FLEXIBLE DESIGN AND CONTROLLABLE BENDING SURFACE OF COMPOSITE HONEYCOMB

Xingyu WEI[1], Jian XIONG[2]

[1] Center for Composite Materials and Structures, School of Astronautics, Harbin Institute of Technology, Harbin 150001, China, Email: xingyu.wei@hit.edu.cn
Web:http://homepage.hit.edu.cn/weixingyu
[2] Center for Composite Materials and Structures, School of Astronautics, Harbin Institute of Technology, Harbin 150001, China, Email: jx@hit.edu.cn Web: http://homepage.hit.edu.cn/jianxiong

Keywords: Composite honeycomb; Bending flexibility; Surface control; Profile accuracy

ABSTRACT

A method for designing flexible composite honeycomb structure is proposed in this paper for low bending flexibility, damage and fracture generated by forced shaping and poor structural accuracy caused by springback in the manufacturing process of complex curved sandwich shell. This method reduces the in-plane elastic modulus and improves the bending flexibility of composite honeycomb by replacing straight cell wall with curved cell wall. It makes the optimum bending flexibility of composite honeycomb reach the same degree as aluminum honeycomb, which can meet the engineering requirements. In addition, the in-plane mechanical properties can be effectively controlled by designing the critical geometric parameters of the honeycomb, so as to control the characteristic bending surfaces and satisfy the requirements of engineering surface, including two-dimensional surface, elliptic parabolic surface and rotating parabolic surface. Finally, it is applied to design and fabricate all-composite antenna reflector. The simulation results show that the residual stress during the manufacturing process, avoid the shape springback, and improve the profile accuracy of the antenna reflector over a wide range of temperatures can be effectively reduced by using curved-wall composite honeycomb.

1 INTRODUCTION

Honeycomb as one of the well-organized topological cellular material has many applications in spacecraft, airplane, high-speed train, architecture and so on. Many engineering constructions with curved surfaces, such as satellite antenna reflector, wing leading edge or geodesic radome, also require honeycomb as the core of their sandwich structure, but there is a lack of honeycomb configurations suitable for special curved structure[1,2]. Most honeycombs are forced to bend into a particular surface, which lead to collapse band caused by conflicting bending surface and wrinkled honeycomb walls[3-6]. It reduces the load-bearing capacity of honeycomb and increases the difficulty of manufacturing high-precision curved structures due to spring-back error, especially for CFRP honeycombs, which is essential to antenna reflector. So it is of great importance to design a kind of honeycomb with tailorable mechanical property and controllable bending surface, which have attracted attentions of many researchers[7].

The production cost will be greatly reduced by bending honeycomb into the desired engineering surface directly. For traditional hexagonal honeycomb, however, it is found that serious damage is caused by local buckling of the honeycomb wall in the forming process of curved sandwich structure. Zhao et al.[8] found the inconsistent bending deformation of honeycomb with the objective molding surface would cause additional buckled cell walls and collapse bands, which will further reduce the load-carrying ability of the whole structure. Thus, well-designed honeycomb configurations attenuate in-plane elastic modulus in a designed way. Not only bending flexibility can be increased, but also the bending surface can be controlled by tailoring mechanical characteristics of honeycomb. The design philosophy of wearable electronics can be referred to improve bending flexibility. The curved or torsional structural unit could be employed to construct flexible soft materials[9-11]. The existing researches on curved-wall honeycomb focus on the stability of walls against elastic buckling and ignore the significance of bending flexibility. Besides, there is almost no theoretical model and characterization methods for designing, analyzing and evaluating bending surface of honeycomb, of which is useful for engineering production.

In order to overcome the limitations in practical applications of CFRP honeycomb, this paper introduces a novel flexible CFRP honeycomb with tailorable mechanical characteristics and controllable bending surface.

2 FLEXIBLE DESIGN

The flexibility of CFRP honeycomb is limited by in-plane elastic modulus. Flexible design based on curved wall is proposed to induce the deformation of cell walls, reduce the in-plane elastic modulus and improve structural ductility, thereby ultimately achieving the flexible CFRP honeycomb. Euler–Bernoulli beam theory is employed to deduce the in-plane mechanical properties of two-dimensional honeycomb configuration. Curved wall is the structural unit of honeycomb. In the analytical derivation, the curved wall is regarded as curved beam. As shown in Fig. 1(a), curved-wall honeycomb can be divided into two kinds of curved beams, and the applied loads can also be divided into horizontal and vertical unit forces. The bending moment functions of curved beams are derived and shown as:

$$\begin{cases} M_{c1}(\theta)=\cos\theta\left[\sin\varphi-\sin(\varphi-x)\right]+\sin\theta\left[\cos(\varphi-x)-\cos\varphi\right] \\ M_{c2}(\theta)=\cos\theta\left[\sin\varphi-\sin(\varphi-x)\right]-\sin\theta\left[\cos(\varphi-x)-\cos\varphi\right] \\ M_{p1}(\theta)=\sin\theta\left[\sin\varphi-\sin(\varphi-x)\right]-\cos\theta\left[\cos(\varphi-x)-\cos\varphi\right] \\ M_{p2}(\theta)=\sin\theta\left[\sin\varphi-\sin(\varphi-x)\right]+\cos\theta\left[\cos(\varphi-x)-\cos\varphi\right] \end{cases} \tag{1}$$

According to force method of structural mechanics, the displacement of curved beams is obtained by integral operation. The vertical displacement of tail end of curved beam can be deduced by

$$\delta_{Curved}=\frac{FR^3}{E_s I}\int_0^{2\varphi} M_{c1}(\theta)M_{c1}(\theta)dx \tag{2}$$

The schematic illustration curved-wall honeycomb is shown in Fig. 1(b). The stiffness ratio of curved to straight wall λ is expressed as

$$\lambda=\frac{(F/\delta)_{Curved}}{(F/\delta)_{Straight}} \tag{3}$$

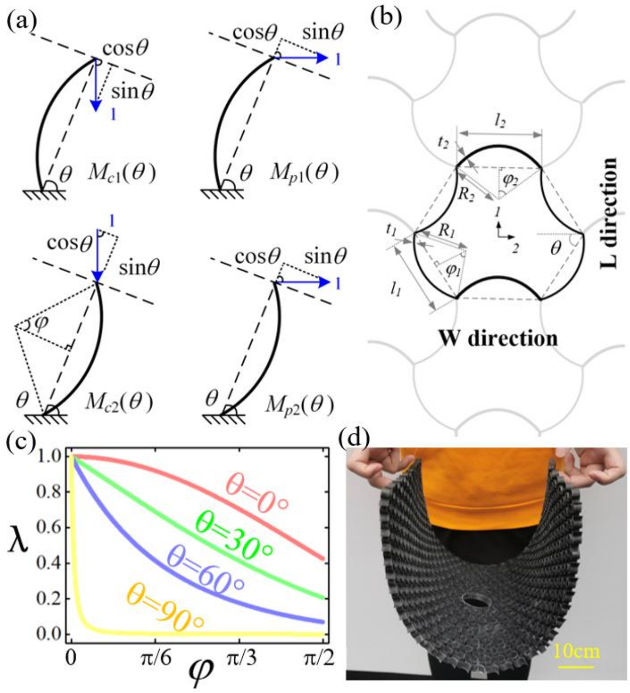

Fig.1 Flexible design: (a) curved wall units (b) Schematic illustration of curved-wall honeycomb (c) Theoretical curve of stiffness ratio varying with curvature of curved wall (d) bending deformation of flexible composite honeycomb

Fig. 1(c) shows the theoretical curve of stiffness ratio changing with curved-wall curvature. It can be found that flexible design can effectively reduce in-plane stiffness. When the curvature of the curved wall reaches the maximum, where the curved wall section is ½ arc, the in-plane stiffness of composite honeycomb is 0.05±0.02MPa, which is similar to that of aluminum honeycomb. Thus, the flexural flexibility of composite honeycomb can be equivalent to that of commercial aluminum honeycomb, as shown in Fig. 1(d).

3 DEFORMATION CHARACTERISTICS OF HONEYCOMB BENDING SURFACE

The bending surface and deformation characteristic of curved-wall honeycomb is investigated in this Section. The deformation equation of honeycomb under out-of-plane bending load in any direction is derived to study the bending surface. A new kind of testing device based on DIC method is invented and established to measure the bending surface of CFRP honeycomb specimens under out-of-plane bending load in W and L principle direction. Finally, bending displacement contours measured by experiments are contrast with contour lines calculated by analytical model to determine the deformation characteristic of honeycomb.

3.1 Analytical model for bending deformation

The honeycomb, which is regarded as an orthotropic thin plate in analytical model, follow Kirchhoff-Love hypothesis. (i) The normal strain perpendicular to the middle plane is negligible $\varepsilon_z \approx 0$; (ii) $\gamma_{zx}, \gamma_{zy}, \varepsilon_z$ is negligible; is non-negligible due to force balance; (iii) Points in the middle plane of the thin plate has no displacement parallel to the middle plane, so that $(\varepsilon_x)_{z=0} = 0,\ (\varepsilon_y)_{z=0} = 0,\ (\gamma_{xy})_{z=0} = 0$. The mathematical expression can be given by:

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = -z \cdot [T]^{-1}[S]^{-1}[T]^{-T} \begin{pmatrix} \dfrac{\partial^2 w}{\partial x^2} \\ \dfrac{\partial^2 w}{\partial y^2} \\ 2\dfrac{\partial^2 w}{\partial x \partial y} \end{pmatrix} \tag{4}$$

The matrix is assumed as $[D] = [T]^{-1}[S]^{-1}[T]^{-T}$, Hence, the force and bending moment of unit element are deduced and given by

$$\begin{aligned} F_{xz} &= \frac{h^2}{2}\left[D_{11}\frac{\partial^3 w}{\partial x^3} + (D_{31} + 2D_{13})\frac{\partial^3 w}{\partial x^2 \partial y} + (D_{12} + 2D_{33})\frac{\partial^3 w}{\partial x \partial y^2} + D_{32}\frac{\partial^3 w}{\partial y^3} \right] \\ F_{yz} &= \frac{h^2}{2}\left[D_{31}\frac{\partial^3 w}{\partial x^3} + (D_{21} + 2D_{33})\frac{\partial^3 w}{\partial x^2 \partial y} + (D_{32} + 2D_{23})\frac{\partial^3 w}{\partial x \partial y^2} + D_{22}\frac{\partial^3 w}{\partial y^3} \right] \end{aligned} \tag{5}$$

$$\begin{pmatrix} M_x \\ M_y \\ M_{xy} \end{pmatrix} = -\frac{h^3}{12} \cdot [D] \begin{pmatrix} \dfrac{\partial^2 w}{\partial x^2} \\ \dfrac{\partial^2 w}{\partial y^2} \\ 2\dfrac{\partial^2 w}{\partial x \partial y} \end{pmatrix} \tag{6}$$

The Z-direction displacement function $w(x, y)$ is assumed as polynomial function, and shown as

$$w = \sum_{i,j=0}^{n} C_{i,j} x^i y^j \tag{7}$$

According to geometric symmetry and constraint conditions, the Z-direction displacement function $w(x, y)$ is simplified as

$$w = C_{2,0} \cdot x^2 + C_{0,2} \cdot y^2 + C_{1,1} \cdot xy \tag{8}$$

After that, the coefficients can be acquired by

$$\begin{pmatrix} C_{2,0} \\ C_{0,2} \\ C_{1,1} \end{pmatrix} = \frac{M}{h^3/12} \begin{pmatrix} \dfrac{\cos^4\alpha}{E_1} + \dfrac{\sin^4\alpha}{E_2} + \dfrac{\sin^2 2\alpha}{2} \cdot \left(\dfrac{1}{2G_{12}} - \dfrac{\nu_{12}}{E_1} \right) \\ \dfrac{\sin^2 2\alpha}{4} \cdot \left(\dfrac{1}{E_1} + \dfrac{1}{E_2} - \dfrac{1}{G_{12}} \right) - \left(\cos^4\alpha + \sin^4\alpha \right) \dfrac{\nu_{12}}{E_1} \\ \dfrac{\sin 2\alpha}{2} \cdot \left[\dfrac{\cos^2\alpha}{E_1} - \dfrac{\sin^2\alpha}{E_2} - \cos 2\alpha \cdot \left(\dfrac{1}{2G_{12}} - \dfrac{\nu_{12}}{E_1} \right) \right] \end{pmatrix} \tag{9}$$

When the bending direction is parallel to the principle direction of orthotropic thin plate, the bending surface is regarded as characteristic surfaces. It means that the angle α between the 1 principle direction of honeycomb and the X-axis of the coordinate system is zero. Hence, the characteristic surface is simplified as

$$w = \frac{M}{2I_1}\left(x^2 - \nu_{12} \cdot y^2 \right) \tag{10}$$

where $I_1 = \frac{E_1 h^3}{12}$ is flexural stiffness per unit width in 1 principle direction.

It is found the shape of characteristic surface is only related to the Poisson's ratio of bending direction. The deformation amplitude is controlled by applied bending load and the flexural stiffness of loading direction.

3.2 Out-of-plane bending deformation test

Poisson's ratio can be controlled by designing the honeycomb geometries so as to change the deformation characteristics of bending surface. An experimental platform for out-of-plane bending deformation was designed in this paper, as shown in Fig. 2(a). The symmetrical moment load at both ends was applied by means of mechanical transmission, the bending degree was controlled by gear scale, spray speculations were carried out by covering latex film, and honeycomb bending deformation surfaces were measured by digital photogrammetry. Fig. 2(b) shows the composite honeycomb specimens for bending test. Fig. 2(c) shows the quantified cloud maps of bending deformation.

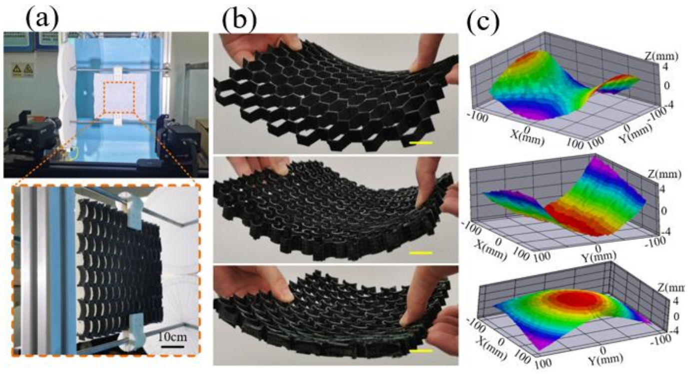

Fig.2 Out-of-plane bending deformation:
(a) experimental system (b) bending surface (c) deformation cloud maps

In this paper, the finite element model of honeycomb structure under out-of-plane bending load is established by using shell element. Fig. 3 shows the deformation surface of hexagonal honeycomb structure obtained by theoretical surface, simulation model and experimental test. The experimental deformation surface verifies theoretical prediction and simulation model. When Poisson's ratio is positive, zero and negative, the corresponding mathematical forms of characteristic curved surfaces are hyperbolic paraboloid, two-dimensional surface and elliptic paraboloid, respectively. The design of Poisson's ratio can control the surface form of honeycomb to meet different engineering requirements. Therefore, the curved surface can be controlled by improving the honeycomb configuration, so as to reduce the residual stress in the honeycomb.

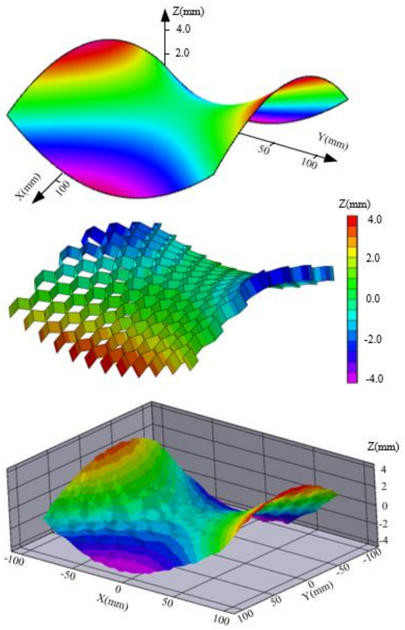

Fig.3 Comparison of bending surface of curved-wall honeycomb
(a) theoretical prediction, (b) simulation, (c) experimental test

4 SIMULATION ANALYSIS OF ALL-COMPOSITE ANTENNA REFLECTOR

The reflector of satellite antenna is a high-precision sandwich structure with special curved surface. Fig 4(a) shows the reflection surface of RICH1 detector[12], whose surface is a two-dimensional paraboloid. A finite element model was established to simulate the bending behavior of honeycomb during manufacturing process. The uniform gradient displacement was applied to the planar honeycomb, as shown in Fig 4(b). The simulation results show that the maximum residual stress of hexagonal aluminum honeycomb is 46.7 MPa and the mean stress is 26.6 MPa. The maximum residual stress of composite curved-wall honeycomb is only 10.0 MPa, and the mean stress is 4.1 MPa. The maximum residual stress of composite curved-wall honeycomb is only 21.4% of that of aluminum honeycomb, and the mean stress is only 15.4%. It proves that the composite curved-wall honeycomb will not break after bending. In addition, the lower residual stress ensures the high profile accuracy of the sandwich structure.

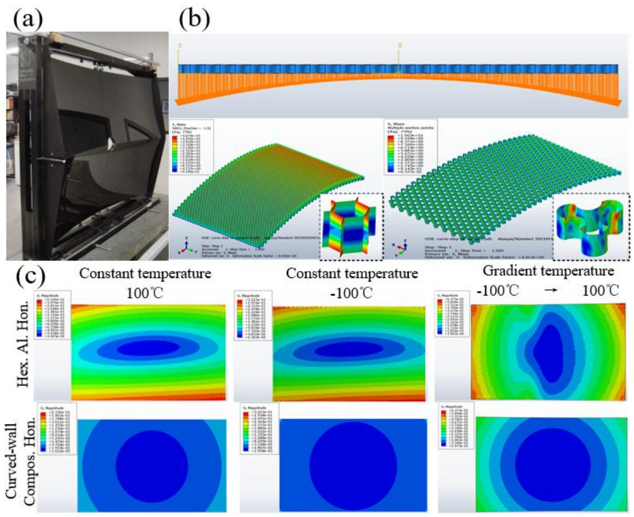

Fig.4 Simulation results of all-composite antenna reflector
(a) RICH1 antenna reflector[12], (b) residual stress after molding honeycomb, (c) comparison of antenna thermal deformation at different temperatures

Fig 4(c) shows the cloud image of thermal deformation occurred in sandwich antennas with different honeycomb cores under different temperature conditions. In order to quantitatively compare the profile accuracy of reflectors with different honeycomb, the root mean square (RMS) of all nodes of the thermal deformed reflector are extracted in this section to calculate the profile accuracy of the satellite antenna reflector. The expression is as follows:

$$\mathrm{RMS}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(x_i-x_i')^2+(y_i-y_i')^2+(z_i-z_i')^2\right]} \tag{11}$$

The RMS accuracy of the reflector surface obtained by simulation calculation is summarized in Table 1. It can be found that the RMS value of the antenna reflector which uses the composite curved-wall honeycomb as the core material is far less than that of the aluminum honeycomb, which is only one-fifth under constant temperature condition and less than half under gradient temperature variable condition. It is proved that the carbon fiber reinforced composite curved-wall honeycomb is more suitable as the core material of antenna reflector.

Table1 Profile accuracy of sandwich antenna

Temperature	RMS value (μm)	
	Al. Hon	Compos.Hon
Constant temperature 100℃	113.9	27.3
Constant temperature -100℃	150.3	33.2
Gradient temperature -100℃~100℃	29.1	12.4

5 CONCLUSIONS

In order to solve the problem that composite honeycomb is not easy to bend and shape, a flexible design method of curved honeycomb is proposed in this paper. The in-plane stiffness is improved to the same order as that of aluminum honeycomb. The bending surfaces and deformation characteristics are regulated by the in-plane mechanical properties. The simulation examples given in this paper show that the curved-wall composite honeycomb has less residual stress and less thermal deformation in different temperature conditions than aluminum honeycomb, which is more suitable for manufacturing high performance spacecraft.

ACKNOWLEDGEMENTS

This work was supported by the National Postdoctoral Program for the Innovative Talents (BX20220383), Young Elite Scientist Sponsorship Program by Heilongjiang Province(2022QNTJ002), the Heilongjiang Postdoctoral Financial Assistance (LBH-Z22170) and the Fundamental Research Funds for the Central Universities (2022FRFK060030).

REFERENCES

[1] Wang P, Zhang Y, Chen H, et al. Broadband radar absorption and mechanical behaviors of bendable over-expanded honeycomb panels[J]. *Composites Science and Technology*, 2018, 162: 33-48.

[2] Ozdemir N G, Scarpa F, Craciun M, et al. Morphing nacelle inlet lip with pneumatic actuators and a flexible nano composite sandwich panel[J]. *Smart Materials and Structures*, 2015, 24(12): 125018.

[3] Wei X, Li D, Xiong J. Fabrication and mechanical behaviors of an all-composite sandwich structure with a hexagon honeycomb core based on the tailor-folding approach[J]. *Composites Science and Technology*, 2019,184:107878.

[4] Wei X, Wu Q, Gao Y, Xiong J. Bending characteristics of all-composite hexagon honeycomb sandwich beams: experimental tests and a three-dimensional failure mechanism map[J]. *Mechanics of Materials*, 2020,148:103401.

[5] Wei X, Qianqian Wu Q, Gao Y, Yang Q, Xiong J. Composite honeycomb sandwich columns under in-plane compression: Optimal geometrical design and three-dimensional failure mechanism maps[J]. *European Journal of Mechanics - A/Solids*, 2022,91:104415.

[6] Wei X, Xue P, Wu Q, Wang Y, Xiong J. Debonding characteristics and strengthening mechanics of all-CFRP sandwich beams with interface-reinforced honeycomb cores[J]. *Composites Science and Technology*. 2022,218(8):109157.

[7] Heath C J C, Neville R M, Scarpa F, et al. Morphing hybrid honeycomb (MOHYCOMB) with in situ Poisson's ratio modulation[J]. *Smart Materials and Structures*, 2016,25(8): 085008.

[8] Zhao Z, Liu C, Sun L, et al. Experimental and numerical study on the constrained bending-induced collapse of hexagonal honeycomb[J]. *Composite Structures*, 2021, 277: 114604.

[9] Saito K, Agnese F, Scarpa F, A Cellular kirigami morphing wingbox concept. *J. Inter. Mat. Syst. Str.*, 0(2011)1-10.

[10] Saito K, Pellegrino S, Nojima T, Manufacture of arbitrary cross-section composite honeycomb cores based on origami techniques. *ASME IDETC/CIE*, Portland, Oregon, USA, 2013,DETC2013-12743.

[11] Saito K, Fujimoto A, Okabe Y, Design of a 3D wing honeycomb core based on origami techniques. *ASME IDETC/CIE*, Charlotte, North Carolina,2016, DETC2016-60419.

[12] Alderson A, Alderson K L, Chirima G, Ravirala N, Zied K M. The in-plane linear elastic constants and out-of-plane bending of 3-coordinated ligament and cylinder-ligament honeycombs. *Compos. Sci. Tech.* 70(2010) 1034-1041.