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Acoustic emission response and progressive failure behaviors of composite adhesively bonded joints loaded by Mode I and II

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Abstract

The analysis of progressive failure process is one of the critical issues in the research of composite adhesive joints. In view of this point, acoustic emission (AE) is applied to real-time monitoring of the dynamic damage process of composite adhesive joints in some loading modes such as Mode I (double cantilever beam (DCB)) and Mode II (end notch flexures (ENF)). Furthermore, the high speed camera and scanning electron microscopy are carried to analyses the damage mechanisms of composite bonded joints. Results show that there are significant differences in the load-deflection curves of the specimens under the loads of Mode I and II. The main failure mode of the two types of loading modes is adhesion failure, and the accumulation of damage observed at the edge of the adhesively bonded layer cause defeat of the composite bonded joints. In addition, AE parameters including amplitude, hits, energy, and duration are connected with the fail mechanism. Furthermore, the dynamic characteristics of the AE signal, especially amplitude spectrum distribution, can provide evidences for studying progressive failure behaviors of composite adhesive joints.

1. Introduction

With the development of Adhesive bonding technology in various industrial fields [1–7], progressive failure behaviors of composite adhesive joints begin to gain more attention. For Adhesive bonding technology, dissimilar materials can be joined in adhesive bonds to obtain connection structures with higher toughness, lighter weight and less stress concentration than traditional mechanical connections (rivet, bolt, weld, etc). For example, it has been widely used for the connection structure of scale wind turbine blades. However, debonding is one of the main reasons for the blade failure, based on researches concerning the failure of wind turbine blade [8–10]. Consequently, it is significance to study progressive failure behaviors of adhesive joints.

For purpose of more efficiently investigating the mechanical behavior of adhesive bonded joints, several numerical simulations [11, 12] and experimental analysis [13–15] have been conducted. Damage assessment of composite adhesion joints on experimental static and fatigue testing were carried out by Mattos et al [16]. Turan et al [17] investigated the progressive damage behavior of reinforced bonded single-lap joints by experiment and numerical. Results showed that the difference between the experimental results and numerical analysis was between 2% and 10%. The ultimate load of reinforced bonded single lap joint was 1.3%–22.8% higher than that of the unreinforced adhesive. Furthermore, mode I [18–20] and mode II [21–23] fracture energy of composite adhesive joints was studied through experiment and theoretical analysis in recent years.

Acoustic emission (AE) technique, as an important non-destructive testing (NDT) method, can be used to analyze the characteristics of stress waves caused by the sudden movement of cracks, and can effectively monitor the occurrence and propagation of adhesive structure damage in real time [24–29]. AE signals were studied for damage characterization of adhesive single lap joints in the tensile test, and identified the different failure mechanisms by Mohamed et al [30]. Croccolo and Cuppini [31] have established a new method capable of to estimate the bond defect and the final release moment of the assembled joints based on AE technique. Zarouchas and van Hemelrijck [32] identified the different damage mechanisms into the material during the loading based
on analyzing AE data, and measured displacements and deformations with digital image correlation technique. At present, there have been many researches on damage mechanisms of composite bonded joints in the loading conditions of mode I and II over many years. However, few studies concerning with progressive failure behaviors of composite bonded joints in the loading conditions of mode I and II were reported.

The purpose of this paper to investigate progressive failure behaviors of composite bonded joints in the loading conditions of mode I and II. DCB tests and ENF tests were performed, and AE technique was used to detect the damage and failure signals throughout the loading progress. With the help of the high speed camera and the scanning electron microscopy, damage behaviors and corresponding AE response of specimens in the loading conditions of mode I and II were discussed.

2. Experimental details

2.1. Material fabrication

The composite laminate was constructed from 6 plies of unidirectional glass fabric ECW600–1270 (areal weight 600 g m$^{-2}$) and thermosetting epoxy matrix were injected into preforms by vacuum infusion method. The mixing ratio for Araldite LY 1564 SP epoxy resin to Aradur 3486 curing agent in weight was 100:34. The dimensions of each laminate were 160 mm $\times$ 25 mm $\times$ 2 mm. The same epoxy resin and curing agent were applied for the adhesive. Provided by manufacturer, the shear and flexural strength of the adhesive were 15 to 18 MPa, 118 to 130 MPa, respectively. The thickness of adhesive layer was about 0.5 mm. The composite adhesive joints were hardened at room temperature for 24 h. Samples were divided into two types: Specimen A (Mode I) and Specimen B (Mode II). For each mode of bonded joint, a total of four samples were used. According to ASTM standard D5528–01 and ASTM standard D7905/D7905M–14, the dimensions of Mode I and II specimen were depicted in figure 1.

2.2. Experimental procedures

Mode I (double cantilever beam (DCB)) tests and Mode II (end notch flexures (ENF)) tests were performed by a mechanical testing machine (CMT5305) with the crosshead velocity of 2 mm min$^{-1}$. Meanwhile, AE signals during the failure processes were collected by an AMSY–5 system.

The detection device for AE monitoring during DCB testing and ENF testing as shown in figure 2. One AE sensor (VS150–RIC) was placed on the surface of the specimen, and silicone grease was used between the sensor and specimen surface to achieve good acoustic coupling. Both distances between the one end of specimen and the sensor under Mode I and II loading were 40 mm. Furthermore, the sensor with a sampling rate of 5 MHz and

![Figure 1. Geometrical configuration of specimens: mode I (a), mode II (b).](image-url)
34 dB output of built-in preamplifier pre-amplification was used for this study. The frequency distribution covers a range of 100–450 kHz, and the center frequency was 150 kHz. Electric and mechanical noises were eliminated using a threshold at the value of 40 dB. On basic of ASTM standard E976–10, pencil tests were performed before each test. Some AE parameters such as relative energy, cumulative hits, amplitude, duration etc were collected during DCB tests and ENF tests. In addition, the morphology of the fractured surface was obtained by a scanning electron microscopy (SEM, JEOL JSM-7500F), and the failure processes of specimens were recorded by using a high speed camera (IDT 18–0614–0538).

3. Results and discussion

3.1. Mechanical characterization of adhesive joints
The typical load versus displacement curve of specimens under the loading conditions of mode I and II as shown in figure 3. From figure 3, for mode I specimen, the load-displacement curve shows linear relationship until reaching the maximum load, then decreases gradually tends to be constant. The peak load and corresponding displacement of the mode I typical composite specimens was 71.1 N and 1.25 mm, respectively; for mode II specimen, the load increases with the increasing of the displacement, then reaches a peak value with the failure of adhesive joint. The peak load and corresponding displacement of the mode II typical composite specimens was 254.7 N and 2.82 mm, respectively. Nearly all nonlinear energy dissipations were contributed by the adhesive fracture. The critical strain energy release rate under the loading conditions of mode I and II were defined as $G_I$ and $G_{II}$, respectively. The experimental value of $G_I$ can be calculated according to equation (1) [33], and $G_{II}$ can be calculated according to equation (2) [34]. The $G_I$ and $G_{II}$ from test results was 0.36 kJ m$^{-2}$ and 0.84 kJ m$^{-2}$, respectively. Compared with mode II loading, mode I loading shows lower levels of strain energy release rate.

$$G_I = \frac{P^2C}{2Ba}$$

Here $P$ and $a$ is peak load and effective non-bounded length, respectively, $B$ and $C$ is the width and compliance of the specimen, respectively.

$$G_{II} = \frac{9P^2Ca^2}{2B(2L^3 + 3a^3)}$$

Where $P$ is peak load, $a$ is effective non-bounded length, $B$ and $C$ is the width and compliance of the specimen, respectively, and $L$ is one-half support spacing.

Figure 4 exhibits high-speed images of mode I specimen. A high speed image was recorded every 0.5 s starting from the position of the crack tip (figure 4(a)). Four pictures recorded at origin, 0.5 s, 1.5 s, and 2 s, respectively were selected to show the progress of the crack propagation. Recording time of the high speed
camera was 2 s, and the length of crack propagation in record time was 50.22 mm according to the scale the specimen. Therefore, the crack propagation speed for adhesive layer was 25.11 mm s$^{-1}$ based on crack length and time intervals.

Figure 5 shows the failure surface SEM images of Mode I and II specimen. Adhesion failure was observed to be the primary failure mode due to the bond strength for the adhesive was lower than the strength of the bond layer itself. Moreover, some fiber failure and cohesive failure were found at the edge of the adhesive layer, which was attributed to the stress concentration at this location.

From figures 4 and 5, with the help of high-speed and SEM images, the primary failure mode was adhesion damage, and with fiber breakage and cohesive failure in the edge of the adhesive layer. More importantly, many
microcracks were found in the edge of the adhesive layers of both Mode I and II specimens due to stress concentration. Experimental results suggest that as load increases, the main crack initiation and propagation toward the edge of the adhesive layer. According to the SEM and high speed camera analysis of the damage, there may be failure mechanism with AE characteristics be present.

3.2. AE response of adhesive joints

Some AE parameters such as relative energy, duration, amplitude and cumulative hits have been analyzed during DCB tests and ENF tests.

Figure 6 shows the time history of the specimens’ force and AE energy. From figure 6(a), for mode I specimen, AE signals with the energy under 5000 eu were collected with the load increasing. The load decreases gradually after the peak and finally stabilizes, nevertheless the AE energy gradually increases to a high level until the adhesive joint fails. AE relative energy was observed during all the whole process of loading, and the peak of AE energy was close to 13000 eu. From figure 6(b), for mode II specimen, few AE signals were obtained in initial loading, and then a high relative energy with the value of nearly 12000 eu was observed with the increasing of
load, and this moment corresponds to the rupture of the adhesive. As the load increases, constant AE signals with the value under 3000 eu were obtained until the failure of adhesive joint. Consequently, it was believed that the macroscopic cracks were formed by lots of micro cracks in the edge of the adhesive layer, and damage initiation and propagation occurred before reaching the failure load. Experimental results agree with numerical results in the literature \[8\].

The relationship between AE hits versus amplitude for specimens can be seen in figure 7. According to figure 7(a), there were fewer AE hits with high amplitude, but more hits with low amplitude produced in mode I specimen. A large number of micro-cracks generated in adhesive layer in initial loading, and the amplitude of AE hits was at a lower level. As the damage accumulated, AE hits with high amplitude generated during failure stage, and the AE amplitude higher than 80 dB correspond to fiber failure. In comparison with figure 7(a), a similar changing relationship between AE amplitude and hit for mode II specimen were obtained in figure 7(b). Furthermore, more AE hits and more damage produced in mode II specimen. The results show that the production of the micro-cracks bring lots of AE hits, and AE hits with high amplitude produced in adhesive layer as the damage initiate and propagate.

Figure 8 presents the results for the AE amplitude spectrum of specimens. The loading procedure was divided into several different damage stages to observe AE amplitude spectrum of all the whole process of loading. From figure 8(a), for mode I specimens, low-amplitude AE events were observed due to the fact that a large number of micro-cracks were dominant in the initial load stage. Over time, AE events in the amplitude range of 60 to 80 dB were observed, and this phenomenon related to micro-cracks accumulation and combination. The occurrence of all AE amplitude events leads to the production of the entire spectrum bandwidth. From figure 8(b), the amplitude spectrum distribution was different from mode I specimen. At the initial stage, the amplitude spectrum ranges from 42 to 72 dB when the loading time increased to 20 s. As the load increases, more AE events were obtained compared with mode I specimen and the amplitude of the AE events increases from 60 dB to 80 dB due more damage accumulation. Therefore, the amplitude spectrum was
the key parameters to describing damage evolutionary process, which the failure of adhesive joints originated from micro-cracks initiation and propagation [35].

The features of AE cumulative hits produced in specimens can be found in figure 9. For mode I specimen, AE cumulative hits increase rapidly with the increase of load, and then become slow when the load tends to be constant. The total of AE cumulative hits was 426 during all the whole process of loading. For mode II specimen, AE cumulative hits increase slowly in initial loading, and then increase significantly with the accumulation of damage. The total of AE cumulative hits was 6280 when the adhesive joint was damaged. Compared with mode I specimen, there were far more AE cumulative hits for mode II specimen. The phenomenon maybe contributed to the fact that more micro-damage produced in the adhesive layer under mode II loading. It has been found that the damage progression was strongly linked to the corresponding AE cumulative hits.

The characteristics of AE amplitude and duration of bonded joints as a function of time were seen in figure 10. From figure 10(a), AE signals with different amplitudes produced in mode I specimen with the increasing of load, and AE signals in the range of 60 to 80 dB increases gradually from damage initiation to the failure of adhesive joint. Furthermore, some AE signals (amplitude above 80 dB) correspond to fiber failure. The duration of most AE signals was distributed in the range below 2000 μs. With micro-damage accumulates, more AE signals over 2000 μs were produced, and the peak value of AE duration time was 6422 μs. From figure 10(b), few AE signals were obtained in mode II specimen due to the non-damage in initial loading. compared with mode I specimen, more AE hits increase continuously until the failure of adhesive joint, especially with the amplitude from 60 to 80 dB. Moreover, most AE signals with the duration time under 2000 μs were obtained during the whole loading process. A small amount of AE signals with a long duration were generated due to the
rupture of the adhesive, and the peak value of AE duration time was 13728 μs. Compared with figure 10(a), more AE signals produced in mode II specimen with the increasing of load, and AE signals in the range of 60 to 90 dB was far more than mode I specimen during failure stage. In addition, the AE duration time was obviously different from mode I specimen, and longer duration time corresponds to higher amplitude. Therefore, it was further proved that AE parameters are connected with the damage processes of composite bonded joints in the loading conditions of mode I and II.

On basic of experimental results, AE energy, cumulative hits, amplitude and duration were connected with the damage initiation and extension in the loading conditions of mode I and II. For mode I specimen, AE signals with different distributions in AE energy and AE amplitude were acquired during entire loading process, and fewer cumulative hits were observed. However, for mode II specimen, few AE signals were obtained in initial loading, and then a large number AE signals with the high relative energy, high amplitude and longer duration were obtained. Compared with mode I specimen, more AE signals in the amplitude range of 60 to 80 dB produced in mode II specimen during failure stage, and the amplitude spectrum can be used to describe from microscopic damage to macroscopic fracture of the composites composite adhesive joints in the loading conditions of mode I and II.

4. Conclusions

In this present work, the damage processes of composite adhesively bonded joints in the loading conditions of mode I and II were studied. Damage mechanisms and corresponding AE behaviors were discussed to investigate progressive failure behaviors of composite adhesively bonded joints.

It can be found that the load-displacement curves under mode I and II loads were different, and adhesion failure was the primary failure cause for mode I and II specimens. The damage evolution observed in the edge of the adhesive layers is the dominant factor in failure of the composite adhesive joint.

In consequence, the AE dynamic characteristics, especially the amplitude spectrum distribution, were verified to be related to the damage process. Moreover, AE response characteristics can be able to research damage mechanisms of composite adhesively bonded joints in the loading conditions of mode I and II, and AE technology was an effective technology to analyze progressive damage behaviors of composite adhesively bonded joints.

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