Study of mould design and forming process on advanced polymer-matrix composite complex structure

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Abstract. Advanced carbon fibre-reinforced polymer-matrix composites are widely applied to aviation manufacturing field due to their outstanding performance. In this paper, the mould design and forming process of the complex composite structure were discussed in detail using the hat stiffened structure as an example. The key issues of the mould design were analyzed, and the corresponding solutions were also presented. The crucial control points of the forming process such as the determination of materials and stacking sequence, the temperature and pressure route of the co-curing process were introduced. In order to guarantee the forming quality of the composite hat stiffened structure, a mathematical model about the aperture of rubber mandrel was introduced. The study presented in this paper may provide some actual references for the design and manufacture of the important complex composite structures.

1. Introduction
As the lightweight and high-performance material, advanced carbon fibre-reinforced polymer-matrix composites are widely applied to aviation manufacturing field due to their high specific strength and stiffness, anisotropy and good designability [1, 2]. Currently, complex composite structures are mainly used in some bearing structures, such as the large wing plates of airfoil and empennage. The wing plates usually employ the long truss as the stiffened structure, and kinds of types such as T type, L type, J type and hat type are often consisted in the long truss stiffened structure, as shown in figure 1. Thus it can be seen that the complex composite structures play an important role in the process of composites manufacturing. Therefore, how to fabricate the complex structures accurately so as to ensure the forming precision and internal quality has become the key issue for the composites manufacturing. In response to this issue, many scholars have done a lot of relative studies in this field. Li [3] fabricated the T-stiffened skins integrally by different tool assembly schemes in autoclave, and discussed the influence of tool assembly schemes and integral molding technologies on the compaction of T-stiffened skins in detail. Huang [4] studied the co-cured process to form the composite panels with T-type stiffeners. Vijayaraju [5] used three configurations to study the failure mechanism and the failure progression of T-stiffened skin. Sala [6] studied the hollow composite components manufactured by the treated elastomeric tooling by analytical, numerical and...
experimental approaches, and the results demonstrated the need to design the mandrel accurately. Huybrechts [7] proposed a theory governing the tooling behavior of hybrid tooling and expansion block tooling, and the theory was validated by experimental data. Williams [8] studied J- and blade-stiffened panels, comparing how well experimental data could be correlated with analysis results for buckling behavior. However, the study on forming and manufacturing process of more complex composite structures were seldom or not systematically introduced. As the best representative composite structure in the aircraft, hat stiffened structures employ a more complex configuration, and the stiffened structures of approximately 80% are hat stiffened structure. Thus, in this paper, the mould design and forming process of the hat stiffened structure were discussed in detail. The hat stiffened structure was taken as a typical example to introduce the manufacture process of complex composite structures. And it may provide some actual reference for the design and manufacture of the important complex structures.

Figure 1. Kinds of stiffened structures in aircraft.

Figure 2. Typical size of the hat stiffened structure.

Figure 3. The assembly relationship of the hat stiffened skin.

2. Mould design

2.1. Design of composite covering plate
The composite covering plate is made by a kind of composite material as similar as the preform, and formed by the autoclave process. There are two advantages using the composite covering plate. Firstly, it plays a key role to locate the long truss with hat stiffener in the skin-stiffener structure. Secondly, because the coefficient of thermal expansion (CTE) is close to the preform, the forming quality of the composite preform can be better ensured. Thus, the composite covering plate may be seen as an indemnity of the external manufacturing environment for the composite hat stiffened structure. The typical size of the hat stiffened structure and the assembly relationship were shown in figures 2 and 3. According to the size and assembly relationship, the mould of the composite covering plate was designed, as shown in figure 4. It can be seen from figures 2 and 3 that two aspects should be considered during the process of mould design for the composite covering plate. On the one hand, the
temperature uniformity of the mould interface is pretty important, which may influence the forming precision of the covering plate. Thus, the modest size and uniform distribution of the air vent should be taken into account. On the other hand, owing to the reason that the preform is covered by the composite covering plate, the size of the mould groove should be larger than the preform. In the common of hat stiffened structures, the thickness of the hat stiffened structures is usually about 1.77 mm. Therefore, the clearance compensation for the groove is often selected about 2 mm.

2.2. Mould design of skin panel
In the curing process, the complex skin panel comes into direct contact with the tooling of skin panel, and the heat is transferred to the skin panel through the mould of skin panel. Generally, as the large bearing composite structure, the size of skin is also pretty big. Thus, it is difficult to achieve an absolute uniform temperature field on the surface of the skin panel. But in the manufacturing process of the complex composite structure, the uniform temperature can make sure to achieve an ideal degree of cure and slight curing deformation, so that the curing quality of skin panel fairly rely on the temperature field. For the complex structure of hat stiffened skin, in order to obtain a relatively uniform temperature, often the mould design and selection of mould material are the key points to focus on. Therefore, enough vent holes and evened-temperature holes are requested in the mould design, which can ensure to achieve a relatively uniform distribution of temperature. In view of the difficulty of manufacturing the composite mould due to the complex structure, the invar steel is often selected as the mould material, which is also based on the approximate CTE between the skin panel and mould material. In addition, the designing accuracy of the mould surface is also very important and noteworthy. The typical mould design of stiffened skin panel is shown in figure 5.

2.3. Mould design of mandrel structure for the hat stiffened structure
Composite hat stiffened structure is a semi-enclosed structure, which needs an internal mandrel to support the hat section so as not to be crushed by the external pressure. In actual production, vacuum bag and rubber mould usually are used as the internal mandrel. However, the vacuum bag method gradually is abandoned due to the reasons such as easy to leak, poor security, so the rubber mould is more and more selected as the preferred tooling to assisted forming the composite hat stiffened structure. The rubber mould is formed by pouring the liquid rubber to a cavity of the hat type and then solidified. Thus, the mould used to pour the rubber mould is needed to design. During the mould design, there are also several issues need to be considered. Firstly, the size of mould cavity and the size of the rubber mould should stay the same. And in order to avoid the excessive liquid rubber pouring into the mould cavity so as not to influence the forming accuracy, a diversion trench about depth of 1mm should be machined on the mould surface. Secondly, in the curing process, the rubber mould expands gradually as the temperature increases. If the inflation is too large, the forming quality may be hard to ensure. To settle the issue, a prefabricated hole can be designed in the rubber mould, and a metallic solid shaft is designed to assembly in the middle of the hat cavity accordingly. Under this condition, the prefabricated hole can be made, and if the prefabricated hole cannot adapt the
manufacturing environment, it can be replaced by changing the shaft diameter to meet the product requirements. Thirdly, all the rounding chamfers are degrees of 3~5, this can be conducive to demould and to obtain a perfect surface of mould. According to the three aspects mentioned above, the exploded views of the mandrel mould were shown in figure 6.

![Figure 6. The exploded views of the mandrel mould.](image)

3. The forming process of composite hat stiffened structure

3.1. Determination of material and stacking sequence

In view of the severe environment that plane suffered, the fibre strength and the resin content should be taken into account firstly, and the volume fraction of fibres is also an important factor that needs to be considered. Recently, the fibres with high tensile strength and modulus as well as the zero-bleeding resin are the main constituent parts of prepreg. High tensile strength and modulus ensure the design strength, while the zero-bleeding resin makes sure the volume fraction of fibres and internal curing quality. For example, the common prepreg tape P2352W-19 and woven fabric FM6673-37KC. In addition, the rubber mandrel material is obtained by curing the RHODORSIL RTV 3248 A and B in accordance with the ratio of 10:1. Besides the determination of material, the stacking sequence of prepregs is another key point. The carbon fibre-reinforced polymer-matrix composite is a kind of anisotropy material, and the mechanical property of each part in the complex structure can be improved by changing the stacking sequence. For the composite hat stiffened structure, the stacking sequence of hat part and panel part are often as follows: the stacking sequence of the hat part is (±45/0/90/0/90/0/±45) and the stacking sequence of the panel part is (±45/±45/90/-45/±45/45/0/45/±45/-45/45/90)_{2s}.

3.2. The autoclave co-curing process

The co-curing process of autoclave is often employed to fabricate the large complex bearing component owing to the higher curing quality, such as the composite hat stiffened panel. In the curing process of autoclave, the temperature and pressure are the two important manufacturing factors, which can make sure the prepregs cured and compacted ideally. Figure 7 showed the typical curing process of complex composite structure. Before temperature was heated, vacuuming to 0.095 MPa at the room temperature firstly, it was mainly aimed at pre-compressing the prepregs and excluding the excrecent particles trapped in the prepregs. Then the temperature was raised to 180°C at a rate of 1.5°C/min and maintained for 150 minutes under the curing pressure of 0.6 MPa. In the end, pressure relief and air cooling were employed when the temperature was cooled to 70°C with the same rate of 1.5°C/min.
3.3. Selection of mandrel structure

The hat stiffener part and panel part is consisted in the hat stiffened structure, thus during the co-curing process, a closed trapezoid cavity will be formed. The stiffener is very soft when it is uncured, if the load is only applied on the surface of the hat stiffener, the hat stiffened structure may collapse. Therefore, the mandrel is requested as a support in the middle of the hat stiffened structure, and silicone rubber mandrel is often chosen as the important support. However, in the curing process, the inflation of rubber mandrel is unavoidable due to the synchronous temperature increase of the mandrel and preform. If the design of mandrel structure is unreasonable, the hat stiffened structure is not enough to keep the shape during the process of raising temperature. If the inflation or the stiffness of the mandrel structure is too small, the mandrel may not hold out the trapezoid cavity, and the defects would follow. In engineering practice, in order to solve the problem, optimizing and selecting proper mandrel structure becomes an effective way to go. In general, a prefabricated adjusting hole is set in the middle of the rubber mandrel to solve the difficulty. It is mainly based on the principle that the inflation of the mandrel generated in the curing process can exactly be absorbed by the prefabricated adjusting hole. Thus, how to determine the size of the prefabricated adjusting hole becomes the key point.

### Table 1. The material property parameters.

| Parameters                  | Value   |
|-----------------------------|---------|
| Elasticity modulus/MPa      | 3.552   |
| CTE/(m.℃⁻¹)                 | 9e⁻⁴    |
| Heat conductivity/(W⁻¹.m.K⁻¹)| 0.23    |
| Poisson ratio               | 0.48    |

To determine the optimal size of the hole is quite time-consuming through specific experiment, while the finite element modelling (FEM) method provides an efficient approach to ensure the optimal size of hole. The boundary condition was set according to the actual conditions, the material property parameters were shown in table 1. Tetrahedral mesh was taken as the meshing scheme of the rubber mandrel, and the typical meshing scheme and the result of the thermal deformation nephogram for the rubber mandrel were shown in figures 8 and 9, respectively.

Through a lot of modelling and simulation, the mathematical model between the size of prefabricated adjusting hole and other technical parameters was established as follows: The volume of the prefabricated adjusting hole:

![Figure 7. Typical curing process of composite structure.](image)
The total volume inflation of mandrel:

\[ \Delta V = \alpha \Delta T V_0 - \frac{3P(1-2\nu)}{E} V_0 \]

Let, \( V = \Delta V \zeta \), there the mathematical model of diameter of prefabricated adjusting hole is as follows:

\[ d = \left( \frac{4V_0}{\pi L} \left[ \frac{\alpha \Delta T - \frac{3P(1-2\nu)}{E} \zeta}{\zeta} \right] \right)^{1/2} \]

Where \( d \) is the diameter of the prefabricated adjusting hole, \( V \) is the volume of the prefabricated adjusting hole, \( L \) is the length of the rubber mandrel, \( V_0 \) is the initial volume of the rubber mandrel, \( \Delta V \) is the change of the rubber mandrel, \( \alpha \) is the coefficient of thermal expansion, \( E \) is the elastic modulus, \( \nu \) is the Poisson's ratio, \( T \) is temperature, \( P \) is the actual curing pressure and \( \zeta \) is the correction factor. Finally, multiple regression tests were employed to the optimal correction factor by FEM method, and \( \zeta \) of 0.658~0.778 was determined, which can provide an academic and practical reference for the selection of the mandrel structure.

4. Conclusions

In this paper, the mould design and forming process of the bearing complex composite structure were introduced using the hat stiffened structure as an example. Some conclusions by this study were as follows.

(1) In the process of mould design for the hat stiffened structure, the mould of composite covering plate, panel and rubber mandrel become the three important factors to take into account. For the mould of covering plate, the vent air should distributed uniformly inner the mould so as to ensure the uniform temperature field, and the allowance of the groove is often selected about 2 mm. For the mould of panel, enough vent holes and evened-temperature holes are requested. The invar steel is often selected as the mould material, and the surface precision should also be ensured. For the mould of rubber mandrel, the size of mould cavity and the size of the rubber mould should stay the same, a diversion trench about depth of 1 mm should be machined on the mould surface, and the diameter variable shaft should be designed to meet the different request of products.
(2) For the forming process of composite hat stiffened structure, the autoclave co-curing process is often employed to fabricate the complex composite structure. Besides the material and stacking sequence of the prepregs, the structure of rubber mandrel is also crucial. By FEM method, the mathematical model between the size of prefabricated adjusting hole and other technical parameters was established, and finally correction factor $\zeta$ of 0.658–0.778 was determined.

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