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The influence mechanism of processing holes on the flexural properties of biomimetic integrated honeycomb plates

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A B S T R A C T

The influence mechanism of processing holes on the flexural properties of fully integrated honeycomb plates (FIHPs) was analyzed using the finite element method (FEM), and the results were compared with experimental data, yielding the following findings: 1) Processing holes under tensile stress have a significant impact on the mechanical properties of FIHPs, which is particularly obvious when initial imperfections are formed during sample preparation. 2) A proposed design technique based on changing the shape of the processing holes from circular to elliptical effectively reduces the stress concentration when such holes must exist in skin or components under tension, and this method motivates a design concept for experimental tests of FIHPs bearing dynamic or fatigue loads. 3) The flexural failure modes of FIHPs were confirmed via FEM analysis, and the mechanism by which trabeculae in FIHPs can effectively prevent cracks from emerging and cause cracks to develop along certain paths was ascertained. Therefore, this paper provides a theoretical basis for the design of processing holes in bionic honeycomb plates and other similar components in practical engineering applications.

1. Introduction

Honeycomb structures are common lightweight, high-strength composites [1–3] with many applications in the fields of aerospace [4–6], transportation and architecture [7–9]. As a result, their mechanical properties and their applications have been extensively studied [10–12]. Numerous advancements have been achieved by previous researchers in this respect [13–15]; however, commercially available honeycomb sandwich plates are currently manufactured by adhesively or mechanically joining the skins and core components, which are produced separately using different processes [16], and consequently, these sandwich plates are easily susceptible to separation between the side skins and the core [17].

To overcome the weaknesses of the multi-body formation of honeycomb plates, JX Chen observed that the microstructure of beetle forewings consists of fully integrated honeycomb plates (FIHPs) with edge-sealing features [18] and developed an approach for producing FIHPs motivated by this structure [19]. This approach carefully incorporates the characteristic features of honeycomb plates with upper and lower skins. Qualitative studies of the flexural and compressive properties of FIHPs have been performed by manufacturing single-sided bonded honeycomb plates (SBHPs) and trabeculae reinforced with long- and short-fiber polymers. By this means, a previous study preliminarily confirmed that the structural integrity of FIHPs is suitable [20]. The effect of using short fibers instead of long fibers on the compressive and shear mechanical properties of honeycomb plates has been further studied through experimental and simulation-based approaches [21]. Recently, we have experimentally investigated the compressive [22] and flexural mechanical properties of FIHPs, and these studies have proven that the orientation of the processing holes (that is, the stress state of the processing holes, i.e., tensile or compressive) plays a critical role [23] in their flexural behavior. However, the stress concentrations, minimum cracking loads and crack development behavior [24,25], especially as related to the locations of the processing holes, also significantly influence the mechanical properties of composite materials. Simultaneously, several outstanding issues remain in our previous study. For example, when the diameters of the processing holes are small, the degree of stress concentration at the edges of the holes is higher, whereas when the processing hole diameters are large, the flexural strength of the FIHPs is directly weakened. These observations raise the question of whether an optimal diameter or shape may exist for the processing holes in FIHPs. As another example, in practical engineering applications, there is a question of how to design the geometric parameters of processing holes used for connection or reinforcement when processing holes already exist in certain plates or components. Thus, to verify the results of previous papers using the finite element method (FEM), this study investigated the influences of the stress states (tensile or compressive) of the processing holes and the diameters (curvatures) of the holes on the flexural behavior of FIHPs. This study introduces a foundation for the design of reasonable processing holes for honeycomb plates and other similar components in practical engineering applications.

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2. Modeling and analysis methods

The overall dimensions of the analytical model (Fig. 1b) used in this study were the same as those of the test samples (Fig. 1a) reported in a previous paper [22]. As shown in Fig. 1(b), the radius (R) of the circle inscribed in a hexagon of the core layer was 7 mm, and the diameters of the trabeculae (D) and processing holes (d) were each 6 mm. The specific geometric dimensions of the different models used for various purposes can be divided into three categories as follows. 1) The parameters of the analytical model used to verify the results of previous papers were identical to those of the experimental samples: the thickness (t) of the honeycomb cell wall was 1.75 mm, the height of the core layer was 6.7 mm, the thickness of one skin (without the processing holes) was 4 mm, and the thickness of the other skin (with the processing holes) was 2.3 mm. 2) In the models used to investigate the influence of different processing hole diameters (d), the thicknesses of both the upper and lower skins were 2 mm, and processing hole diameters of 4, 5, 6, 7, and 8 mm were considered. 3) To investigate the influence of different values of the curvature radius (r) of the processing holes, two series of models were considered, one in which the minor axis (b) of the ellipse was 2 mm and one in which it was 2.5 mm, and each model series was divided into three groups, corresponding to major axes (a) equal to 1, 1.5 and 2 times b.

Abaqus was used to establish the models specified above for a short-basalt-fiber-reinforced polymer (BFRP), and the meshing is shown in Fig. 1(b). The element type for the skin without processing holes was C3D8R, whereas the element type for the skin with processing holes and the core layer was C3D6. The number of elements for each model ranged from 50 to 70 thousand. The parameters of the BFRP composite material (density = 0.85 g/cm^3, volume fraction of fiber = 15%, mass ratio = 38.4%, fiber length = 3 mm) that were used in the FEM analysis were specified in accordance with the latest experimental results obtained by our research group. The constitutive model of this material is shown in Fig. 1(c); the tensile and compressive elastic moduli are 7.12 GPa and 2.99 GPa, respectively, and the Poisson's ratio is 0.36. In accordance with the results of previous papers, the pressurization mode of the analytical models was chosen to correspond to the application of displacement loading, the same as for the test samples (Fig. 1a), and the vertical displacement applied was 3 mm or 1 mm when the perforated surface was facing upward or downward, respectively. The value of the principal stress (S22, called stress for brevity) was used as the index because the failure of FIHPs in three-point bending experiments depends on their span in the Y-axis direction.

3. Results and discussion

In this section, the FEM results are compared with the structure of the experimental samples to analyze the influence of processing holes on the mechanical properties of samples under tensile and compressive stress. Then, the specific influences of the diameters and shapes of the holes and the structure of the FIHPs on the flexural properties of the plates are studied, and the failure modes of the experimental samples and their underlying mechanisms are discussed in terms of stress contours.

3.1. The influence of processing holes in different stress states on the mechanical properties of FIHPs

Fig. 2 shows the FEM results for the models corresponding to the experimental samples. Fig. 2(a) indicates that when the perforated surface is facing upward or downward, the difference between the analytical and experimental values of the failure loads of the FIHPs is 1.1% or 30%, respectively. In the former case, the analytical results are very close to the experimental results, whereas in the latter case, they are quite different. It is generally accepted that a model with the former error magnitude is precise, whereas one with the latter error magnitude is imprecise; however, we do not believe that this interpretation always strictly holds. In the case of the current object of study, the experimental samples were fabricated using a composite material of fiber-reinforced resin, and their structure is that of complex integrated honeycomb plates. Their mechanical properties are influenced by various factors during the process of sample preparation. In other words, the experimental samples are imperfect with respect to parameters such as the evenness of the fiber distribution and the precise fiber size, whereas the model materials used in the FEM analysis are ideally isotropic and flawless. Therefore, even the former error, although it is only 1.1%, provides only a qualitative indication, or at most a half-quantitative one, that the analytical values are consistent with the experimental values. Of course, in the latter case, reasons must be found to explain why the experimental values are 30% lower than the simulated ones. The authors believe that these reasons lie in the sample preparation process. During sample preparation, a male wax mold is first fixed on a slab, and short fibers are then filled in between the mold and the slab to form the lower skin, whereas fibers are laid on top of the mold to form the upper skin. Because the space is very narrow, it is more difficult to fill the space between the mold and the slab with short fibers than it is to lay the fibers onto the mold; therefore, the density and uniformity of the lower skin are inferior to those in the dumbbell-shaped samples that were prepared specifically to experimentally measure the mechanical properties of the fiber-reinforced composite material. When the skin that contains the processing holes is facing downward and is in a tensile state, the holes can produce high stress concentrations; moreover, the skin with holes is thinner than that without holes and thus is more sensitive to initial imperfections of the FIHPs. In practice, the time elapsed before crack formation at the edges of the holes is less than that in the ideal FEM model, which leads to the observed error of up to 30%. By contrast, when the perforated surface is facing upward and is in a compressive state, the holes are not as sensitive to the initial defects of the FIHPs and damage or cracking first occurs in the lower skin without processing holes. Therefore, the initial imperfections

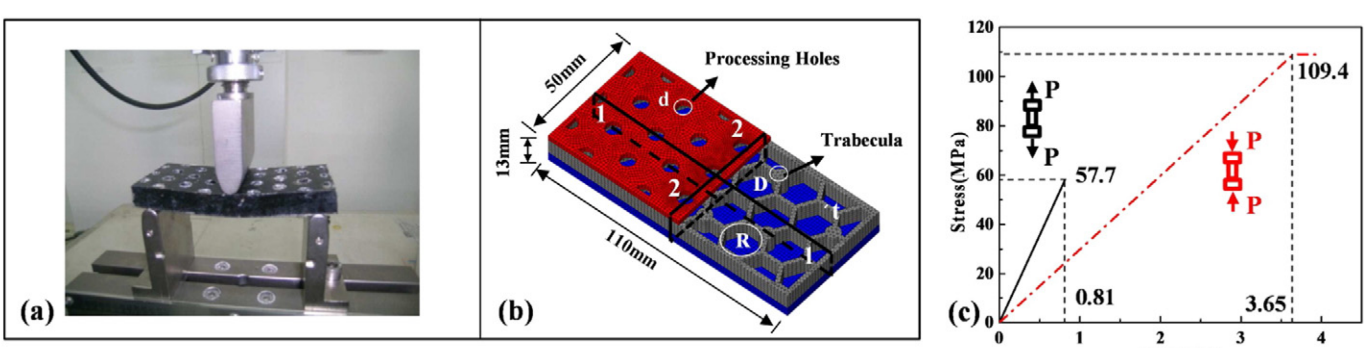

Fig. 1. (a) The test model and pressurization mode, (b) the dimensions of the analytical model of an FIHP, and (c) the constitutive model of the material.