

Research Article

Investigation on the Behavior of Tensile Damage Evolution in T700/6808 Composite Based on Acoustic Emission Technology

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T700/6808 composite has been widely used in aerospace field and the damage in composite will seriously influence the safety of aircraft. However, the behavior of damage evolution in T700/6808 composite when it suffered from tensile loading is seldom researched. In this paper, the acoustic emission (AE) technology is employed to research the process of damage evolution in T700/6808 composite under tensile loading. Results show that the damage in T700/6808 composite is small in the initial stage of tensile loading, and main damage is the matrix cracking. The composite has serious damage in the middle stage of tensile loading, which mainly includes the matrix cracking and the interface damage as well as the fiber breakage. The number of fiber breakages decreases rapidly in the later stage of tensile loading. When it comes into the stage of load holding, the composite has relatively smaller damage than that in the stage of tensile loading, and the fiber breakage rarely occurs in the composite. Analysis of damage modes shows that the criticality of the matrix cracking and the interface damage is higher than the fiber breakage, which illustrates that the reliability of T700/6808 composite could be improved by the optimization of matrix and interface.

1. Introduction

T700/6808 composite is a new kind of carbon fiber reinforced epoxy resin matrix composite, which has been widely used in the aircraft structure for its excellent properties, such as light weight, high specific strength, and well resistance to the fatigue fracture [1, 2]. During the manufacturing and flight process of structure, damage would occur in the T700/6808 composite which will influence the structural safety of aircraft.

At present, detection methods for the composite mainly include the visual method, X-ray method, and ultrasonic testing method. Acoustic emission (AE) technology is a kind of nondestructive detection method, which could be used for detecting the defect or the damage in composite, such as container leakage, blade damage, and wing crack detection [3–5]. In the past few decades, the AE research has obtained attentions from scholars. Chou et al. [6] used the AE method to detect the damage in carbon fiber composite pressure vessel. Al-Jumaili et al. [7] presented an AE parameter correction method which could be used for the damage detection in large composite component. Maillet et al. [8] proposed an AE

detection method with double sensors, which could evaluate the energy attenuation of damage process in composite structure. Saeedifar et al. [9] used AE method for detecting the delamination damage in glass reinforced epoxy resin composite. Liu and Xia [10] applied AE system to detect the fatigue damage in composite blades. Masmoudi et al. [11] combined AE method with piezoelectric technology to detect the damage in composite sandwich structures.

Despite several advancements reported on the AE research, however, little published works have been focused on the damage monitoring in T700/6808 composite, and its damage evolution behavior remains unclear. At present, researchers mainly focused on the mechanical property analysis of T700 series composite. Zhou et al. [12] developed a method to characterize the fatigue strength distribution of T700 carbon fibers by fiber bundles testing. Zhang et al. [13] researched the difference of mechanical properties between two kinds of T700 composite, which shows that the fiber defect may lead to the property difference. Wang et al. [14] carried out the tension-tension fatigue test on T700/9368 composite laminate and explored the damage mechanism by ultrasonic C-scan. Chiu et al. [15] investigated the behavior

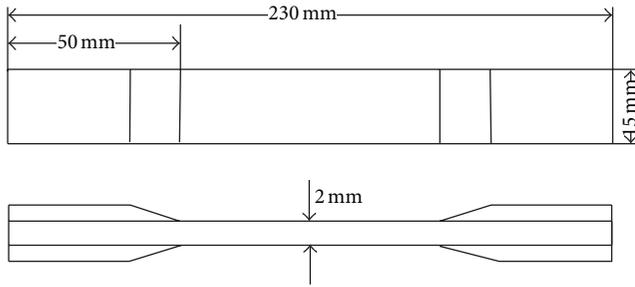


FIGURE 1: Schematic diagram of the specimen.

of T700/M21 composite energy absorber under static and dynamic loading, and the consistent damage modes and measured force responses were obtained.

In order to obtain the behavior of damage evolution in T700/6808 composite and discover the weakness of the material, the tensile testing and acoustic emission technology were used to analyze the T700/6808 composite in the paper. The damage behavior of T700/6808 composite under tensile loading, as well as the weakness in composite, could be obtained and the result provides the basis for the optimization and improvement of the material.

2. Materials and Methods

2.1. Specimen Preparation. Tensile specimens were designed according to the national standards GB/T 3354-1999 [16] and three specimens had been prepared in the experiment. Detailed geometry of the specimen is shown in Figure 1. The specimen is made of T700/6808 carbon fiber reinforced epoxy resin matrix composite, and the composite is unidirectional ply.

2.2. Experiment Design. The experiment platform is shown in Figure 2. The platform consisted of a tensile testing machine and a set of AE system. The room temperature is $27^{\circ}\text{C} \pm 2^{\circ}\text{C}$. During the tensile testing, the AE system was employed to record the damage signal from the T700/6808 composite. Tensile testing for the specimen was conducted on WDW-300 tensile testing machine as shown in Figure 2(a), and the loading rate was set as 50 N/s and the maximum load was set as 40 KN. When the tensile load reaches 35 KN, the system automatically enters into the state of load holding for 24 hours. The AE system is MISTRA 2001 E1.12 which is made from Physical Acoustics Corporation. The information of PAC-WSa sensor is shown as follows. (1) As shown in Figure 2(b), the AE sensor is pasted on the middle of the specimen with vacuum grease and it is fixed with elastic for well contact. (2) The detection frequency is 0–551.36 KHz. (3) The preamp gain is 40 dB. (4) The sampling rate is 1 MSPS.

3. Results

3.1. AE Signal Analysis of T700/6808 Composite under Tensile Loading. Three specimens were used in the experiment, and it is found that the damage behavior and the change trend of

AE signal are similar among three specimens during tensile testing; therefore, the specimen of number 1 is studied in detail. The change of AE hit number with the tensile loading time is shown in Figure 3.

As shown in Figure 3(a), in the initial stage of tensile loading (0–60 s), the AE hit number is mainly distributed in the interval between 0 and 20. When it comes into the middle stage of tensile loading from 60 s, the AE hit number suddenly increases to about 85. In the middle stage of tensile loading (60–580 s), the value of AE hit number relatively maintains a high level, such as 132 at 125 s, 138 at 220 s, and 107 at 520 s. It indicates that, in the middle stage of tensile loading, the composite suffered severe damage which led to the occurrence of large quantity of AE hit number. From 580 s, when it comes into the later stage of tensile loading, the value of AE hit number begins to decrease. The minimum AE hit number is 17 when the testing time is close to 700 s, which indicates that the damage in composite was small in the later stage of tensile loading (580–700 s).

From 700 s, the tensile system automatically enters into the stage of load holding. From final phase of Figure 3(a), it can be seen that the value of AE hit number mainly stays under 25 in the initial stage of tensile loading (700–1000 s). In Figure 3(b), most of the AE hit number stays under 20 in the middle stage of load holding (1000–10000 s), except for 118 at 1800 s. In Figure 3(c), the AE hit number still remains little in the later stage of load holding (10000–80000 s); however, the quantity of AE hit number is more than that in the middle stage of load holding.

The change of AE hit amplitude with the tensile loading time is shown in Figure 4.

As shown in Figure 4(a), most of AE signal is distributed between 55 dB and 70 dB from 0 s to 60 s; however, none of AE signal is distributed between 70 dB and 100 dB. From 60 s to 580 s, the AE signal is mainly distributed between 55 dB and 100 dB. Among them, the number of AE signals which is distributed between 55 dB and 60 dB is the most, and the number of AE signals which is distributed between 70 dB and 100 dB is the least. From 580 s, the number of AE signals begins to decrease and the AE signal distributed between 60 dB and 100 dB reduces the fastest. From 700 s to 1000 s, the AE signal is mainly distributed between 55 dB and 60 dB and little signal is distributed between 60 dB and 70 dB; meanwhile, none of signal is distributed between 70 dB and 100 dB.

As shown in Figure 4(b), from 1000 s to 10000 s, the AE signal is mainly distributed between 55 dB and 60 dB, and the following is the AE signal which is distributed between 60 dB and 70 dB. However, the number of AE signals which is distributed between 70 dB and 100 dB is the least. From Figure 4(c), it can be seen that the distribution of AE signal from 10000 s to 80000 s is similar to the distribution from 1000 s to 10000 s.

3.2. Damage Evolution Analysis in T700/6808 Composite. In order to obtain the damage characteristic in T700/6808 composite during tensile testing, a preparation experiment used to establish the relationship between the damage modes and AE signal had been conducted before the formal tensile

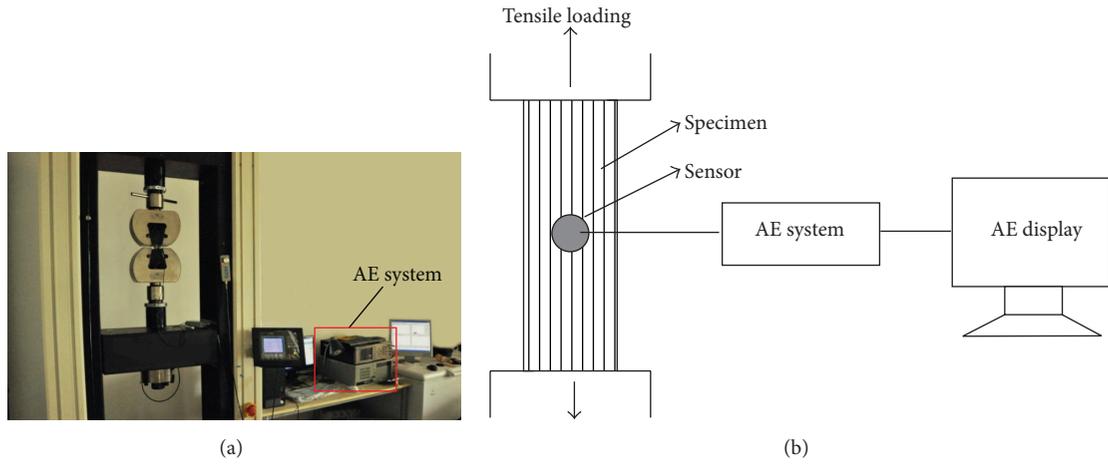


FIGURE 2: Experiment platform. (a) Experimental equipment; (b) diagram of equipment connection.

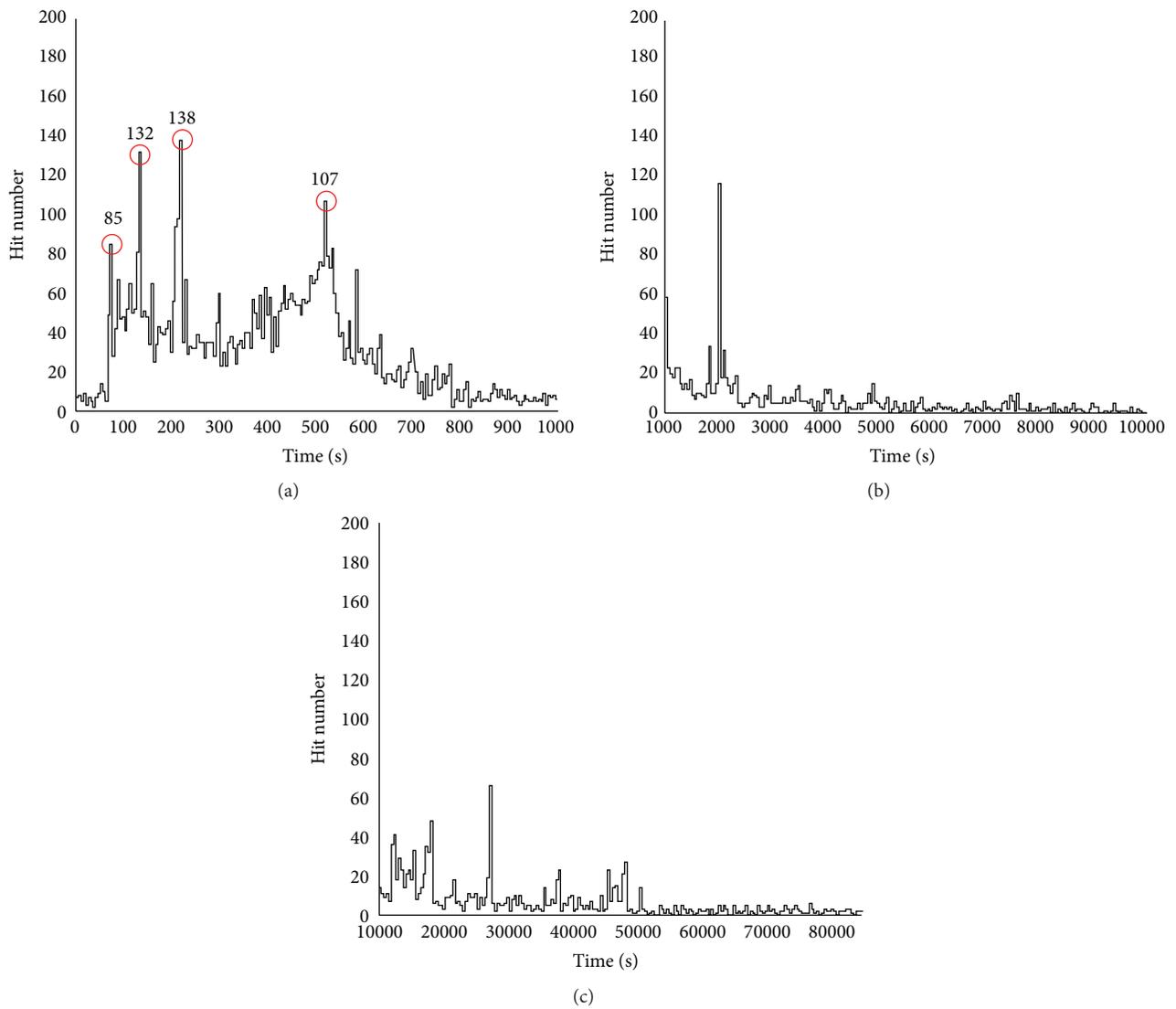


FIGURE 3: Change of AE hit number with the tensile loading time: (a) 0 s–1000 s; (b) 1000 s–10000 s; (c) 10000 s–80000 s.

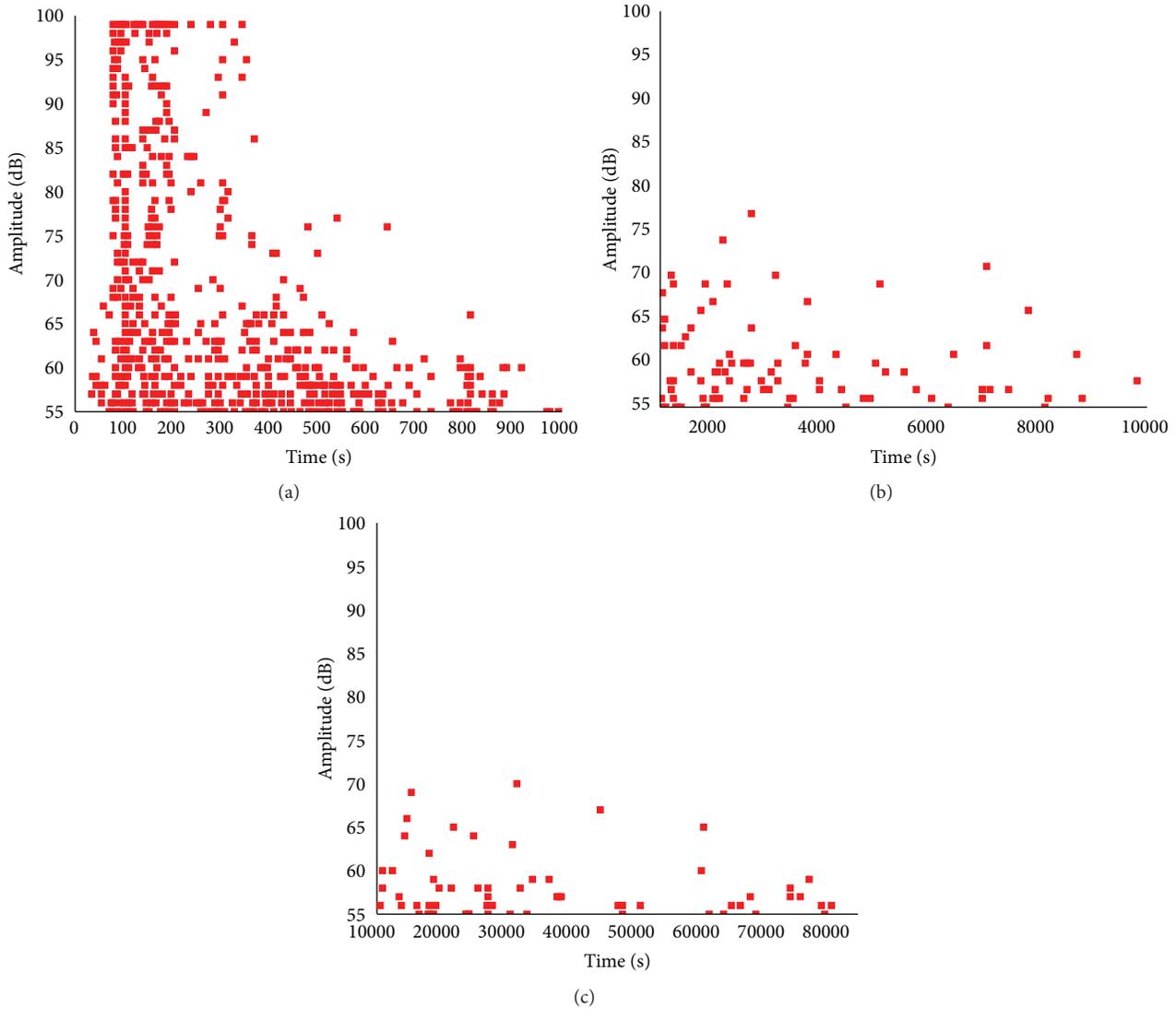


FIGURE 4: Change of AE hit amplitude with the tensile loading time: (a) 0 s–1000 s; (b) 1000 s–10000 s; (c) 10000 s–80000 s.

testing. Several specimens were prepared and the method of material microscopic analysis was used in the experiment.

During the experiment, the specimen was taken off the tensile testing machine as needed according to the variation of AE amplitude. Damage morphology could be observed under microscope and electron microscope. Based on the repeated testing and observation, and other references [17–19] being learned also, the relationship between AE signal and damage mode in T700/6808 composite could be established.

From the preparation experiment, it is found that the matrix cracking had occurred when the AE amplitude reached 55 dB, and the micromorphology is shown in Figure 5.

As tensile loading time increases, the value of AE amplitude also increased. When the value of AE amplitude reached 60 dB, the interface damage occurred in the specimen, and the micromorphology is shown in Figure 6(a). When the value of AE amplitude came into 70 dB, the fiber breakage could be observed in the specimen as shown in Figure 6(b).

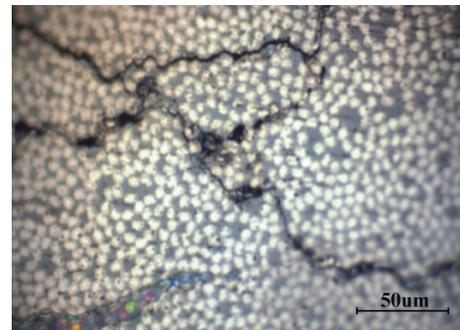


FIGURE 5: Micromorphology of matrix cracking in T700/6808 composite (AE amplitude ≥ 55 dB and ≤ 60 dB).

From Figure 6(a), it could be observed that the interface damage with parallel linear form occurred in the specimen. In Figure 6(b), large area of fiber breakage could be observed

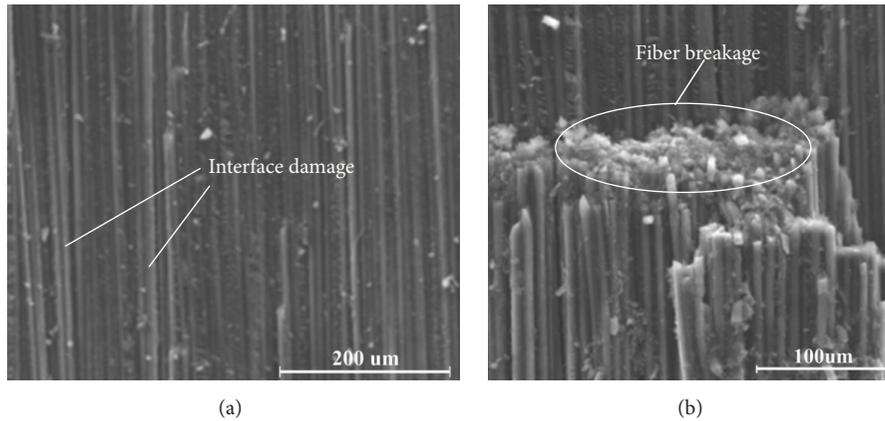


FIGURE 6: Micromorphology of damage modes in tensile specimen: (a) interface damage (AE amplitude ≥ 60 dB and ≤ 70 dB); (b) fiber breakage (AE amplitude ≥ 70 dB and ≤ 100 dB).

clearly in the specimen and a small amount of interface damage appears in the distance. Consequently, the AE amplitude corresponding to the damage mode in T700/6808 composite could be defined as follows: (1) 55 dB–60 dB is matrix cracking; (2) 60 dB–70 dB is interface damage; (3) 70 dB–100 dB is fiber breakage.

It could be obtained from Section 3.1, in the initial stage of tensile loading (0–60 s), the number of AE signals is little and the AE amplitude is low. It indicates that the damage in T700/6808 composite is small in this period, and a small amount of matrix cracking occurs. In the middle stage of tensile loading (60–580 s), the number of AE signals increases and the maximum value reaches 220 s. The range of AE amplitude is 55 dB–100 dB; however, the number of AE signals above 70 dB is significantly less than the number of signals below 70 dB. From the distribution of damage modes, it is known that the major damage is matrix cracking, the secondary damage is interface damage, and the number of fiber breakages is the least. In the later stage of tensile loading (580–700 s), the number of AE signals decreases quickly. The range of AE amplitude is 55–70 dB, and high amplitude signals almost no longer appear. The number of signals distributed between 55 dB and 60 dB is more than that of signals distributed between 60 dB and 70 dB. It indicates that the matrix cracking and interface damage are the major damage in the later stage of tensile loading; however, the number of fiber breakages decreases rapidly for the reduction of the load.

When it comes into the initial stage of load holding (700–1000 s), the incidence of AE signal reduces to the minimum. The signal is mainly distributed in the 55–60 dB between 700 s and 1000 s, and high amplitude signals almost no longer appear. It indicates that the damage number decreases rapidly in the initial stage of load holding and the damage modes are matrix cracking and interface damage; however, the fiber breakage almost no longer occurs. In the middle stage of load holding (1000–10000 s), the level of signal incidence is low. The amplitude of signal is distributed between 55 dB and 80 dB from 1000 s to 10000 s, and high amplitude signals rarely appear. It indicates that the damage in the composite is

small and the major damage is matrix cracking and interface damage; however, the fiber breakage rarely occurs. In the later stage of load holding (after 10000 s), the signal incidence reduces to the lowest level. The signal amplitude is less than 70 dB after 10000 s, and the quantity of signal with the amplitude between 55 dB and 60 dB is more than that with the amplitude between 60 dB and 70 dB. It indicates that the damage in composite decreases to the lowest level, the matrix cracking is the major damage, and none of fiber breakages occurs.

3.3. Criticality Analysis of Damage Modes in T700/6808 Composite. In the fiber reinforced epoxy resin matrix composite, the elastic modulus of fiber is about 235 Gpa; however, the elastic modulus of matrix is 4 Gpa or lower. Therefore, 99% of strength of T700/6808 composite is undertaken by the fiber, and the damage of matrix also has great influence on the life of composite. Different damage modes will have various effects on the reliability of the material; in order to analyze the criticality of damage modes to the safety of T700/6808 composite, the criticality analysis was conducted on T700/6808 composite.

After the filtering of the AE signal with the amplitude between 55 and 70 dB, the change of AE hit number with the tensile loading time for fiber breakage could be obtained as shown in Figure 7.

From Figure 7, it can be seen that the fiber breakage mainly occurs in the middle stage of tensile loading (60–580 s), and the incidences of fiber breakage are different among three specimens during this period. In the later stage of tensile loading (580–700 s), the incidence of fiber breakage decreases rapidly. When it comes into the stage of load holding (700–10000 s), the fiber breakage could be hardly found in the specimen of number 1, and none of fiber breakages occurs in the specimen of number 2; however, the fiber breakage occurs occasionally in the specimen of number 3.

Figure 8 shows the change of cumulative number of fiber breakages with the tensile loading time in three specimens, obtained by the data processing in Figure 7.

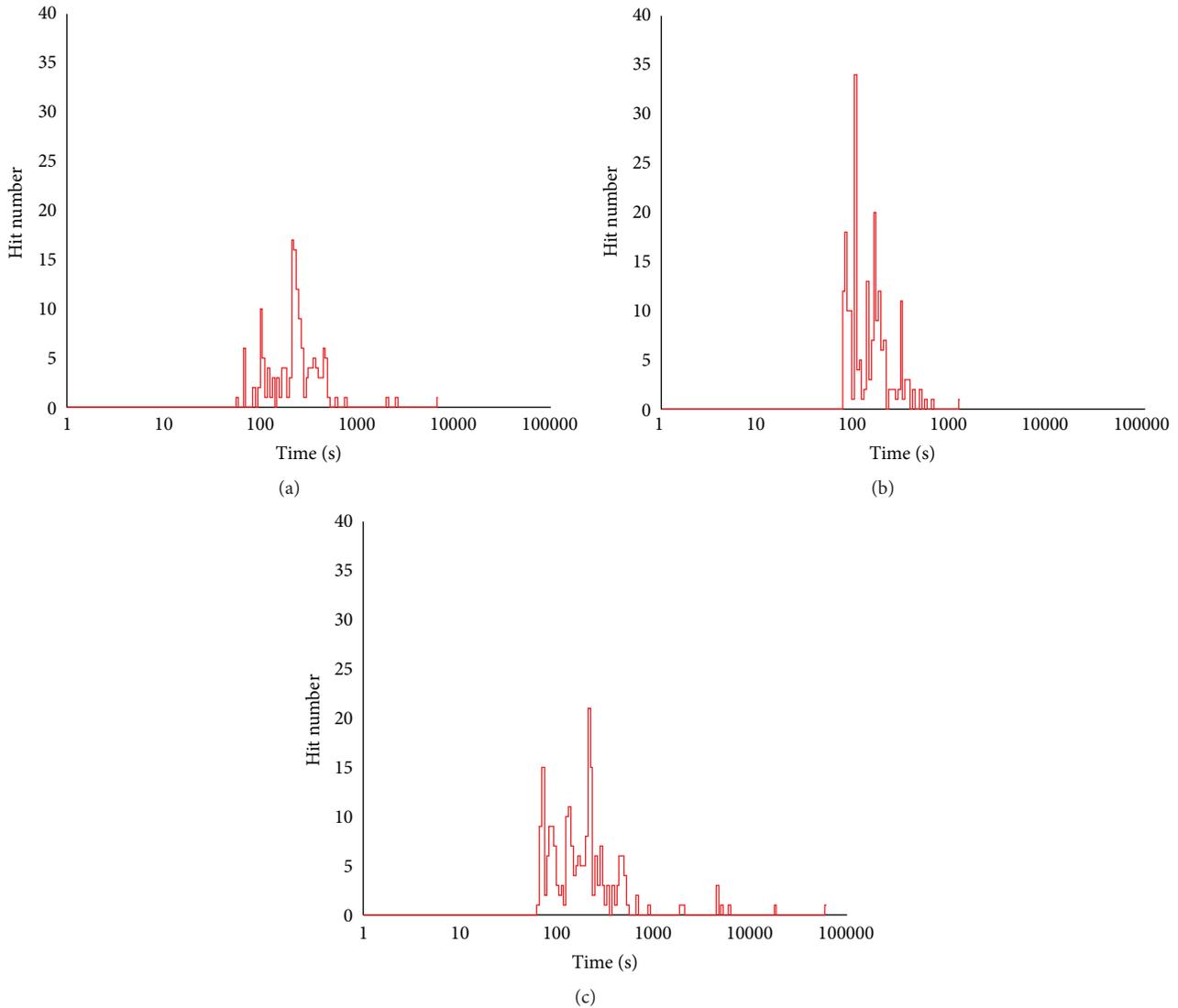


FIGURE 7: Change of AE hit number with the tensile loading time for fiber breakage in three specimens: (a) specimen of number 1; (b) specimen of number 2; (c) specimen of number 3.

As shown in Figure 8, fiber breakages nearly occur from 70 s to 700 s in all three specimens, and the number of fiber breakages becomes stable in the end of tensile loading at 700 s.

In the load holding stage, the number of fiber breakages is, respectively, 4 in specimen of number 1, 2 in specimen of number 2, and 12 in specimen of number 3. At the end of tensile testing, the cumulative numbers of fiber breakages are different among three specimens: the specimen of number 1 is 158, the specimen of number 2 is 209, and the specimen of number 3 is 223. The number of fiber breakages and the damage process are different among three specimens, caused by the instability of forming technology and discreteness of fiber strength in the T700/6808 composite.

After the filtering of the AE signal with the amplitude between 71 and 100 dB, the change of AE hit number with the tensile loading time for matrix and interface damage could be obtained as shown in Figure 9.

As shown in Figure 9, it can be seen that the damage of matrix and interface mainly occurs in the middle stage of tensile loading, and the incidences are different among three specimens. In the later stage of tensile loading, the incidence decreases rapidly, and the incidence is less than 100 when it comes into the load holding stage in most of specimens.

After the data processing in Figure 9, the change of cumulative damage number of matrix and interface with the tensile loading time is shown in Figure 10.

As shown in Figure 10, nearly all the damage of matrix and interface occurs from 60 s in three specimens. In the stage of tensile loading (0–700 s), the damage of matrix and interface has high incidence in three specimens, and the incidence reduces when the tensile loading finished. In the stage of load holding (after 700 s), the curves of cumulative damage are parallel which indicates that the damage incidence is identical in the stage of load holding. At the end of the

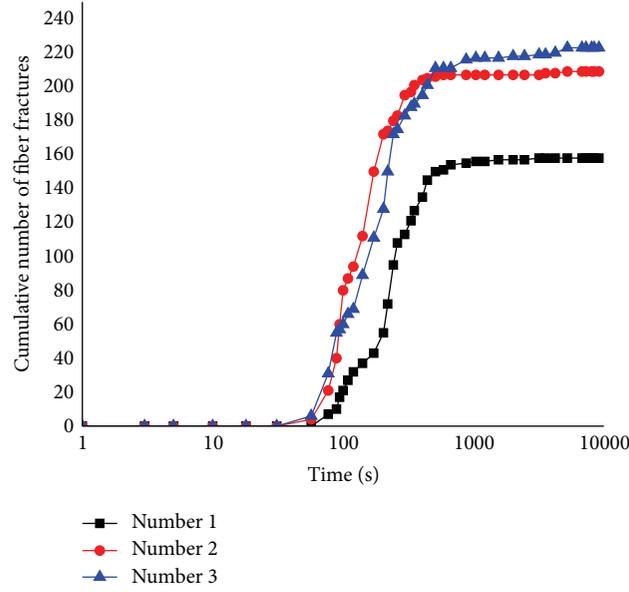


FIGURE 8: Change of cumulative number of fiber breakages with the tensile loading time in three specimens.

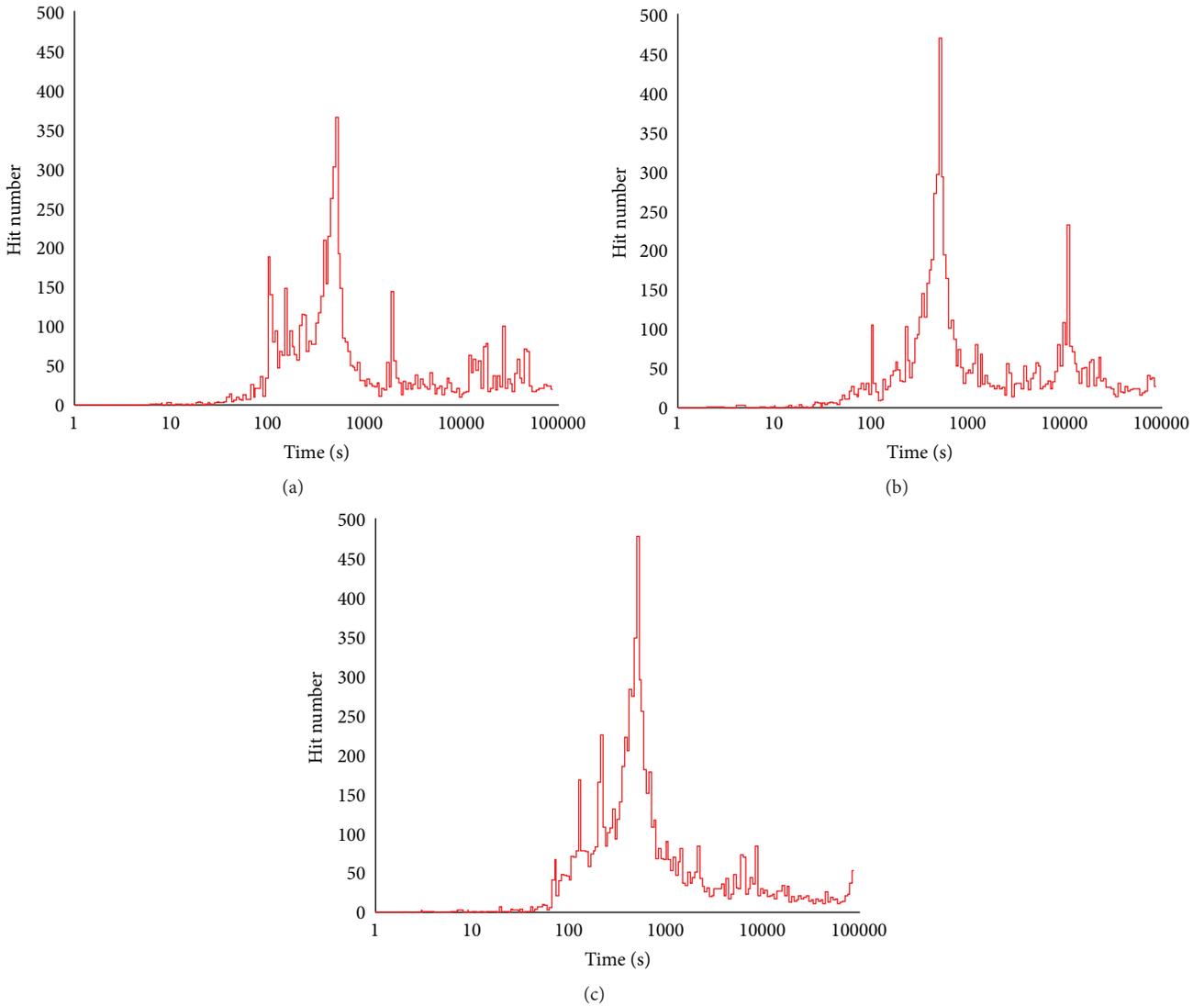


FIGURE 9: Change of AE hit number with the tensile loading time for matrix and interface damage in three specimens: (a) specimen of number 1; (b) specimen of number 2; (c) specimen of number 3.

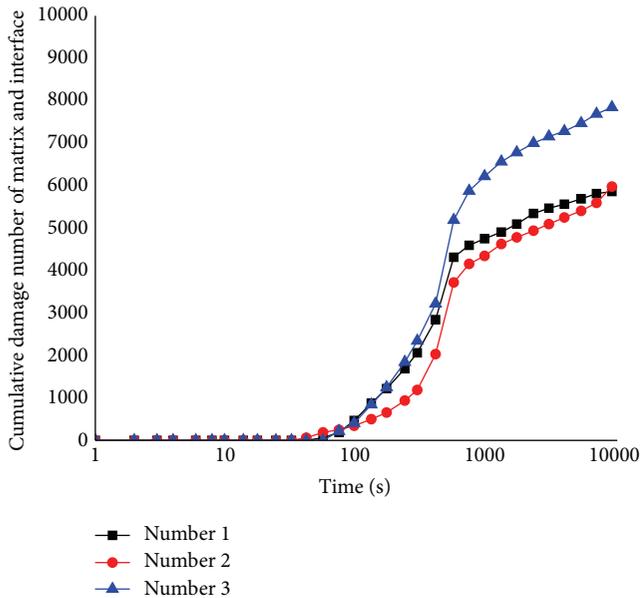


FIGURE 10: Change of cumulative damage number of matrix and interface with the tensile loading time.

tensile testing, it can be seen that the cumulative damage number of matrix and interface is, respectively, 5862 in specimen of number 1, 5977 in specimen of number 2, and 7844 in specimen of number 3. The difference of cumulative damage number among three specimens shows the difference properties of matrix and interface, and it is mainly related to the discreteness of material molding process and the fiber breakage number.

From Figure 10, it can be seen that the cumulative damage number of matrix and interface is more than that of fiber, and the damage of matrix and interface still maintains high and stable incidence in the stage of load holding. The criticality of damage mode is the product of the incidence and damage duration, which illustrates that the matrix and the interface are the weakness affecting the reliability of T700/6808 composite.

4. Discussion and Conclusions

The study presents an investigation of damage evolution process in the T700/6808 composite based on AE technology, and some discoveries were obtained from the research. In the initial stage of tensile loading, due to the design bearing capacity of the material, small damage occurs inside the composite. The composite suffered from severe damage in the middle stage and the later stage of tensile loading, which mainly include the matrix cracking, the interface damage, and the fiber breakage. It is shown that the damage of T700/6808 composite mainly occurs in the stage of tensile loading.

The damage of T700/6808 composite had been decreased rapidly in the stage of load holding. The matrix cracking and interface damage are two major types of damage in T700/6808 composite; however, the fiber breakage rarely

occurs. The fiber breakage mainly occurs in the middle stage of tensile loading; however, it seldom occurs in the later stage of tensile loading and load holding stage. It is shown that the fiber breakage of T700/6808 composite rarely occurs in the stage of load holding.

The maximum numbers of fiber breakage are different among three specimens, caused by the discreteness of fiber strength and the instability of forming technology of T700/6808 composite. The matrix cracking and interface damage have higher incidence and longer duration than the fiber in the whole process of tensile loading, which illustrates that the matrix and interface are the weakness affecting the reliability of T700/6808 composite.

Competing Interests

The authors declare no conflict of interests.

Authors' Contributions

Weihan Wang was responsible for drafting of paper; Weifang Zhang was responsible for designing of experiment; Sheng-wang Liu was responsible for conducting of experiment; Xiaoshuai Jin was responsible for analyzing of data.

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