Structural behaviors of edge-closed titanium honeycomb sandwich panels with a repaired penetrating damage under a unidirectional tensile load

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Abstract. This paper deals with penetrating damage experimental and numerical investigation on edge-closed titanium honeycomb sandwich panels under uniaxial tension. Three damage state specimens were designed and manufactured for tests including intact, prefabricated penetrating damage, and repaired. The test results show the diameter of penetrating hole has a great impact on failure mode and load, and the failure mode of repaired specimens is consistent with the intact. A parametric numerical methodology containing structural damage details was established. Numerical analysis successfully simulated the failure process of all damage states, which was consistent with the experimental observations. Scarf and inlay repair technique can be used to restore the mechanical properties of edge-closed titanium honeycomb sandwich panels.

Keywords: Titanium honeycomb sandwich panels; Penetrating damage; Edge-closed; Scarf and inlay repair.

1. Introduction

In recent years, titanium honeycomb sandwich structures have been gradually applied in the fuselage, wings, and thermal protection systems of some newly developed aircraft in China [1-4]. Compared to traditional aerospace sandwich structures, titanium honeycomb sandwich structures have superior strength, stiffness, sound insulation, thermal and corrosion resistance [5].

There are two common forms of honeycomb sandwich structures including edge-closed and edge-opened, as shown in Fig. 1. Edge-closed titanium honeycomb sandwich panels are widely used in the cover structures of several newly developed aircrafts in China. Penetrating damage is primarily typical of the damage formed by impact loading during actual equipment service [6]. To ensure the safety of titanium honeycomb sandwich structures for aerospace engineering applications, it is significant to investigate the residual load-bearing capacity after penetrating damage[7, 8].

In the past decades, a lot of experimental and theoretical studies on honeycomb sandwich structures containing damaged defects have been explored. The depth of damage is taken as the basis for distinction including unilateral panel damage, unilateral panel and honeycomb core damage, and penetrating damage. According to the published literature, Silva et al. [9] investigated the effect of honeycomb cell wall deficiency on the elastic modulus of honeycomb materials. Guo et al. [10] analyzed the effect of regular hexagonal honeycomb with damage on Young's modulus, elastic buckling strength, and plastic failure strength of structures by the finite element method.

They analyzed the effect of single isolated defects of different sizes and the distance between two defects on the elastoplasticity of structures. Some researchers have found that impact damage may reduce the compressive strength of composite sandwich structures by 50% [11]. However, according to the published literature, there are few studies on titanium honeycomb sandwich structures containing damage defects, especially penetrating damage.

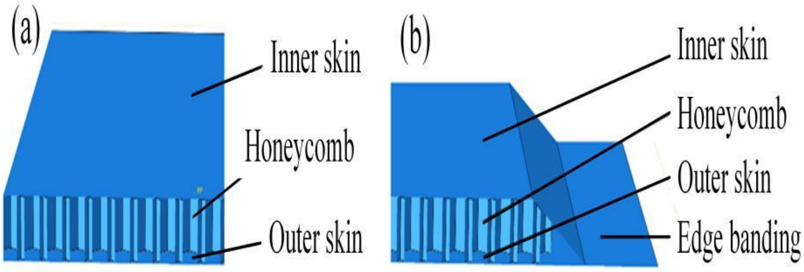


Fig. 1 Two forms of honeycomb sandwich structures: (a) Edge-opened; (b) Edge-closed.

This paper focuses on the experimental and numerical study of intact, penetrating damage, and repaired damage titanium honeycomb sandwich panels subjected to unidirectional in-plane tension. The typical failure mode and failure load were obtained experimentally. The residual strength of the sandwich structure after damage was obtained by comparing the test and numerical analysis results.

2. Experimentation

The design of specimens was based on a titanium honeycomb sandwich structure that has been successfully applied to an advanced warplane in China. The edge-closed titanium honeycomb sandwich structure used a lightweight honeycomb as the core, and the core was connected to the panel by brazing. The specific details of the specimen are shown in Fig. 2. The unpublished research results of the thesis research institution show that when the diameter of penetrating damage is less than 20mm, the penetrating damage has little effect on the load-bearing capacity of titanium honeycomb sandwich structures. Thus, the prefabricated penetrating damage diameters were 30mm, 40mm, and 50mm. The scarf and inlay repair technique was used to deal with the penetrating holes. Three damage states are shown in Fig. 3.

The specimen was made of the inner skin, the outer skin, the reinforcing sheet, and the honeycomb core. The material of the specimens is TC4 (Ti-6Al-4V). The material properties of TC4, as listed in Table 1, were acquired through experiments according to ASTM test standard E345 [12]. The red wireframe section in Fig. 2(c) is the edge-closed bevel area, indicating the transition of the sandwich structure from the full-height honeycomb area to the edge-closed honeycomb area.

A gradually increasing uniaxial tensile load was applied along the L-direction of the specimen. The test loading rate was 1 mm/min. The load and displacement were recorded at the same time during the whole loading process. During the loading process, as the tensile load increased, the specimen appeared to rattle caused by core and skin damage. When the load exceeded the limit load, the rattle became more intensive until the specimen failed completely.

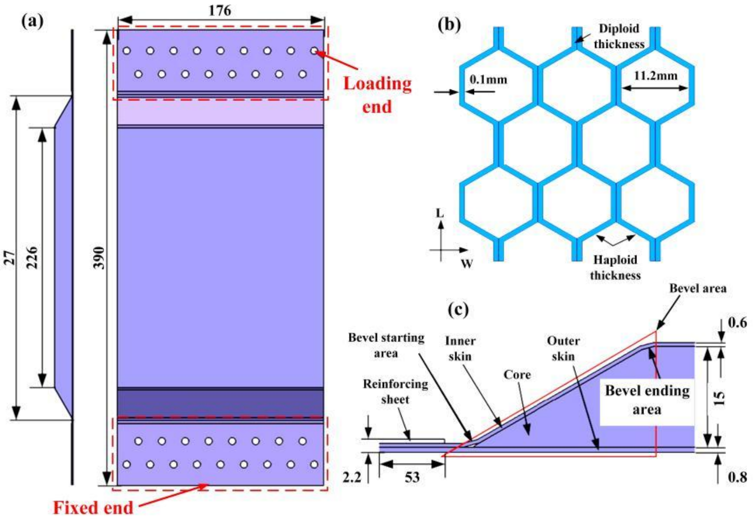


Fig. 2 The specimen: (a) Dimensions (mm); (b) Details of the core; (c) Details of the bevel area.

Table 1. The mechanical properties of TC4.

Density (g/cm3)	Tensile modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Ultimate strength (MPa)
4.4	108.48	0.3	860.59	967.12

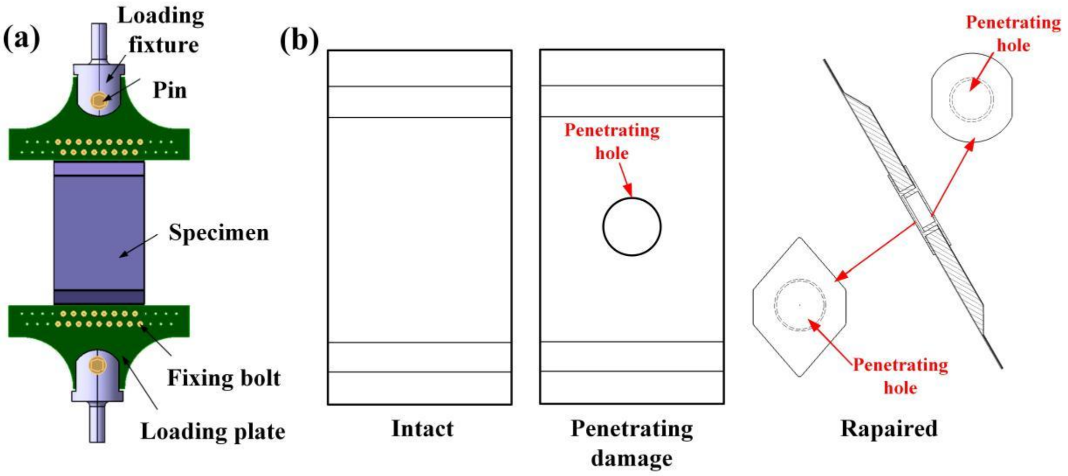


Fig. 3 Fixture design and specimens with different damage state

3. Numerical analysis

The finite element models containing the structural and damage details were used to predict the failure process of sandwich structures under uniaxial tension, as shown in Fig. 4. In the finite element analysis, TC4 is defined as a nonlinear elastoplastic material, and the elastic properties are obtained experimentally, as shown in Table 1. The nominal stress (σnominal) and nominal strain (εnominal) obtained experimentally can be converted to the real stress (σreal) and real strain (εreal) used in commercial finite element software by Equation (1) and Equation (2). In Equation (3), the plastic strain (εpl) is obtained by subtracting the elastic strain (εel) from the total strain (εt). The elastic strain (εel) can also be defined as the ratio of the true stress (σreal) to Young's modulus (E). In this study, the true stress and plastic strain are used as the input parameters of the software, as listed in Table 2.

$$\sigma_{real} = \sigma_{nominal}(1+\varepsilon_{nominal}) \tag{1}$$

$$\varepsilon_{real} = \ln(1+\varepsilon_{nominal}) \tag{2}$$

$$\varepsilon^{pl} = \varepsilon^{t} - \varepsilon^{el} = \varepsilon^{t} - \sigma_{real} / E \tag{3}$$

Table 2. The true stress and the plastic strain of TC4.

Stress	782.37	800	850	889.74
Plastic strain	0	0.0009	0.0030	0.0054

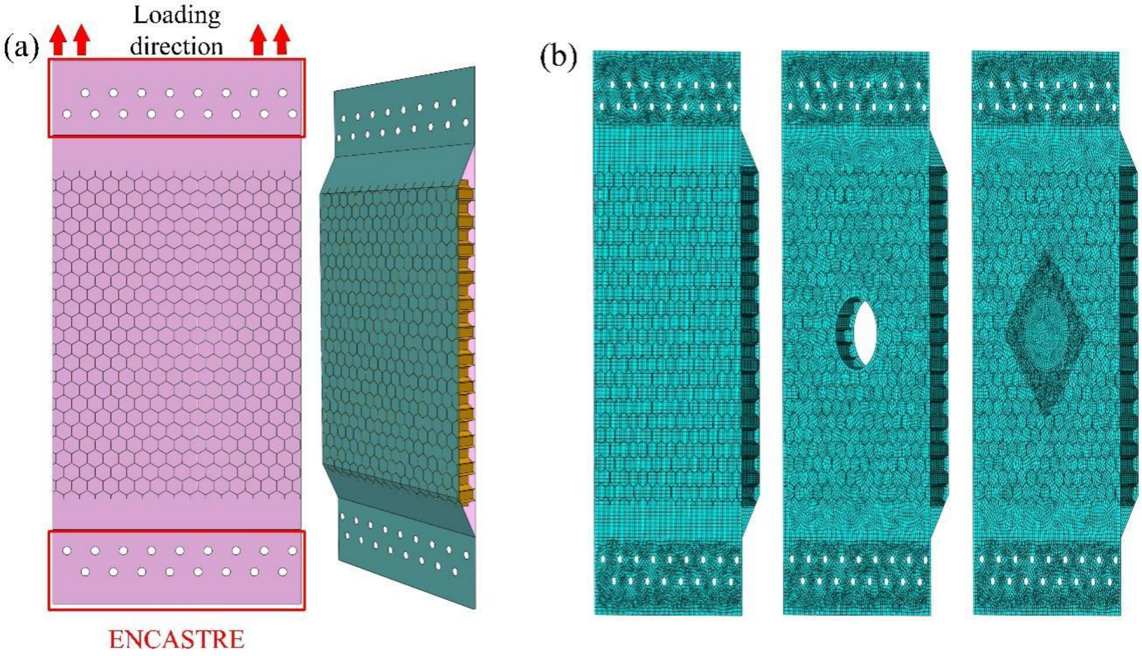
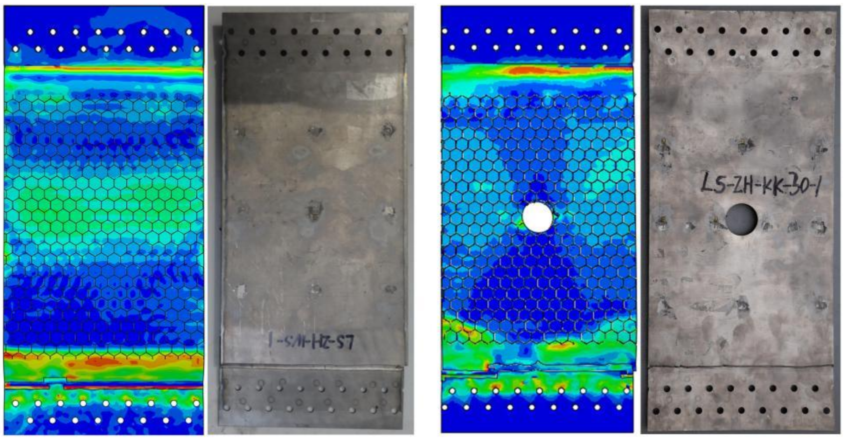


Fig.4 The finite element model: (a) Boundary conditions; (b) Mesh

4. Results and discussion

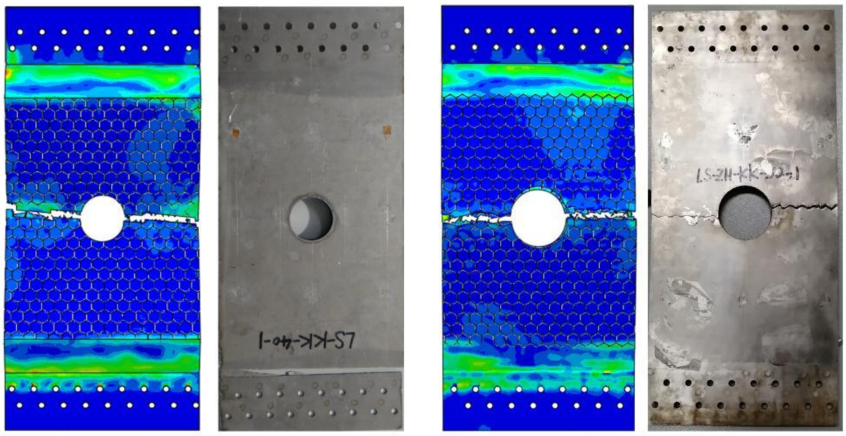
The comparison between the tests and the numerical analysis of the failure mode results is summarized in Fig. 5. The failure mode of the honeycomb sandwich structure with 30mm diameter penetrating damage is the tensile fracture of the outer skin at the bevel starting area of the fixed support end. The failure mode may be created by one end of the specimen being fully fixed and as the load increases, stresses concentrate in this area until fracture failure. However, when the diameter of the penetrating damage is 50 mm, the skin and honeycomb core occur in cross-sectional fracture along both sides of the penetrating damage hole. The failure mode may be caused by the penetration reducing the tensile strength of the damaged location, and the stress concentration phenomenon occurs first in the damaged area. The failure loads and fitting results are summarized in Fig. 6.

The failure modes of the specimens with repairing penetrating damage (50 mm diameter) obtained from numerical prediction and tests are shown in Fig. 7. The failure mode changes from tensile fracture of panels and cores on both sides of the penetrating damage to tensile fracture of panels in the bevel area. In the case of a 50mm diameter penetrating damage, the failure load of post-repair is increased by about 9.56% compared to the pre-repair and restored to approximately 96.4% of the intact. The scarf and inlay repair plays an obvious role in attenuating the effect of the penetrating damage on the in-plane tensile failure mode of the honeycomb structure.



Intact

Diameter=30mm



Diameter=40mm

Diameter=50mm

Fig. 5. Failure modes (Numerical analysis vs. Test results)

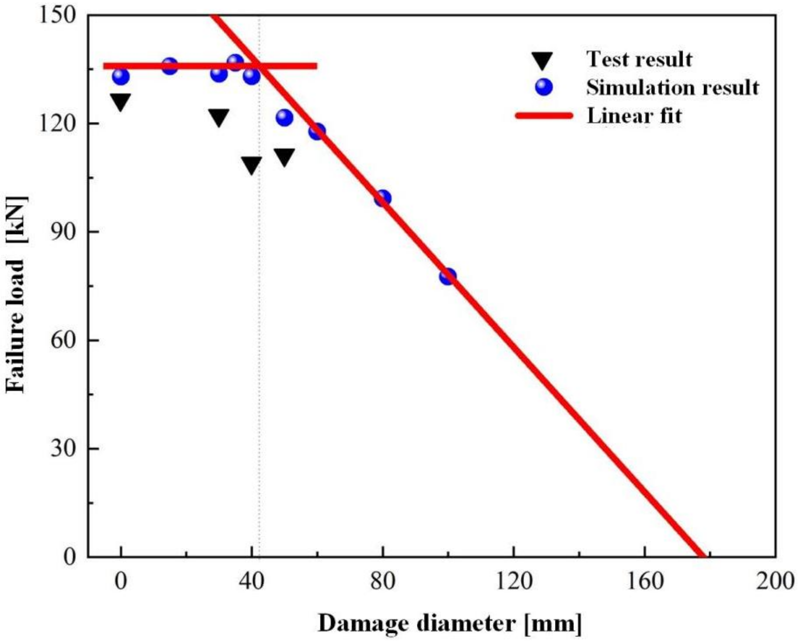
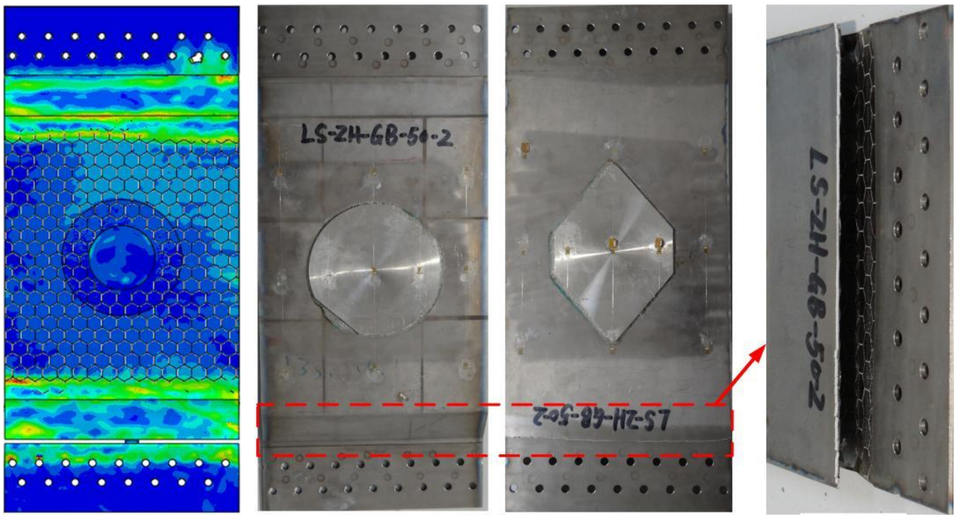


Fig.6 Failure loads and fitting analysis



Numeric analysis **Test results** **Failure detail**

Fig.7 Failure modes of repaired penetrating damage (Numerical prediction vs. test results)

5. Conclusion

According to the experimental study and numerical analysis, the effect of penetrating damage diameter on the failure load has a boundary. When the penetrating damage diameter is less than the critical value (30mm), the influence on the failure load and failure mode is not obvious. When the diameter of the penetrating damage exceeds the critical value, the failure load decreases almost linearly with the diameter increase, and the failure mode is transformed fundamentally. Based on the conclusion, the damage tolerance of edge-closed titanium honeycomb sandwich structures and the repairability after penetrating damage can be explored to provide the theoretical and practical basis.

The numerical analysis successfully captured the failure process of the sandwich structure under unidirectional tension. The predicted failure modes were consistent with experimental failure modes. A good correlation in the failure strength between the test results and numerical results had been reached with satisfied accuracy.

Tensile Mechanical Properties after repairing penetrating damage of the edge-closed titanium honeycomb sandwich can restore to the intact state. The scarf and inlay repair technique can be widely used in the field of patching penetrating damage of honeycomb sandwich structures. \

Acknowledgments

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