ORIGINAL RESEARCH

Simulation and experimental analysis of autoclave co-curing CFRP hat-stiffened panels with silicone airbag mandrels

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Abstract

The inflatable mandrel is easy to be broken and wrinkled during the co-curing process of the hat-stiffened wall panels. The metal mandrel is difficult to demold, the water-soluble mandrel is easy to be broken, and the pressure transmission uniformity of the silicone mandrel with preformed apertures is difficult to ensure during the manufacturing process. To solve these problems, a new process for co-curing carbon fiber-reinforced polymer hat-stiffened panels based on silicone airbag mandrel was proposed in this paper. The co-curing process of the hat-stiffened panels was simulated using finite element software and the effects of silicone airbag mandrels with different thicknesses on the thickness and pressure of the parts were studied by establishing a thermo-force-flow multi-field coupling finite element model, and found that the thickness and pressure of the parts were relatively uniform during the manufacturing process of the new method. The correctness of the finite element model was verified by the autoclave co-curing experiment. At the same time, it demonstrated the feasibility of a new process of autoclave co-curing CFRP hat-stiffened panels with silicone airbag mandrels. This new process greatly improved the accuracy of the carbon fiber-reinforced resin matrix composite hat-stiffened panels compared to conventional processes.

Introduction

As a new type of material with excellent performance, carbon fiber-reinforced resin matrix composite material has a series of advantages, such as high specific strength, high specific modulus, high temperature resistance, corrosion resistance, fatigue resistance, good damping and shock absorption, good safety, good designability and functional integration. This composite has gradually becomes one of the indispensable main structural materials in aerospace materials, mainly used in large main bearing structures such as aircraft wings, tails and fuselage [1]. To improve various performances of the aircraft's main bearing structures, the reinforced structures are commonly used in aircrafts. Composite stiffened panels are generally classified into T-type, J-type, I-type, and hat-type (Ω-type) according to the structure of the long truss. Among them, the hat-stiffened structure is widely used in the curved structure of the aircraft owing to its advantages such as good structural stability, high efficiency for the axial load transfer and high buckling strength. More than 80% of the aircraft cabins are equipped with hat-stiffened panels, such as the rear side panels of the rear fuselage of the C919 [2].

The autoclave process dominates the manufacture of aerospace composite materials because of its excellent product quality, and the autoclave process is still the main manufacturing method nowadays.

For open-type stiffened panels, such as T-shape, J-shape, I-shape reinforced wall panels, domestic and foreign scholars have done a lot of researches. Wang et al. [3–5] studied the effects of pressure distribution, packing, tool assemble scheme and overall forming process on the compaction of T-reinforced panels. Ma [6] studied the compaction effect of the T-shaped stiffened panel triangle by vacuum-assisted

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resin infusion/prepreg co-curing process. Chen et al. [7] studied a new method for curing CFRP by high-pressure microwave. Zhou et al. [8] studied the effect of filler radius on the forming quality of T-stiffened panels. Elaldi et al. [9] studied a new method of forming J-stiffened panels. Bai [10] studied the impact properties of a co-cured J-shaped stiffened panel. Peng et al. [11] studied the structure of the mold and the control of the forming process to improve the quality of the parts. Ye et al. [12] studied the curing scheme, pre-adhesive material and curing parameters of the co-bonding process of I-stiffened panel. Hong [13] adopted a new molding process to shape the I-reinforced panel and J-reinforced panel. However, these open-hole types are easy to demold, and the molding method is not suitable for the molding of closed-hole types such as hat-stiffened panels.

For the closed-hole hat-stiffened panels, Xu et al. [14, 15] studied the co-bonding, secondary bonding and co-curing of the hat-stiffened panels by thermocompression curing. Tarfaoui et al. [16] studied a new type of adhesive to improve the co-bonding properties of the hat-stiffened structure. Co-curing molding has a small number of using cans, which greatly reduces the cost. Co-curing does not require glue adhesive, so we can obtain good interface mechanical properties, light weight and small deformation, which is beneficial for heavy weight and precise size requirement structures like aircraft fuselage section. Therefore, some scholars studied the molding process of closed-hole types. Kim et al. [17] studied the influence of the metal mandrel and silicone rubber mandrel on the bearing pressure of the hat-stiffened parts, but did not study the influence of the shape of the mandrel on the forming quality. Xun et al. [18] used the vacuum-bags as auxiliary airbags to co-cure hat-stiffened panels. Due to the tendency of wrinkles and leaks in vacuum bag mandrels, they are now being phased out by factories. Xiao [19] invented a low-cost water-soluble mandrel to make hat-stiffened panels. The water-soluble mandrel has less thermal deformation, which can well maintain the shape of the hole in the forming process, and it is convenient to demold, but the water-soluble core mold itself is of poor quality and is prone to rupture during the experiment, so that the surface quality of the inner wall surface of the hat-shaped part is poor, and it has not been put into production. Li and Zhou et al. [20, 21] studied the process of silicone rubber mandrels with prefabricated round holes, and analyzed the shape of the hat-shaped long truss under this process, and found that the shape of the hat-stiffened panel was difficult to control. The reason was that the silicone rubber mandrel with prefabricated holes exerted pressure through its own thermal expansion, which tended to cause uneven pressure on the hat body, induced dimensional defects or defects in precision, and the process adjustment was difficult.

In view of this, this paper developed a new molding process for silicone rubber airbag mandrel. In this paper, for the

purpose of ensuring molding quality of CFRP hat-stiffened panels, the computer simulation of the co-curing process of hat-stiffened panels was carried out, and the hat-stiffened panels were manufactured through experiments. The effects of different thickness of silicone rubber airbags on the shape of the parts were studied. The influence of pressure on the quality of the panels was analyzed, which laid a foundation for the co-curing of CFRP hat-stiffened panels.

Experimental

Prepreg material

The materials of the CFRP hat-stiffened structure are C135 unidirectional prepreg and BCP200 fabric prepreg produced by Shandong Dingsheng Composite Technology Company (China). The substrate material is DS1207.3 heat-resistant prepreg special for epoxy resin.

Hat-stiffened structure and mold

Hat-stiffened structure and layup

The hat-stiffened structure is shown in Fig. 1. The hat-stiffened panel is composed of hat-stiffened long truss and skin plate.

The unidirectional prepreg is laminated with the woven prepreg using axial direction as 0°, and the stacking sequence of hat part is $[\pm 45°/0°/90°/0°/90°/0°/90°/0°/\pm 45°]$. The stacking sequence of the plate is $[\pm 45°/\pm 45°/90°/-45°/\pm 45°/45°/0°/45°/\pm 45°/-45°/45°/90°]$.

Principle of new curing process

The principle of the new process is that the hat-shape long truss is placed in the frame mold, and the silicone airbag mandrel is placed in the hat-shaped closed aperture mold. The silicone airbag mandrel is inserted into the canister pressure of the autoclave to support the formation of hat-shaped long truss; the skin mold is placed at the top of the preformed material to function as a pressure equalizing skin. The mold placement and curing package are shown in Fig. 2. The curing temperature and pressure curve are shown in Fig. 3.

The advantage of this scheme is that the hat-shaped long truss is placed in the frame mold, and the position in the width direction is positioned by the cavity frame mold, which has higher dimensional accuracy; the silicone airbag mandrel has uniform pressure transmission because of the thin wall structure, and it is easy to place and extract in the closed aperture mold.
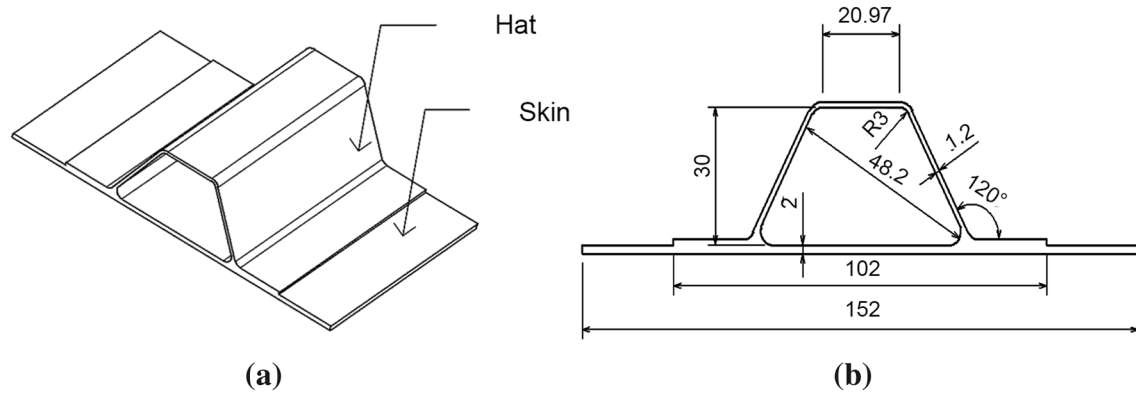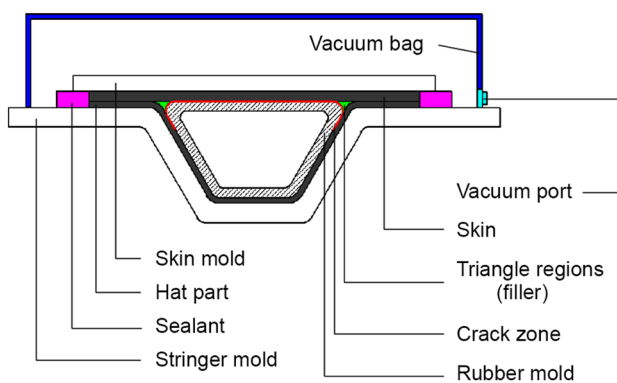
Fig. 1 CFRP hat-stiffened panel

Fig. 2 Co-curing process of hat-stiffened structure with autoclave
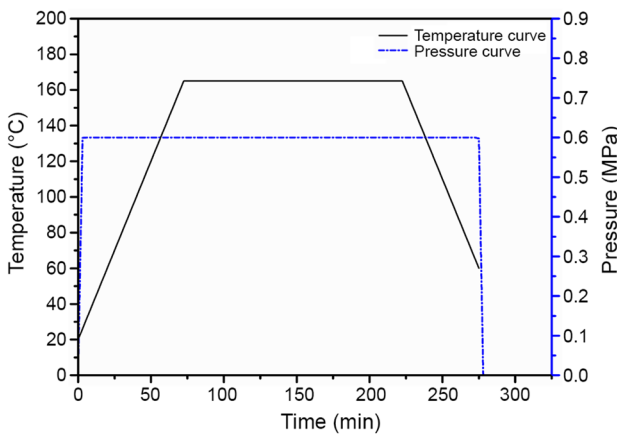

Fig. 4 Mandrel manufacturing mold

Fig. 3 Processing curve

Mandrel preparation

To achieve easy release of the mandrel, the silicone airbag mandrels were produced using the mold shown in Fig. 4. Different sizes of mandrel 4a, 4b and 4c were selected to
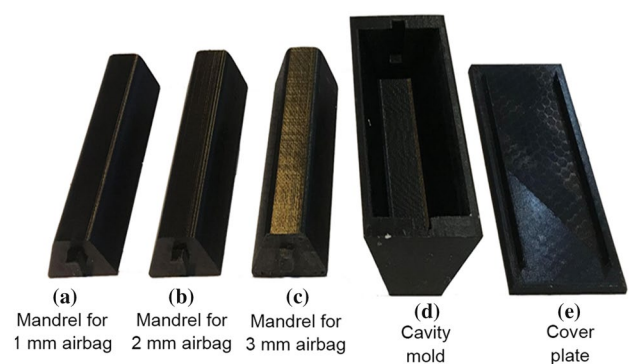
match the shell mold 4d and the cover mold 4e to produce silicone airbags with different thicknesses. Take appropriate amount of 881# silica gel solution and curing agent, mix according to the mass ratio of 100:2.5, stir evenly and then pour into the mold. After half an hour, the silica gel begins to solidify. Take out 6–8 h later after complete curing. The silicone airbags with different thicknesses (1, 2 and 3 mm) are shown in Fig. 5.

Design and manufacture of steel molds

The long truss mold is a frame cavity mold made of Q235 steel, and the skin mold is a cover mold made of Q235 steel. The long truss mold and the skin mold are shown in Fig. 6.

Finite element modeling

Thermal conduction and solidification kinetic equation

In the curing process of carbon fiber-reinforced resin matrix composites, the temperature field and the curing reaction of the resin play a major role in the internal stress and pore
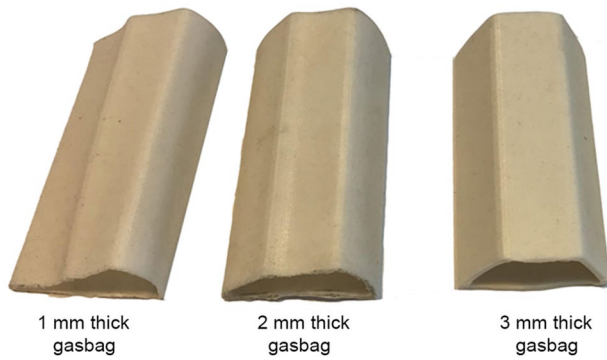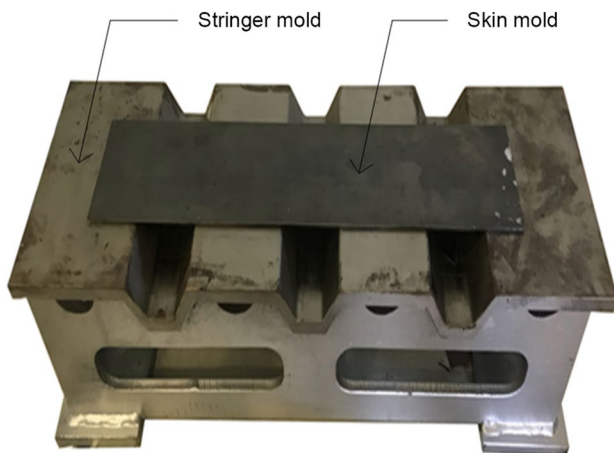
Fig. 5 Silicone rubber mold

Fig. 6 Steel mold

defects of the stiffened panels. The temperature field is mainly determined by the external heat source, the exothermic heat of the resin curing reaction, and the heat exchange between the materials.

Based on the Fourier heat conduction law, the thermochemical model considered the effect of the resin solidification exotherm on the temperature field during the curing process:

$$\rho C \frac{\partial T}{\partial t} + \rho_r C_r V_i \frac{\partial T}{\partial i} = \frac{\partial}{\partial i}\left(K_{ii}\frac{\partial T}{\partial i}\right) + Q \quad (1)$$
$$(i = 1, 2, 3),$$

$$Q = \rho_r v_r H_u \frac{d\alpha}{dt}, \quad (2)$$

where ρ, C and K_{ii} are the density, specific heat capacity and heat transfer coefficient of the composite, respectively; ρ_r, C_r and V_i are, respectively, the density, specific heat capacity and flow rate of the resin; Q is the heat release of the resin; v_r is the volume fraction of resin in composites; H_u is the

total heat release of resin at the completion of the curing reaction; α is the degree of curing of the resin; $d\alpha/dt$ is the instantaneous curing rate of the resin [22].

Kinetic equation of resin curing reaction:

$$\frac{d\alpha}{dt} = \begin{cases} (K_1+K_2\alpha)(1-\alpha)(0.47-\alpha)(\alpha \le 0.3) \\ K_3(1-\alpha)(\alpha > 0.3) \end{cases} \quad (3)$$

$$K_i = A_i \exp(-\Delta E_i / RT) \ (i = 1, 2, 3),$$

where $K_i, A_i, \Delta E_i \ (i = 1, 2, 3)$ are, in the order given, the rate parameter, frequency factor and activation energy of autocatalytic reaction.

Finite element model

Comsol multiphysics software is applied in large-scale advanced numerical simulation analysis. It excels at multiphysics coupling simulation.

The porous medium heat transfer, the curing generalized partial differential equation and the porous elastic module of Comsol software were used to model and simulate the co-curing process of carbon fiber-reinforced resin matrix composite hat-stiffened panels.

Since the axial solidification process was basically the same, to reduce the calculation work-load, this simulation used two-dimensional simulation. To accurately reflect the deformation of the hat-stiffened panels in the curing process with the autoclave, it was necessary to add relevant boundary conditions to the steel mold and the silicone mandrel:

1. The outer surface 1 of the prefabricated parts, the upper surface 2 of the skin mold and the inner surface 3 of the silicon were loaded with a curing temperature curve as shown in Fig. 3, and the remaining boundaries were thermally insulated.
2. The surface 1 of hat-stiffened long truss was in direct contact with the frame mold, so a fixed constraint was added. Since the sides 4 and 6 were symmetric surfaces, a symmetrical constraint was added; since there was more than one hat-shape long truss, so the side surface 5 was symmetrically restrained in the horizontal direction.
3. The curing pressure was set to 0.6 MPa on the upper surface 2 of the steel mold and the inner surface 3 of the silicone mandrel.

To compare the forming quality with document 17, the article also performed finite element modeling on a hat-stiffened panel made from a silicon mandrel with a 12.5-mm preformed aperture. The boundary conditions were adding a pressure of 0.1 MPa in the preformed apertures, and the rest was not changed [15].

For the two models above, the grid was divided by a free-form quadrilateral mesh. The mesh of the mold and the mesh of the prefabricated parts are shown in Fig. 7.

Implementation plan

Co-curing experiments were carried out by placing silicone airbag mandrels with different thicknesses, and then the parts were analyzed dimensionally. On the basis of the experiment, the influence of thickness of silicon airbag on pressure and deformation of the parts was analyzed by finite element numerical simulation, and the solidification forming mechanism of

the new process was explained. Furthermore, we compared the results of the finite element displacement map of the silicone airbag mandrel with pre-formed aperture mandrel to tell the advantages and disadvantages of the two processes.

Results and discussion

Shape and thickness analysis

The shape and thickness of the hat had a great influence on the mechanical properties of the hat-stiffened panels, so the
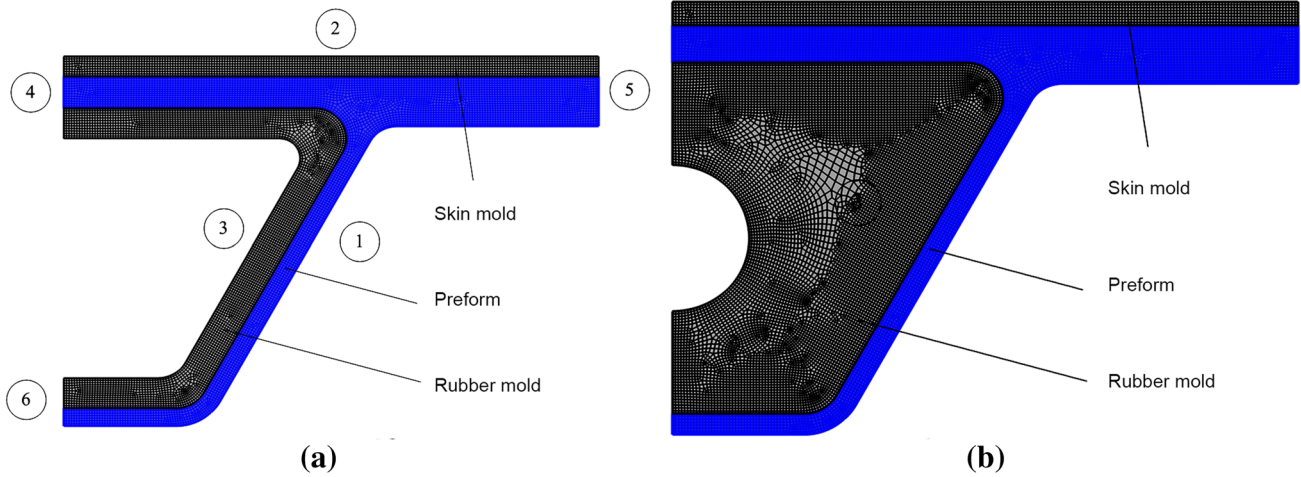

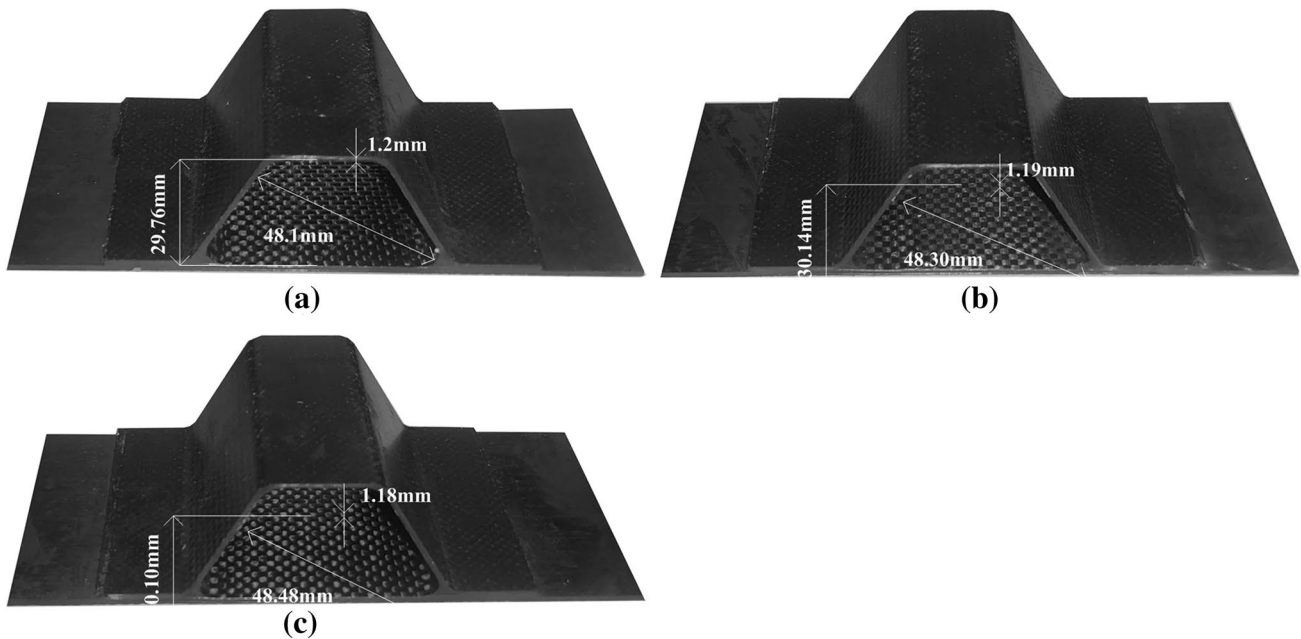**Fig. 7** Finite element meshing

Fig. 8 Experimental results of appearance accuracy test of hat-stiffened structure

shape of the hat had to be analyzed. The effects of different mandrel thicknesses (1, 2, and 3 mm) on the shape and thickness of CFRP hat-shaped panels were compared and analyzed through experimental research.

It can be seen from the cured hat-stiffened panel that the surface was smooth and no abnormality was evident. The results of the size measurement are shown in Fig. 8. The height of the inner wall of the work piece was between 29.76 and ~30.14 mm, and the basic deviation was less than 1%. The vertical distance from the triangle to the edge of the hat was between 48.1 and 48.48 mm, compared with 48.16 mm in the structural design, the deviation was within 1%, and the forming result was good.

The top, the edge and the bottom of the hat were taken from their respective parts formed under different thicknesses, and four points for the histogram were selected. The results are shown in Fig. 9. In Fig. 9b–d, it can be seen that the minimum size of the four points is 1.18 mm, the maximum is 1.2 mm, the deformation is 0.02 mm, and the

basic deviation is within 2%. The maximum deformation of the bottom of the hat is 0.05 mm, and the basic deviation is 2.5%. The deformation of these three places in the hat is less than 2.5%. Dimension fluctuations in new forming technology are smaller.

Analysis of finite element results

The finite element simulation of the silicon airbags mandrel with different thicknesses was carried out, and the displacement map and the 20-times enlarged map of the hat-shaped stiffened panels were obtained. It can be seen from Fig. 10 that the stiffened panels had a certain amount of deformation, the largest deformation region was the triangular region, and the deformation at the top of the hat was the second. It can be seen from Fig. 10b, d, f that as the wall thickness of the silicone airbag increased, the deformation of the stiffened panels also began to increase. The maximum displacement of the triangle area was changed from 0.043 to
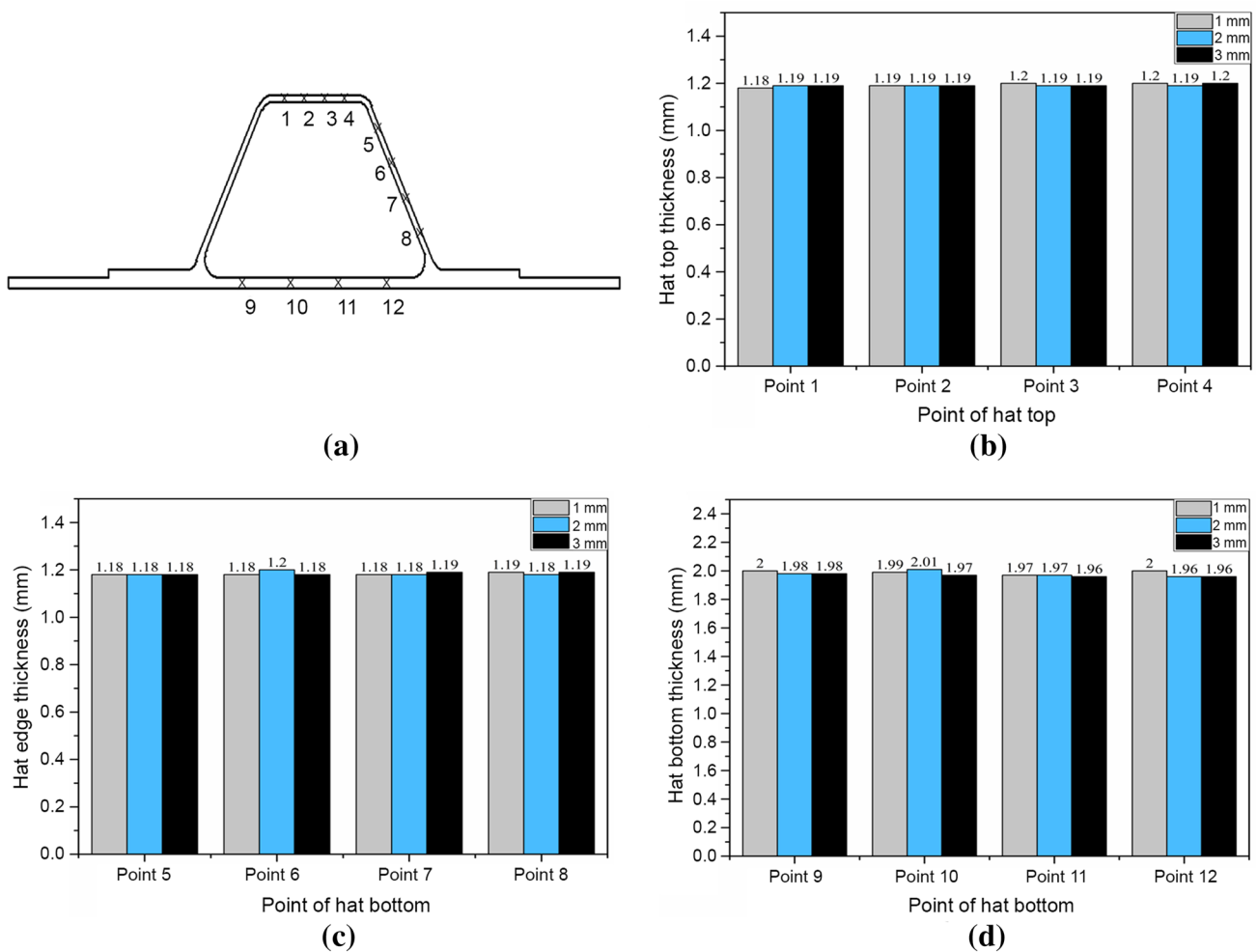

(a)

(b)

(c)

(d)

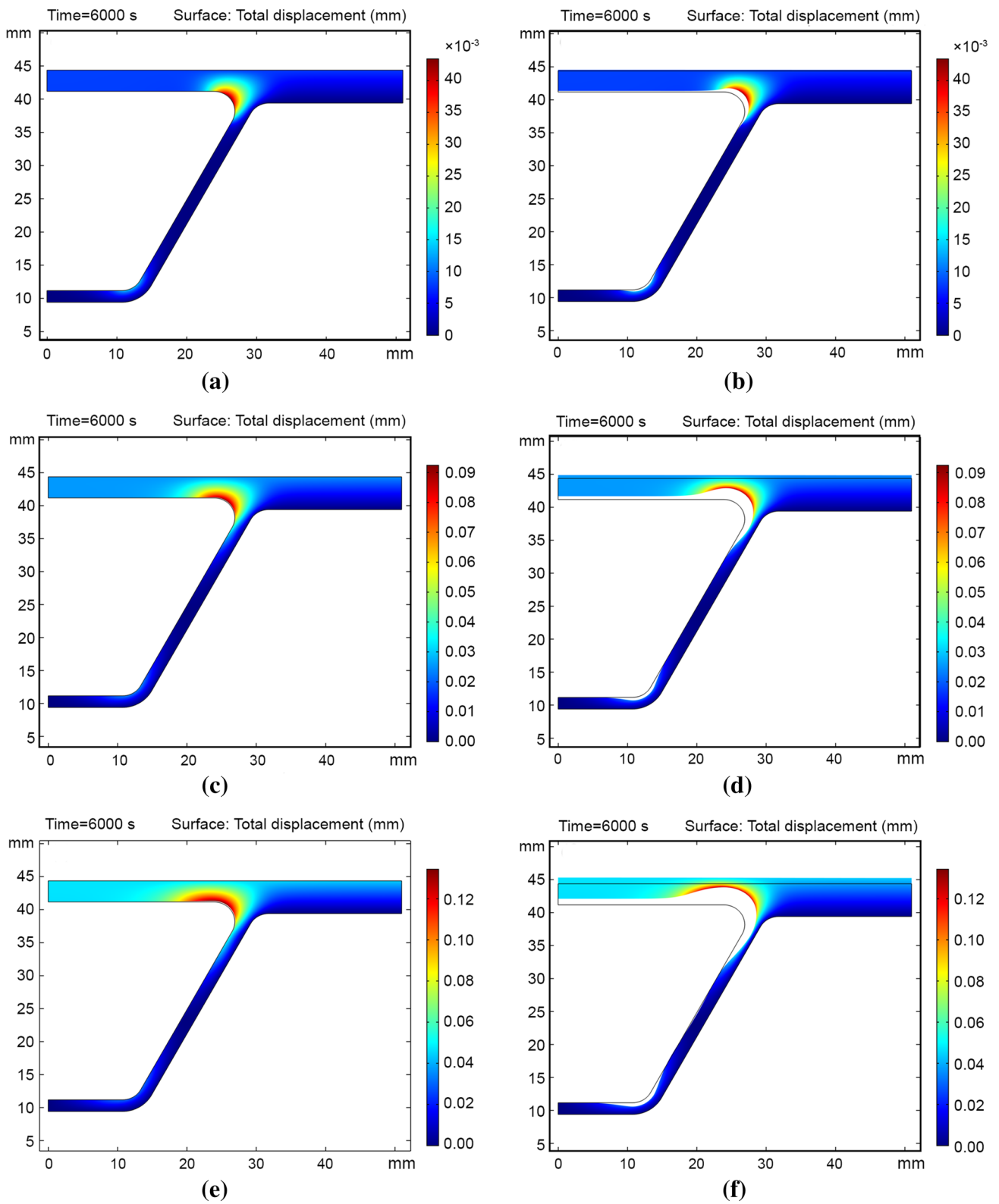**Fig. 9** Size changing chart of hat-stiffened parts

Fig. 10 Maximum displacement diagram and 20 times enlarged diagram of CFRP hat-stiffened panels
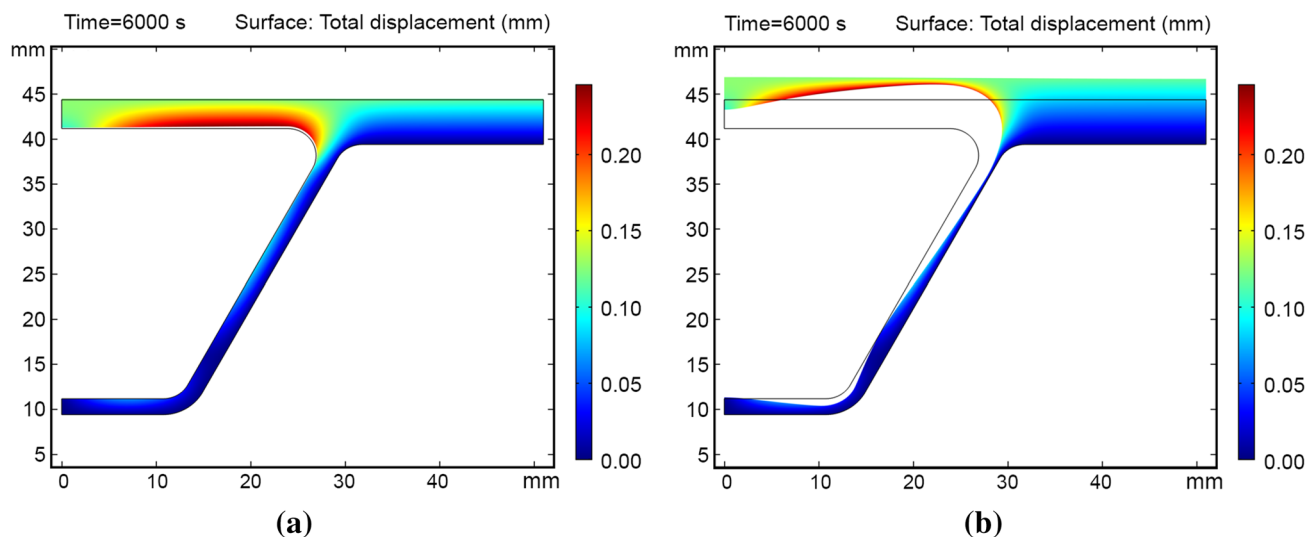
Fig. 11 Maximum displacement diagram and 20 times enlarged diagram of hat-stiffened panel manufactured by 12-mm prefabricated aperture mandrel

0.12 mm; the displacement of the hat top was also increased from 0.015 to 0.04 mm, because the amount of expansion at the same temperature increased when the thickness of the silicon airbags was increased as well.

In summary, the maximum deformation in the triangle area and the hat shoulder was small, indicating that the silicone airbag as a mandrel was effective.

The CFRP hat-stiffened panels using silicone mandrel with a 12.5-mm pre-formed aperture were modeled as shown in Fig. 7b. The finite element displacement map is shown in Fig. 11. Following the analysis, it was found that under the same processing conditions, the maximum size deformation of the triangle with the pre-formed silicone mandrel was 0.25 mm, which was twice that of 3-mm thickness airbag molded parts, 3 times that of 2 mm thickness airbag molded parts, and 6 times that of 1 mm thickness airbag molded parts.

It indicated that the new process proposed in this paper was better than the preformed aperture process.

Hat pressure analysis

The pressure and its uniformity in the solidification process had a great influence on the property of the part, and it had to be analyzed. According to the finite element simulation results, pressure of the top of the hat A, the bottom B, the triangle C and the flange D was taken to draw the pressure curve to analyze the effect of the silicone airbag mandrels with different thicknesses on the pressure and its uniformity. The results are shown in Fig. 12.

As shown in Fig. 12a–d, the pressure was the highest at the top of the hat, which was due to the fixed constraint on the

outer surface 1 of the long truss, the pressure of the canister and the silicone expansion force on inner surface. The force at the bottom of the hat was relatively uniform. The reason was that the upper and lower sides of the hat were pressed by the canister and the upward silicone expansion force was applied at the same time, and the skin mold was deformed to offset some of the expansion force. The force at point C in the triangle was the most uniform. Because both sides of point C were pressed by the canister force and subjected to the expansion force of silicone at the same time. Therefore, the force here was closer to 0.6 MPa than point B. The force at point D in the flange area was the lowest because the outer surface 1 of the long truss was firmly constrained, and the tank pressure in the Y-axis direction was partially offset by the expansion force of the silicone airbag.

From Fig. 12, it can be seen that the pressure range of the molded parts of the 1-mm-thick silicone airbag mandrel is 0.5997–0.6004 MPa, and the pressure range of the 2-mm-thick silicone airbag mandrel is 0.5996–0.6006 MPa. The 3-mm-thick silicone airbag had a pressure range of 0.5995–0.6035 MPa. When the thickness of the silicone airbag mandrel was larger, the pressure range of the work-piece was bigger. But the pressure at four points was basically around 0.6 MPa, and the fluctuation was small, and the hat-stiffened structure had a uniform curing pressure, so the size was uniform, consistent with the uniform thickness results described in shape and thickness analysis. The hat was also free of distortion, which could maintain the initial design dimensions; so the feasibility of the new process was further demonstrated.
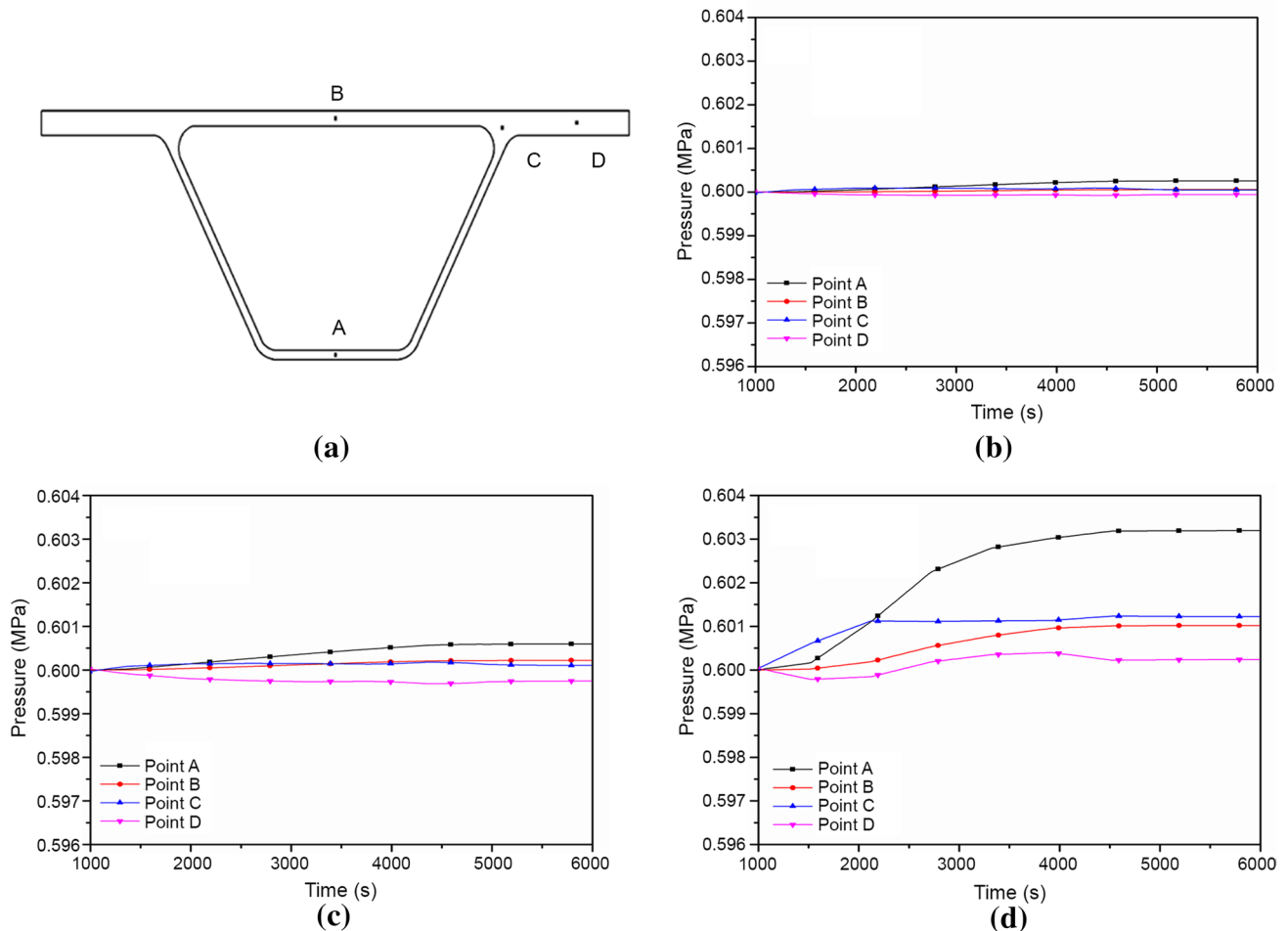
Fig. 12 Pressure diagram of different points of hat-stiffened part

Conclusion

The work-pieces manufactured with different thicknesses (1, 2 and 3 mm) silicone airbags were compared through experimental research, and the thickness deviation of the top and the edge of the hat was 0.02 mm, and the deviation of the bottom of the hat was 0.05 mm. The wall thickness was relatively uniform. The pressure of the four points of the hat was obtained through the finite element simulation analysis, and the pressure range of the molded parts with different wall thicknesses was 0.5997–0.6004 MPa (1 mm), 0.5996–0.6006 MPa (2 mm), and 0.5995–0.6035 MPa (3 mm), and the parts were under relatively uniform pressure. In summary, the size and thickness of the experimental parts and the pressure of the finite element simulation results were relatively uniform, which proved the feasibility of the autoclave co-curing CFRP hat-stiffened panels with silicone airbag mandrels. The correctness of the mathematical model and the finite element analysis method was verified by experiments, which provided theoretical and experimental support for the manufacture of composite hat-stiffened structures. The limitation of the study is that no mechanical properties have been tested. The next research direction is to conduct research on impact resistance and so on.

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