

On-line Monitoring by Acoustic Emission of Butt Joint Structure on the Composite Fuselage Frame

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Abstract. Acoustic emission (AE) technique is an online and dynamic non-destructive testing technology by diagnosing sounds, applicable to damage identification of all sorts of materials and structures. In order to fulfill the requirement of on-line monitoring for butt joint structure on the composite fuselage frame in static loading, Acoustic Emission (AE) is employed in this article. The experiment research is focused on examining the damage evolution process of the specimen subjected to mechanical tests by constantly monitoring the AE and strain responses. Combined with strain results, the recorded acoustic signals are analyzed using AE characteristic parameters such as AE amplitude and AE accumulative energy to identify five different damage stages and conclude the corresponding damage style during the entire test. The outcomes of this article can be available for supplementation and improvement of the current on-line non-destructive testing research for composite structures.

1. Introduction

In recent decades, especially after the 1950s, acoustic emission (AE) technology has developed rapidly and been widely used in various engineering fields since it is a dynamic non-destructive testing method that provides a new means for technicians to conduct non-destructive testing[1]. It is particularly worth mentioning here that in contrast with other non-destructive testing methods, AE possesses the capability of achieving early damage recognition, allowing real-time monitoring of damage process, and identifying different kinds of damage mechanisms[2], which is attributed to its high sensitivity, passivity and dynamic nature. By the use of the AE method, on-line monitoring for the damage evolution of the specimen can be implemented with the assistance of other non-destructive testing methods. For example, the initiation point, expansion speed and expansion time of the damage can be comprehensively understood by means of AE. Hence, this article investigated the damage behavior of composite structure based on the AE technique.

At present, researchers have conducted a great quantity of investigation to explore the AE technique application in many kinds of engineering fields. For example, Yongwei Z et al. [3] investigated the relationship between AE characteristic parameters and rock failure process, and accordingly determined the crack type by the average frequency and the reciprocal of rise angle. In an effort to identify the damage mechanisms in metal plates, Kordatos E Z [4] recorded AE activity during fatigue experiments in metal CT specimens with a V-shape notch which were loaded in fatigue until final failure, and thus discovered that AE parameters exhibited a sharp increase approximately 1000 cycles before than final failure. In the fatigue life prediction for steel bridges, Yu J et al. [5] performed fatigue tests to detect AE signals from fatigue cracks and then investigated AE characteristic parameters and crack growth rate of the steel bridge. Accordingly, the study indicates that the



correlation of AE absolute energy rate with crack growth behavior is of paramount importance and prognosis for in-service steel bridges.

In particular, in the case of composite materials, to attempt the relationship between AE response and the corresponding damage mechanism, many investigations based on the AE technique have been performed up to now. After examining AE response of loaded composite material, Sause MGR [6] considers the highest frequency AE signals to be related to fiber breakage, while the lower frequency AE signals are in general caused by mechanisms such as matrix fracture or fiber pull-outs. In the studies of Masmoudi S et al. [7], the AE signals were analyzed by using the classification k-means method to identify the different damage mechanisms and to follow the evolution of these mechanisms for composite materials. In addition, after employing broad band and high fidelity sensors to acquire abundant AE signals, Prosser W H et al. [8] adopted a waveform based AE response handling system to study the initiation of transverse matrix cracking in cross-ply graphite/epoxy composites.

In this context, this article proposed the use of AE technique to implement the on-line monitoring for butt joint structure on the composite fuselage frame in an attempt to attain the damage evolution process of the specimen. Combined with strain measurement technique, the research utilized AE characteristic parameters such as AE amplitude and AE accumulative energy to analyze the recorded AE signals and to identify five different damage stages and the corresponding damage style of the specimen during the entire test. In the light of the investigation, the five damage stages were summarized as elastic deformation stage, initial damage stage, stable damage development stage, rapid damage expansion stage and overall failure stage. The research results can provide real-time damage prediction for composite structure verification tests and valuable data sources for further improvement of AE technology. The outcomes of this article can be used for supplementation and improvement of the current on-line non-destructive testing research for composite structures.

2. Acoustic emission technique

Acoustic Emission is a common physical phenomenon, which is transient elastic wave generated by the rapid release of energy from localized sources within a material. Under the action of excitation (such as force, temperature, electricity, etc.), the material will behave local stress concentration, resulting in energy release and further generating acoustic emission waves coupled with damage activation mechanisms. After transforming AE waves into the corresponding electrical signals by a sensor, the information about the intensity and activity of the sound source can be obtained by analyzing the signals and, thus the evaluation of material integrity can be realized.

The commonly used procedure for AE monitoring is as follows[9]. Firstly, piezoelectric sensors are employed to convert surface vibrations caused by acoustic emission waves transmitted to the surface of the material into electric signals. Secondly, these electric signals are collected and analyzed by acoustic emission detection equipment. Finally, after investigating AE characteristic parameters, relevant information about the AE source can be obtained, and further the evaluation of the activity, intensity and severity of the sound source can be realized. The parameters commonly used for the analysis of AE signals include threshold, peak amplitude, energy, rise time, duration, counts, etc.

3. Experimental procedure

3.1. Material and geometry of the specimen

IMA_M21E unidirectional strip material was used for the main parts of the specimen, including the skin, the stringer, the frame, etc. The material meets the specification of CMS-CP-309, and the thickness of single layer is 0.184mm. The specimen is of C-shaped thin frame, and its geometry is displayed in Figure 1, where the radius of the skin on the curved frame is 2960 mm, the span angle is 28.45°, and the width is 620 mm. In this experiment, the area of concern is located on the butt joint section in the middle of the specimen, marked by a red rectangle in Figure 1. Furthermore, in order to allow more focused observation during the test, two embedded defects were prefabricated in the butt joint structure of the specimen in the process of manufacturing, as shown in Figure 2. Accordingly, the

AE sensor was mounted on the location indicated by the red dot in Figure 1 in order to carry out the on-line monitoring for the damage evolution of the butt joint structure in the specimen.

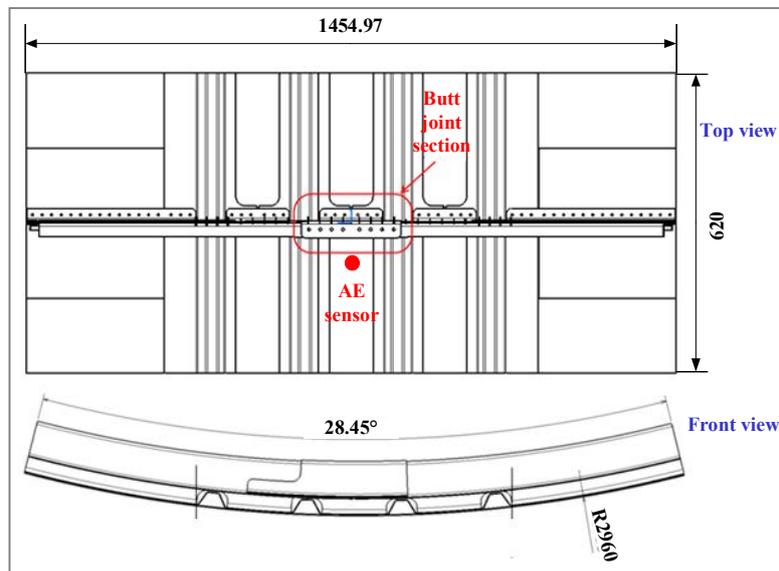


Figure 1. The specimen geometry.

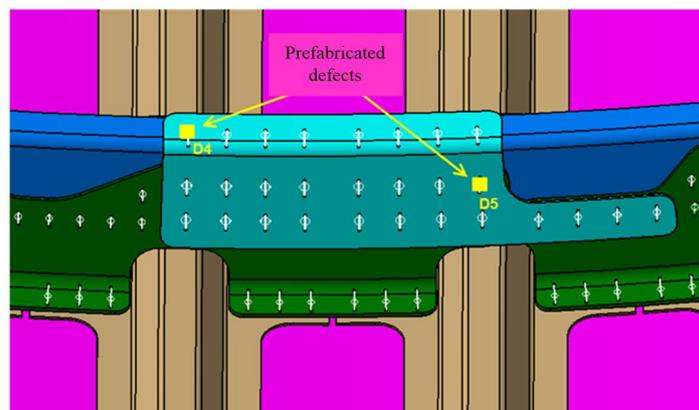


Figure 2. Schematic diagram of the locations of embedded defects.

3.2. Experiment procedure

At ambient temperature, the specimen was subjected to reverse four-point bending in static loading until failure. As depicted in Figure 3, two supporting points of the fixed platform on the lower part of the load machine support the specimen upwards while two loading points on the upper part of the load machine force the specimen downwards, so as to form the force coupling and achieve the reverse bending effect. Hence, the inner edge of the frame would be pulled while the skin compressed under the loading condition.

3.3. AE monitoring system

In the test, AE signals were sensed by AE sensor R15 α from Physical Acoustics Corporation (PAC) with a frequency range of 50 kHz-200 kHz and a resonant frequency of 150 kHz, and then were amplified by the preamplifier provided by PAC with a 40dB uniform gain across all frequencies. Subsequently, the acquisition of AE signals was carried out by the master computer that utilizes SAMOS PCI-8 data acquisition board with 8 channels. In particular, All AE signals were bandpass filtered before recording between 100kHz and 400kHz which effectively removes the mechanical

noise of low frequency and electronic noise of high frequency, and all signals were recorded with a Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) of 50, 200, 300 μ s, respectively at a sampling rate of 3MHz.

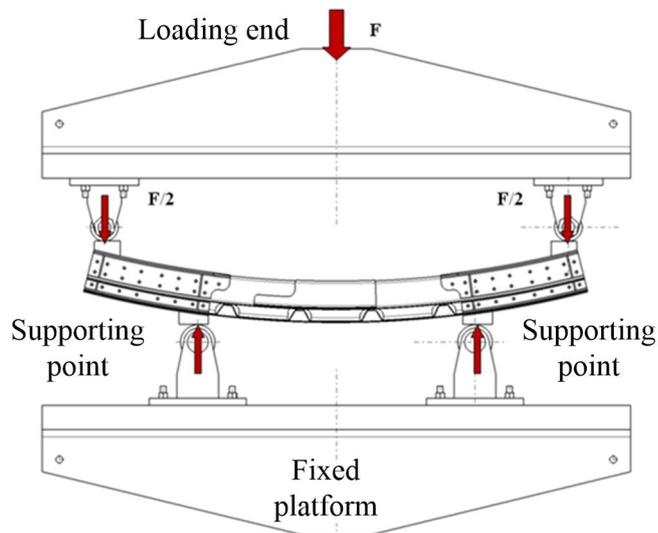


Figure 3. Schematic diagram of the specimen tested in reverse four-point bending

4. Results and analysis

In this article, we adopted the method based on the characteristic parameters to analyze the recorded AE signals during the entire test. Figure 4 shows the relationship between AE characteristic parameters and times, including AE amplitude vs. time and AE accumulative energy vs. time. In this figure, the black vertical solid lines represent some special time labels, and the corresponding descriptions can be seen in Table 1.

Table 1. Time labels information.

Time label position(s)	Load value	remark	Time label position(s)	Load value	remark
69	40%		260	38 kN	
82	50%		290	40 kN	
95	60%		340	42 kN	Persons could hear sounds.
140	30kN		480	45 kN	
165	32 kN		530	45.6 kN	Sounds became very loud.
200	34 kN		560	46.718 kN	Failure of the specimen.
220	36 kN				

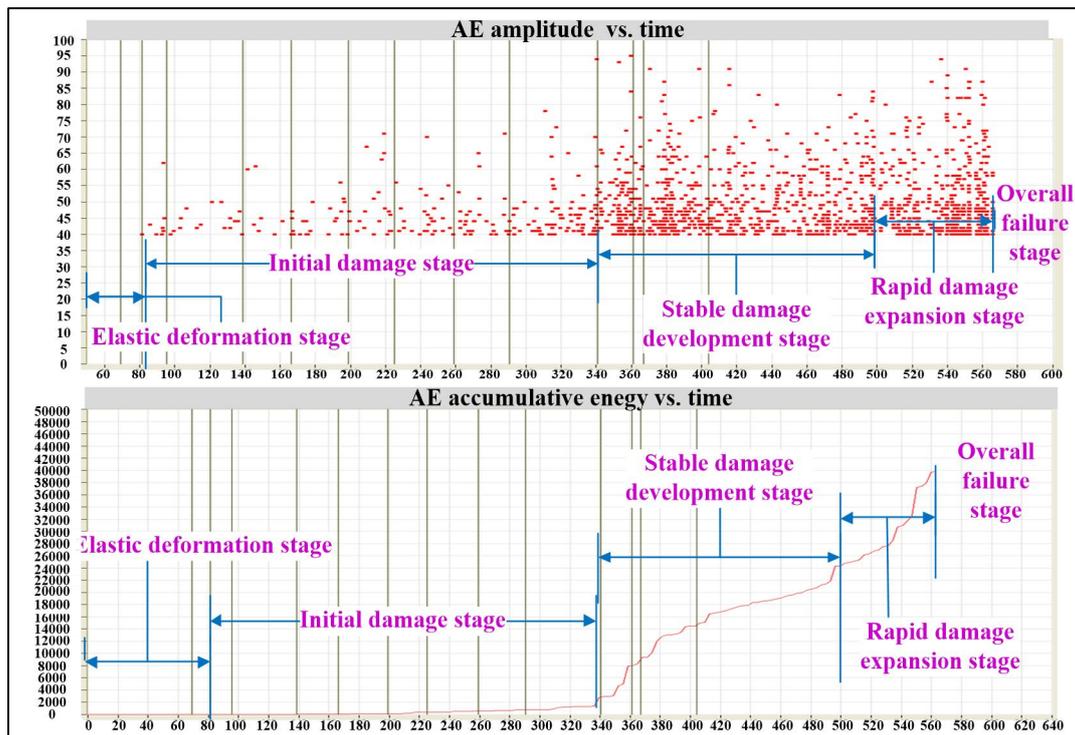


Figure 4. AE different characteristic parameters vs. time during the entire test.

Besides, the strain behavior of the strain gauge near the fracture location, identified by the red oval in Figure 5, is also illustrated in Figure 6. The combination of Figure 4, Table 1 and Figure 6 was utilized to identify the damage evolution process in the static test for the specimen, which is remarked in Figure 4 and Figure 6 and comprises five different stages.

The first stage (0-82s) is the elastic deformation stage. It can be seen from the diagram of AE amplitude vs. time in Figure 4 that there is no acoustic emission event, representing no new damage in the composite material. This conclusion can be confirmed by the curve in Figure 6 where the load level of the first obvious turning point is 12, and the corresponding load is 60% load (as shown in Table 1, the time position of the AE history diagram corresponding to 60% load is 95s). The strain change rate before turning point is larger, which implies the elastic deformation of the specimen. During this period, corresponding to the elastic deformation stage of acoustic emission. The strain change rate after the turning point becomes smaller, which represents plastic deformation caused by the damage of composite materials. In addition, the above results also show that acoustic emission monitoring (83s) can detect the damage initiation earlier than strain monitoring (96s).

The second stage (83-335s) is the initial damage stage. From Figure 4, it can be seen that the AE amplitude in this stage is basically below 65dB, and the energy released by AE activities is also at a low level. A large number of low-amplitude and low-energy AE signals are caused by the damage of the composite matrix, and micro-cracks begin to appear in the composite matrix during this stage. The damage types in this stage mainly include delamination at weak joints caused by the embedded defects, extrusion damage and primary micro cracks of the matrix, etc.

In the strain-load level curve of Figure 6, the initial damage stage is between 13-328 load level, corresponding to 60% load-42kN load. According to Table 1, this stage corresponds to the range of 95-340s of AE monitoring time. Thus, it is found that AE monitoring (83-335s) is also ahead of strain monitoring (95-340s) in the initial stage of damage perception.

The third stage (336 ~ 500s) is the stable development stage of damage. As can be seen from Figure 4, the AE activity is more frequent in this stage, the amplitude of AE events increases, and the energy begins to increase, which means that the damage is becoming more and more serious. From Figure 4, it can be seen that the AE signal with amplitude ranging from 65 dB to 95 dB increases obviously, and the energy vs. time curve also increases rapidly. In this stage, the damage mainly

comes from the further propagation of the primary crack in the matrix formed in the first stage, which results in the debonding of the matrix and the fibers at the front of the crack tip, the buckling of the interface and the instability of the specimen. A more careful observation of Figure 4 shows that in the latter half of this stage the amplitude of AE events falls back and the energy growth slows down. This is mainly because after the release of most energy the phenomenon of local stress concentration is greatly alleviated, thus causing the damage expansion of the specimen to be relatively flat.

This stage is between 329 and 453 load level in Figure 6, corresponding to 42kN to 45.4kN load. According to Table 1, this period is about 341-515s of AE monitoring time. It can be seen that the AE monitoring (336-500s) is also ahead of the strain monitoring (341-515s) to perceive this stage.

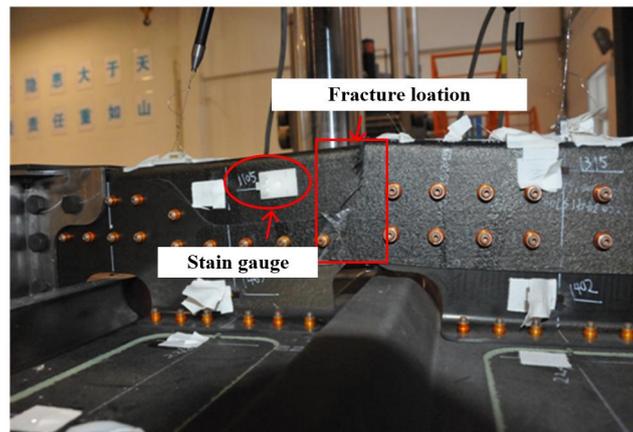


Figure 5. Picture of strain gauge location and fracture location.

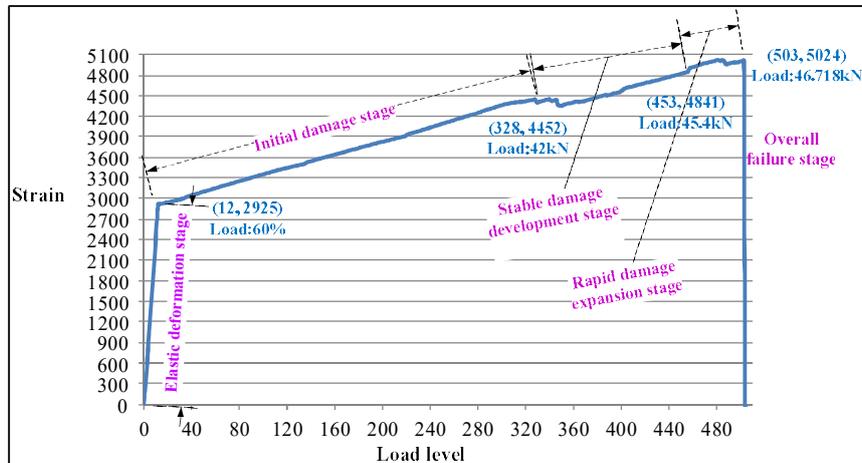


Figure 6. Strain-load level curve of strain gauge near the fracture location.

The fourth stage (501-560s) is the rapid expansion stage of damage. As can be seen from Figure 4, at this stage the AE energy increases sharply and AE activity becomes frequent again. This is because with the increase of load, damage continues to accumulate, resulting in a rapid decline in the bearing capacity of the structure and further rapid expansion of damage. At this stage, the damage begins to expand unstably, and the matrix damage is further aggravated, accompanied by delamination and fiber breakage. Since the matrix has been completely broken before the fiber breaks, the AE events in the mid-term of this stage decrease significantly. In the later stage, with the further increase of load, the fibers are pulled out from the matrix, even some fibers break, and a greater stress concentration is formed near the fracture surface.

In Figure 6, this stage is between 453 and 503 load level, and the corresponding load is 45.4 kN to 46.718 kN, which is about 516 s to 560s of AE monitoring time. Consequently, AE monitoring (501-560s) is also ahead of strain monitoring (516s-560s) in sensing this stage.

The fifth stage (the moment of fracture) is the failure stage of the specimen. At this stage, a large number of reinforcing fibers in the specimen were pulled off instantaneously, the AE energy increased rapidly to the maximum value, and ultimately the beam of the specimen was destroyed at the embedded defect D5 (see Figure 2 and Figure 5). At this time, the specimen had been in the stage of overall failure. It can also be seen from Figure 6 that the strain decreases sharply at the moment of fracture, which is because the strain gauge is also destroyed at the same time.

5. Conclusions

In this article, AE technology was employed to monitor the docking test of composite fuselage frame, and it can be found that the process of crack initiation, propagation and destruction of composite materials can be identified by using the analysis of AE signal characteristic parameters, which verifies that AE technology can be used in the on-line monitoring of composite structures. According to the preceding investigation, the following conclusions can be drawn.

1) By combining the AE signal characteristic parameters and the strain-load level curve of the specimen, the damage evolution process of the specimen can be achieved and divided into five stages: elastic deformation stage, initial damage stage, stable damage development stage, rapid damage expansion stage and overall failure stage. The damage accumulates in the first stage, the crack originates in the second stage, buckling begins in the third stage, rapid propagation is in the fourth stage, and destruction is in the fifth stage.

2) The main types of damage in each stage are as follows: no new damage occurs in the first stage; the second stage mainly includes delamination damage at weak joints caused by embedded defects, extrusion damage and primary micro cracks of matrix; the third stage mainly includes matrix crack, matrix and fiber debonding; the fourth stage mainly includes matrix damage, delamination damage and a large amount of fiber breakage; in the fifth stage, a large number of reinforced fibers were pulled off instantaneously and the specimen was broken.

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