Experimental and numerical study on debonding damage propagation of brazed titanium alloy honeycomb under fatigue load

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Abstract. In this paper, the fatigue damage propagation of honeycomb structures under three-point bending fatigue load is studied by experiment and numerical simulation. Firstly, the three-point bending fatigue experiment of honeycomb structure with prefabricated damage was carried out, and the length of interfacial debonding with loading cycle was studied. Then, the damage propagation model of honeycomb structure is established based on VCCT theory and Pairs formula. The results show that the numerical results are in good agreement with the experimental results. The numerical model was validated.

1. Introduction
As an ideal lightweight structure, titanium alloy light honeycomb structure is much lower in material and manufacturing cost than carbon fiber composite, and has been widely used in aviation industry. In practical application, the honeycomb wall is usually designed to be very thin, usually between 0.5mm and 1mm. The connection between skin and honeycomb with brazing technology will inevitably lead to manufacturing defects, such as false welding, empty welding. Therefore, it is urgent to evaluate the safety of such products.

Boukharouba et al. [1] carried out experiments and model analysis on the fatigue properties of carbon fiber/epoxy resin skin and Nomex hexagonal honeycomb core sandwich beams under three-point bending cyclic loading at different load levels. The fatigue experiments shows that the stiffness degradation in the number of cycles can be divided into three different stages according to the load level. The long-term bending fatigue life of CFRP Nomex honeycomb composite sandwich beams was studied by using time temperature superposition principle [2]. In the range of experimental scattering, the fatigue behavior under given frequency and load ratio is consistent with the experimental results. Abbadi et al. [3, 4] studied the fatigue behavior of honeycomb sandwich panel without / without damage by four point bending test. Experimental results showed that the lifetime of the L configuration is larger than in the W-direction. Hussain [5] studied the static and fatigue loads of honeycomb sandwich structure by experiment and numerical analysis. The fatigue response of aluminum honeycomb sandwich panel under three bending load was studied [6]. The research results show that supports span has a significant influence on the collapse mechanisms. At present, the research on fatigue interface failure of honeycomb structures is mainly based on the experiment method, which will cost a lot of time and money. The numerical simulation based on the finite element method can not only solve the above problems, but also obtain the mechanical field and damage propagation during the whole loading
process. Unfortunately, the research on predicting the damage propagation of honeycomb interface under fatigue loading is rare.

In this paper, the fatigue damage propagation of honeycomb structures under three-point bending fatigue load is studied by experiment and numerical simulation. The VCCT technology is used to simulate interface debonding, and Pairs formula is used to calculate the number of cycles. The experimental results verify the validity of the established finite element model. This research is helpful to predict the interface debonding of honeycomb structures under fatigue loading.

2. Three-point bending fatigue test

2.1. Test specimen
The test specimen and its dimension are shown in Figure 1, and the dimension is 200*50*10 mm. At the right end of the test piece, a 40 mm long through crack was prefabricated. The cell size and thickness of core is 12.8 mm and 0.05 mm respectively, and the thickness of upper and lower panels is 0.6 mm. The material of panel and core is TC4 and TC1 respectively. The material properties are shown in Table 1.

![Figure 1 Test specimen and its dimension](image)

### Table 1 Properties of titanium alloy materials

| Properties | Elastic modulus $E$ (GPa) | Poisson’s ratio | Tensile strength $\sigma_b$ (MPa) | Yield strength $\sigma_{0.2}$ (MPa) | Density $[\text{g/cm}^3]$ |
|------------|--------------------------|----------------|-------------------------------|-----------------------------------|------------------------|
| TC4        | 110                      | 0.34           | 925                           | 870                               | 4.44                   |
| TC1        | 127                      | 0.34           | 590                           | 460                               | 4.55                   |

2.2. Experimental procedure
After the test specimen was assembled with the fixture, the three-point bending experiment was conducted by the electro-hydraulic servo static and dynamic testing machine of SDS-100, as shown in Figure 2(a). The fatigue load is a sine wave with a maximum load of 871N, a stress ratio of 0.1 and a frequency of 1 Hz. A paper scale was pasted on the surface of the test piece to mark the crack length. During the experiment process, a video microscope was used to record the crack length during fatigue loading, and the collection frequency was 2 fps. Two specimens were tested to prevent accidental test. The failure specimen is shown in Figure 2(b).
3. Damage propagation prediction of honeycomb structure

3.1. Numerical method

Pairs formula, which establishes the relationship between stress intensity factor range $\Delta K$ and crack propagation rate $da/dN$, is the theoretical basis for predicting fatigue crack propagation in engineering applications. In ABAQUS software, the $\Delta K$ is replaced by the range of strain energy release rate, as shown in the following formula:

$$
da / dN = c(\Delta G_{eq})^n,
$$

where $da/dN$ is the crack propagation rate, $c$ and $n$ are the material constants, and $\Delta G_{eq}$ is the range of equivalent strain energy release rate.

There are three common mixed mode criteria for calculating the critical equivalent strain energy release rate: BK law, power law and Reeder law. In this paper, the power law is used to calculate the equivalent strain energy release rate at the front end of debonding.

$$
G_{eq} = \left(\frac{G_I}{G_{Ic}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIc}}\right)^\beta + \left(\frac{G_{III}}{G_{IIIc}}\right)^\gamma,
$$

where $G_{Ic}$, $G_{IIc}$ and $G_{IIIc}$ are the critical strain energy release rates of mode I, II and III, and $G_I$, $G_{II}$ and $G_{III}$ are the strain energy release rates. The strain energy release rate at the crack tip can be calculated by VCCT according to the nodal force and displacement near the crack tip.
Based on the above theory, the debonding damage propagation prediction model under fatigue load is established as shown in Figure 3. The detailed steps are as follows:

1. According to the geometry model of honeycomb structures, the finite element mesh is established, and the corresponding boundary conditions, material properties and analysis steps are defined;
2. According to the damage location and size, the interface model of damage propagation is established by using VCCT technology;
3. Mechanical response of the honeycomb structure is solved, and the strain energy release rate of each crack tip is obtained;
4. The strain energy release rate is assumed to be constant when the crack propagates from \( a \) to \( a + \Delta a \). According to formula (1), the number of cycle required to propagate \( \Delta a \) is calculated;
5. Above process is repeated until the structure fails or the number of cycles is greater than 1e6.

3.2. Finite element model

Based on commercial finite element software ABAQUS, the finite element model of honeycomb structure under three-point bending fatigue load is established, as shown in Figure 4. It contains 19630 elements and 37333 nodes. The element type used in the model is C3D8R. According to the boundary conditions of the test, the displacement constraint in Z direction was applied at the position 30mm away from the end of the lower skin. The corresponding fatigue load spectrum was applied in the middle of the upper skin.
Figure 4 Finite element model of honeycomb structure under three-point bending fatigue load

Figure 5 shows the Mises stress of honeycomb core under maximum load 871N. It can be seen that the maximum stress is 807MPa, which is near the loading position. And the stress level is also high at the support of the lower skin. In addition, there is a higher stress level in the red ellipse region. The reason is that the existence of damage makes the honeycomb core need to bear more loads.

Figure 5 Mises stress of honeycomb core under maximum load 871N

Figure 6 shows the debonding propagation of the honeycomb structure at 0, 4000, 6000, 8000, 10000, 11000 cycles, where 0 (blue) indicates that the node has been released, and 1 (red) indicates that the node has not been released and there is no damage. The value between 0 and 1 indicates that the node has not yet reached the release state despite the damage. When \( N = 0 \), due to the existence of initial defects, the nodes with 40mm in one side are released and displayed in blue. With the increase of number of cycles, the nodes release continuously, thus the debonding continues to propagate, and the blue area gradually increases. Moreover, it can be found that because the width of the prefabricated initial defect is equal to the width of test specimens, the prefabricated defect extends to the middle position of the test piece in the process of fatigue growth.
Figure 6 Debonding propagation of the honeycomb structure at 0, 4000, 6000, 8000, 10000 and 11000 cycles

Table 2 shows the comparison of the experimental and numerical results for the number of cycles with debonding $\Delta a$. It can be seen that the error between the numerical and experimental results of the two test specimens is 7.68% and 6.30% respectively, that is, numerical results are in good agreement with experimental results. Moreover, both the experimental and numerical results show that the damage propagation rate increases with the damage. It should be pointed out that although the two test specimens are produced in the same batch, there are some differences in the test results between them. This is due to the characteristics of the honeycomb structure, which makes the damage starting position of the two different, that is, the starting position of a test specimen may be closer to the junction of the honeycomb walls.

The above numerical results show that the numerical simulation based on finite element method can reasonably predict the interface debonding propagation of honeycomb structures under fatigue load. The method established in this paper can be used as an effective and economical method to predict the
debonding propagation of honeycomb structures before experiments and to study the mechanism of debonding after experiments.

Table 2 Comparison of experimental and numerical results for the number of cycles with debonding $\Delta a$

| $\Delta a$/mm | 1# test specimen | Numerical results | Error/% | 2# test specimen | Numerical results | Error (%) |
|-------------|-------------------|-------------------|----------|-------------------|-------------------|-----------|
| 0.7         | 4000              | 3621              | 9.5      | 1.2               | 4000              | 4269      | 6.7       |
| 1.5         | 6000              | 5273              | 12.1     | 2.1               | 6000              | 6441      | 7.4       |
| 2.9         | 8000              | 7403              | 7.5      | 4.4               | 8000              | 8830      | 10.4      |
| 6.3         | 10000             | 9652              | 3.5      | 12.3              | 10000             | 10410     | 4.1       |
| 19.2        | 12535             | 11803             | 5.8      | 15.3              | 11274             | 11604     | 2.9       |

4. Conclusion
The interface failure propagation under fatigue load is experimentally and numerically studied in this paper. The experimental results are employed to validate the established prediction model of debonding propagation. The experimental and numerical results show that the damage propagation rate increases with the debonding propagation. The error between the numerical and experimental results of debonding propagation the two test specimens is 7.68% and 6.30% respectively. The comparison between numerical results with experimental results indicates that they are in good agreement.

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Reference
[1] Boukharouba W, Bezazi A, Scarpa F. Identification and prediction of cyclic fatigue behaviour in sandwich panels. Measurement 2014; 53: 161-170.
[2] Rajaneesh A, Zhao Y, Chai GB, Sridhar I. Flexural fatigue life prediction of CFRP-Nomex honeycomb sandwich beams. Composite Structures 2018; 192: 225-231.
[3] Abbadi A, Tixier C, Gilgert J, Azari Z. Experimental study on the fatigue behaviour of honeycomb sandwich panels with artificial defects. Composite Structures 2015; 120: 394-405.
[4] Abbadi A, Azari Z, Belouettar S, Gilgert J, Freres P. Modelling the fatigue behaviour of composites honeycomb materials (aluminium/aramide fibre core) using four-point bending tests. International Journal of Fatigue 2010;32(11):1739-1747.
[5] Muzamil H, Rafiullah K, Naseem A. Experimental and computational studies on honeycomb sandwich structures under static and fatigue bending load. Journal of King Saud University-Science 2018; 31:222-229.
[6] Palomba G, Crupi V, Epasto G. Collapse modes of aluminium honeycomb sandwich structures under fatigue bending loading. Thin-Walled Structures 2019;145: 106363.