites, which implies that fiber-matrix debonding follows matrix cracking and precedes delamination.

**Figure 8.** AE absolute energy vs. time plot during 0~17000 cycles in fatigue test.

### 3.4. Analysis during 17000~56000 cycles

The intensity diagrams with different features during 17000~56000 cycles are displayed in figure 9, where the PZT testing was performed during 800–980 s, 2450–2560 s, 4690–4700 s, respectively. Similar to the above, AE signals during these periods will be ignored when analyzed.

In general, the damage must continue to expand with the test and further forms macroscopic damage following the matrix cracking, fiber-matrix interface debonding and microscopic delamination, which can be noted from figure 9, in which the amplitude and energy show increasing trends from the beginning, indicating that the damage of the specimen is expanding and going to develop into macroscopic damage soon. Furthermore, the absolute energy in figure 10 also shows a very obvious trend of rapid growth after 1400 s, and especially after 2380 s (38250 cycles) the maximum absolute energy increases by leaps and bounds and has remained at a high level ever since, representing the macroscopic damage is emerging and growing, which is verified at 2800 s (42420 cycles) by observed delamination damage with a length of approximately 1mm.

In addition, several thick lines appear in figure 9, and after enlarging a portion of thick lines, these AE signals have the same amplitude and are in a periodic distribution with the same frequency of 10 Hz as loading. Accordingly, these AE signals can be caused by fatigue crack growth with periodic loading, which can be confirmed by the characteristic parameter list of AE signals, where all periodic AE signals with a 70 dB amplitude occur at the peak of loading.

**Figure 9.** AE various characteristic parameters vs. time during 17000~56000 cycles.
3. Results

According to the above analysis, the damage evolution process of the specimen can be attained as follows: a small number of defective fibers broke during 200 to 500 cycles; matrix damage appeared from the beginning of fatigue test and persisted throughout the test; interface debonding occurred from 8000 to 11000 cycles, and microscopic interlaminar separation began from 16850 to 17000 cycles; at approximately 38250-40000 cycles, micro-damage gradually evolved into macro-damage and became visible to the naked eye.

To verify AE monitoring, AE was coupled with FBG and PZT in this test. The FBG results strongly indicate that the damage occurred for the first time after at 4000 cycles; at 11000 cycles, damage occurred for the second time; at 40000 cycles, damage occurred for the third time. However, the specific damage mechanism cannot yet be achieved by the technique at present. In addition, according to PZT results, the conclusion could be drawn: at 2000 cycles, the specimen has produced damage; at 40000 cycles, new damage appeared again. Similar to FBG, PZT also has no ability to give specific damage mechanism. What is more, PZT cannot provide the specific occurrence time of damage since this technique doesn’t belong to real-time detection.

Consequently, compared to other traditional NDT methods, the AE technique has greater superiority in identification of the material damage, which can detect the occurrence of damage in advance, distinguish different types of damage and determine the occurrence time of damage.

4. Conclusions

In the article, the composite laminate of T800 carbon fiber/BMI resin under cyclic loading was monitored by AE in an effort to investigate the fatigue behavior of this material. Accordingly, the following conclusions can be drawn.

1. The absorbing adhesive can successfully remove the noise caused by the vibration of the hydraulic cylinder and hence provide a good basis for improving the quality of AE datasets.

2. Leveraging the AE features, the fatigue damage mechanisms and evolution of the specimen were effectively recognized according to the workflow proposed in the study, which was partly verified by FBG and PZT. A small number of defective fibers broke during 200 to 500 cycles. Matrix damage appeared from the beginning and persisted throughout the test. The interface debonding occurred between 8000 and 11000 cycles, and microscopic interlaminar separation was realized from 16850 to 17000 cycles. At approximately 38250-40000 cycles, the micro-damage gradually evolved into macro-damage and became visible to the naked eye.

3. Compared to FBG and PZT, the AE technology exhibits several obvious advantages, such as realizing early damage identification and distinguishing different damage types.

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