

## Research on stratified evolution of composite materials under four-point bending loading

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**Abstract:** In order to explore the effect of stratified evolution and delamination on the load capacity and service life of the composite materials under the four-point bending loading, the artificial tectonic defects of the different positions were set up. The four-point bending test was carried out, and the whole process was recorded by acoustic emission, and the damage degree of the composite layer was judged by the impact accumulation of the specimen - time-amplitude history chart, load-time-relative energy history chart, acoustic emission impact signal positioning map. The results show that the stratified defects near the surface of the specimen accelerate the process of material failure and expansion. The location of the delamination defects changes the bending performance of the composites to a great extent. The closer the stratification defects are to the surface of the specimen, the greater the damage, the worse the service capacity of the specimen.

### 1. Introduction

Glass fiber reinforced composite materials have excellent plasticity, fatigue resistance, and durability. Therefore, they are widely used in aerospace, shipbuilding, military equipment, sports equipment, water conservancy, infrastructure, and many other areas [1-5]. However, during their operation, sub-layer damage may enhance the composite material stratification, which issue becomes more and more topical.

Some scholars and experts have made a study of composite materials. Huget et al [6] used the acoustic emission (AE) method to monitor the AE signal of polyester / GF composites during static tensile loading. By analyzing the data on duration, the two types of failure modes of fracture and debonding were found and the neural network was used to identify the damage. Alander et al [7] performed a three-point load loading test on composite specimens and found that the damage of the specimen occurred at 19% -32% of the failure load. Wu [8] used the Weibull function to describe the composite layer by the material damage mode and found that the tensile strength of the material with the number of layers is gradually decreased. The tensile strength values of the two-, three- and four-layer fiber reinforced composites were lower that of single-layer ones by 10, 20, and 25%, respectively. However, there is scarce research on the stratified damage evolution behavior of glass fiber reinforced composites, which is critical to the bearing capacity and service life of composite materials.



The acoustic emission can monitor and record the development and evolution of damage in real time, and can provide real-time or continuous information with defects such as load, time, temperature and other external variables to detect the activity of these defects under external structural stress [9-14].

In this paper, four-point bending loading was realized via a universal testing machine, and composite specimens with different tiered defects were loaded and tested. The whole process was monitored by the AE method, and the damage behavior and degree of composite layered defects was assessed by analyzing the amplitude, impact accumulation, and relative energy. It is an important basis for the safety and efficient application of composite materials and the reliability of the composite materials [15,16].

## 2. Four-point bending test of specimens with different internal defects

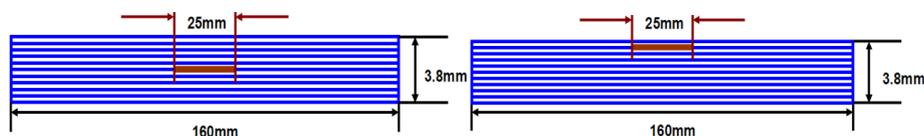
### 2.1 Experimental equipment and materials

Full-wave acoustic transmitter, computer control electronic universal tensile testing machine, vacuum oven, glass template, vacuum bag plastic film, release cloth, diversion network, glass fiber unidirectional cloth (ECW600-1270, 600g/m<sup>2</sup>), teflon film, epoxy resin, epoxy resin curing agent, sealing tape, resin tube.

### 2.2 Preparation of test pieces

The glass fiber unidirectional cloth was cut into a rectangular shape of 280 × 200mm, tiled on a flat die, and ten layers were laid in the same direction. The polytetrafluoroethylene film with width of 25 mm was placed in the middle of the different layers to obtain different depth of stratification defects. In the experiment, polytetrafluoroethylene film was placed on the first, second, fifth and sixth layers, respectively.

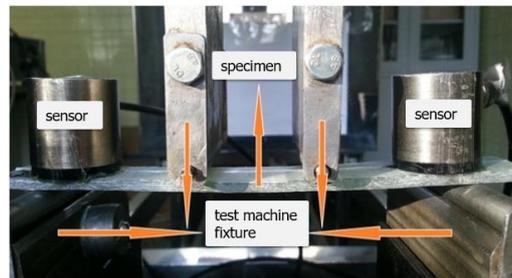
After the laying of the epoxy resin, the epoxy resin was vacuum-filled and allowed to stand at room temperature for 48 hours. Then, the temperature of the vacuum oven was set at 80°C, and the cured material was heated for 12 hours, and then cooled to the temperature of the room, and the laminates with thickness of about 3.8 mm were obtained. Finally, 160 × 25 mm composite specimens were prepared. The schematic of specimens is shown in figure 1.



**Figure 1.** Sketch map of specimen

### 2.3 Mechanical loading and acoustic emission monitoring

In the experiment, high vacuum grease was used to couple the two VS150-RIC sensors to the specimen, and the tape was tight on both sides of the specimen 25mm. The position of each sensor was set in the same way as the artificial, the centerline of the tiered defect is 60 mm apart, the bands are 100 kHz to 450 kHz, the amplifier gain is 34 dB, the center frequency is 150 kHz, the sample frequency is 5 MHz, and the threshold is set to 40dB. To ensure the reliability of the experimental data, the number of valid specimens for each type is at least five. The loading of the sensor, specimen and fixture is shown in figure 2.

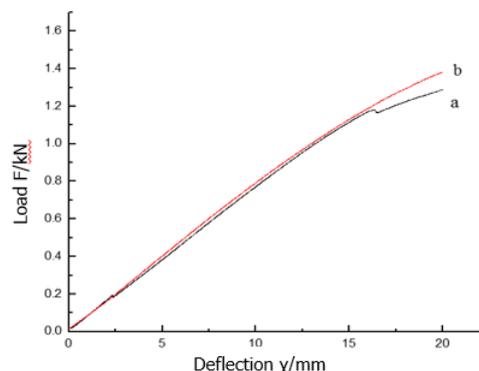


**Figure 2.** Schematic diagram of specimen loading

### 3. Results and discussion

#### 3.1 Mechanical properties and failure characteristics of composite materials with artificial prefabricated layers

The load-deflection curve of the specimen used in the experiment is shown in figure 3. The delamination defect of specimen *a* lies in the first two layers, and the stratification defects of specimen *b* are located between the fifth and sixth layers. When the loading is over, the load of specimen *a* is 1.29 kN and the load of specimen *b* is 1.38 kN.

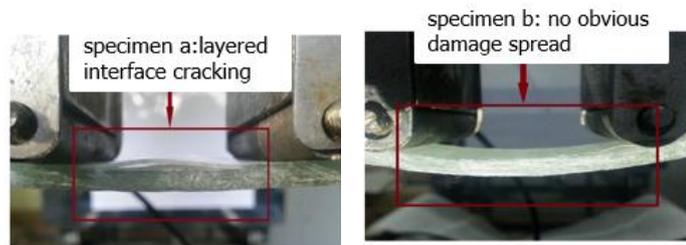


**Figure 3** Load deflection curves of composite specimens

From curve *a*, we can see that the whole loading process can be divided into two stages, the first stage of the load and the deflection curve as a whole linear relationship, but with a slight fluctuation, which is due to the initial loading of the specimen, the bottom of the specimen occurred slightly fiber broken and so on. In the second stage, the load and the deflection show obvious nonlinear relationship, which shows that there is obvious damage occurs, with the increase in deflection, damage continues to accumulate, when the load reaches a certain degree, the specimen a prefabricated crack cracking and fiber/matrix interface layered expansion, the sudden expansion of the crack led to a rapid decline in load, the curve is still stable and increased. Until the application of the load process cut off, respectively, to the left extension of 1 cm, extended to the right by 0.8 cm. This indicates that the specimen stiffness and strength decreased significantly.

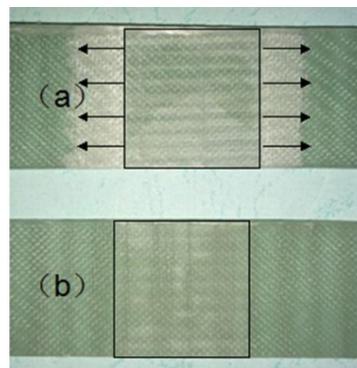
It can be seen from curve *b*, that the relationship between load and deflection is a good linear characteristic, indicating that when the stratification defect is located between the fifth

and sixth layers, the mechanical properties of the specimen are not significantly affected, and the bending resistance of the specimen is good.



**Figure 4.** Specimen failure site map

Figure 4 is for the stop loading, the two types of specimen site map, we can see that specimen *a* experienced a layer interface cracking, while specimen *b* had no obvious damage. Figure 5 shows the failure characteristics of the specimen, the black box that the manual placement of layered defects, arrows indicate the direction of damage to the expansion of the direction, we can see that in the load phase, the specimen *a* has significant damage expansion, and concentrated in the specimen near the surface area, the main form of damage is prefabricated layered interface cracking, interlayer cracking and fiber fracture, and the specimen *b* did not experience any significant damage.



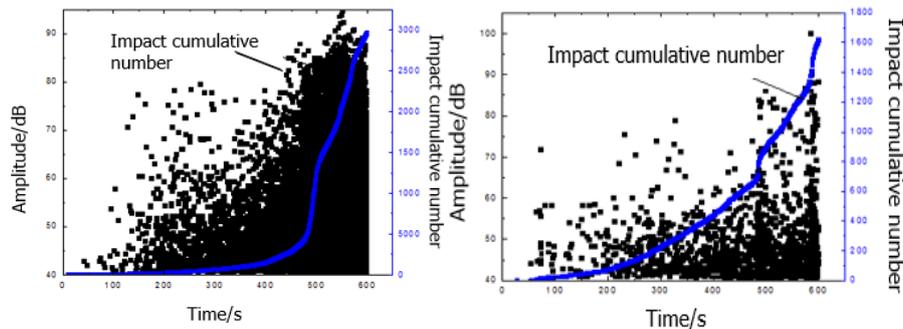
**Figure 5.** Specimen failure characteristics

By comparing the above two specimens, it can be found that the closer the stratification defect is to the surface of the specimen, the worse is the interface carrying capacity and the easier is the specimen damaged. The delamination defect is located at the center of the specimen interface, which has little effect on the load capacity of the specimen interface. This indicates that the stratum is in the part of the specimen, which is closely related to the load capacity of the specimen. The closer the stratification defect is to the surface of the specimen, the lower the load capacity of the specimen.

### 3.2 Acoustic emission response of composites with artificial stratification

Figure 6 is the impact accumulation-time-amplitude plot of the test piece in the test of the acoustic emission during the four-point bending load, impact accumulation and amplitude

change reflect the intensity and frequency of acoustic emission, so as to study the damage behavior of composite specimens.

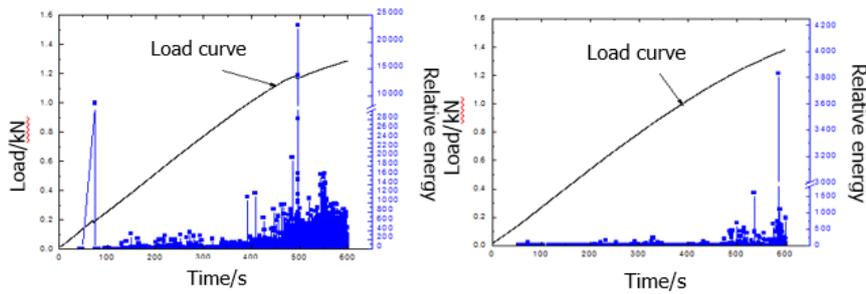


**Figure 6.** Impact accumulation/time/amplitude history diagram for specimen *a* (a) and specimen *b* (b)

It is seen in figure 6(a) that specimen *a* underwent three processes during the test: the initial stage, the surface rupture stage and the stratified evolution damage stage. At the beginning of the loading of the specimen, the load on the specimen is small, the deformation is very subtle, the signal collision cumulative curve is very gentle, only a few low frequency signals appear; with the increase of load, the specimen has a certain degree of deformation, structural damage, the signal increases, the amplitude increases, amplitude in the 50 dB ~ 70 dB floating, in the stratified interface cracking stage; load continues to increase, the specimen bending deformation Large-scale and high-amplitude acoustic emission signals appear, the amplitude range increases to 70 dB ~ 90 dB, and the damage of stratified damage is intensified, and the cumulative number of acoustic impact signals is increased abruptly. The final specimen to reach the bending limit, was destroyed failure.

It can be seen from figure 6(b) that, in the initial stage, the specimen bending deformation is small, the cumulative increase in the number of crash, only a small amount of low-amplitude signal appears, in the evolutionary stage, the load increases, the bending curve of the specimen becomes larger, the signal is higher than 70dB, and the load is about 480s, the cumulative number of impacts increases abruptly and rises linearly, and the signal is higher than 80dB, indicating that the specimen under the action of deformation increased, began to damage.

Figure 6(a) and (b) shows that the two experimental phenomena are in accordance with the bending theory, and relative *b* specimen, a specimen in the stratification evolution failure stage amplitude, impact number and other acoustic emission signals are more abundant, The value is higher, the impact number is more, the change is very obvious. The more the position of the layered defect is closer to the surface of the specimen, the higher the amplitude signal, the greater the impact on the interface carrying capacity, the worse the bending resistance of the specimen.



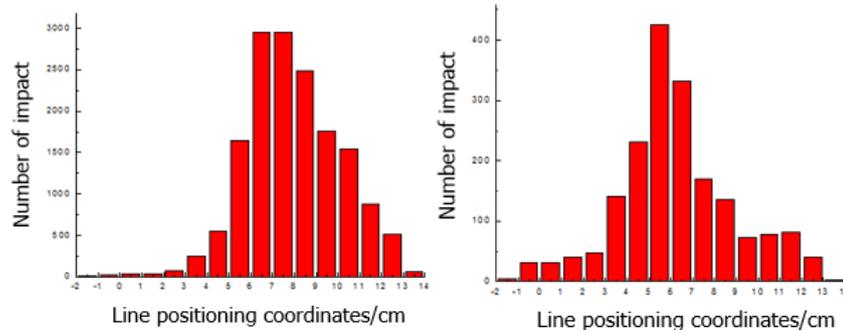
**Figure 7.** Load/time/ relative energy diagram for specimen *a* (a) and *b* (b)

Figure 7 depicts the load-acoustic emission relative energy-time history of the four-point bending tests of two composite material specimens. It can be seen from figure 7(a) that the relative energy of the acoustic emission signal is close to zero at the initial stage of loading, load and bending deformation is small; with the increase of load, the bending deformation of the specimen increases and the structure is obviously damaged. In the prefabricated stratified cracking stage, the relative energy reaches the high-energy signal level of 8609.98, indicating that the prefabricated stratification has completely cracked and destroyed; the load continues to increase, Deformation continues to grow, damage continues to accumulate, the relative energy compared to the previous stage as a whole increase, the final specimen fiber / matrix interface layered expansion damage, and produce the highest relative energy signal. It can be seen from the figure (b) that the relative energy of the acoustic emission signal is very low at the initial stage, the load and the bending deformation are very low. Under the load, the bending deformation of the specimen is only slightly damaged. When the experiment is carried out for 480s, the acoustic emission signal becomes relatively active, the relative energy is from 240 to 1600, the bending deformation of the specimen is aggravated, and the damage is seriously serious. When the load is about 600s, the relative energy signal is close to 3818.99. This phenomenon coincides with the trend of the crash-time-amplitude plot of the specimen *b* after 480 s.

Comparing the four-point bending loading experimental results of two specimens, these are in accordance with the bending theory. The relative AE energy of specimen *a* is 23119.90, and that of specimen *b* is much lower, namely 3818.99. The magnitude in the cumulative time amplitude diagram of specimen *a* is significantly larger than that of specimen *b*. It can be seen that the closer the layered defect is to the surface of the specimen, the better the bending resistance and the bearing capacity of the specimen.

Figure 8 depicts the AE impact signal positioning map for the composite material specimen bending failure process: In figure 8(a), bending deformation increases with the load, the AE signal of specimen *a* is mainly concentrated in the central part of the right side, while that on the left is relatively small. In figure 8(b), the acoustic emission positioning signal not only appears in the center of the specimen, but also a certain number appears in the adjacent area, which corresponds to the failure characteristics of the composite in figure 5. Comparison of the two maps shows that the number of AE targets for specimen *a* and *b* is 13865 and 1869, respectively, which difference is due to a poor bending resistance, prefabricated crack cracking and fiber/body interface stratification expansion of specimen *a*. Specimen *b* has better bending resistance, which drops only due to the occurrence of fiber damage and other

defects. This indicates that a smaller distance between the stratified defect and the specimen reduces the bending ability of the composite material, which exacerbates its damage evolution and failure.



**Figure 8.** AE impact signal location diagrams of specimen *a* (a) and specimen *b* (b)

#### 4. Conclusions

Through the four-point bending load of composite specimens containing artificial defects, the delamination evolution behavior is studied, and the following conclusions are obtained:

(a) Delamination defects located at the specimen surface, in the experiment process, there will be set manually in layered interface cracking, fiber / matrix interface crack and fiber breaking damage types; no significant defects in the specimen breakage phenomenon near the middle position.

(b) The experimental results of the two kinds of specimens are in line with the bending theory. The defects at the surface, the load deflection curves show obvious nonlinear characteristics, the specimen showed defects in a middle position for good linear characteristics, that delamination location has a great influence on the bending properties of composite materials.

(c) When the defect is located in the surface layer, the evolution stage is shortened obviously, and the specimen is locally damaged prematurely. When the defect is located in the middle, no obvious damage or damage occurs during the loading process. It shows that the delamination near the specimen surface accelerates the failure process of material expansion.

(d) In four-point bending loading test, with the load and bending deformation increasing, delamination defects in the specimen position, relative to the defects in the specimen surface, its amplitude is smaller, the impact cumulative number is less, the highest relative low energy is lower, specimens from the interface crack to layer failure evolution amplitude has been 40 ~ 90 dB defect on the surface, the extent of damage is more serious. Therefore, the smaller the distance of the delamination to the surface of the specimen is, the worse the bending resistance of the specimen is, the more likely it will be damaged or fractured, and the more severe will be the damage.

(e) In the four-point bending test process, with the damage increasing, the relative energy, amplitude, cumulative hits etc. acoustic emission signals constantly enrich and change. Therefore, to study the four-point bending loads with delamination defects in the application of acoustic emission monitoring experiment process of glass fiber reinforced composite delamination damage evolution behavior is correct and effective, which will promote the further development of research on the history of composite materials.

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