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Improvement and evaluation of polymer-matrix composite panels with hat stiffeners

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Abstract. Hat-stiffened composite panels fabricated by co-curing technologies are widely used in the fuselage panel due to the good structural stability and high efficiency of axial load transferring. The bonding capability between the stiffener and skin is a primary criterion to assess the co-curing quality. In this paper, two reinforcement technologies of filling filler in the triangle region and adding split-stopping tape between the stiffener and skin were employed to improve the bonding capability. Effect of filler and split-stopping tape on the interface strength was analyzed, and the optimal size range of the filler and split-stopping tape were obtained. To improve the universality of application for the two reinforcement techniques, the filling coefficient of 0.62~0.77 and the split-stopping tape width coefficient of 0.56~0.67 were obtained by calculation. Results of the study can be used to develop other kinds of stiffened panels and will ultimately lead to optimized skin/stiffener designs.

1 Introduction

Polymer-matrix composite materials are widely used in the field of aviation mainly due to the high stiffness-to-density and strength-to-density ratio [1-6]. In addition, other distinct performances such as easy to form large section and excellent corrosion resistance, which are also made weight reducing and cost saving possible in the actual manufacturing process. At present, technologies of automatic manufacturing and integration forming have become the important ways to obtain efficient composite structures. Not only automatic manufacturing technology can improve manufacturing efficiency of composites, but also can ensure the quality stability of products. While as for integration forming technology, a substantial reduction in the number of parts and fasteners makes it possible to realize the integrated formation of composites from design to manufacture. Due to the depletion in numbers of fasteners and decrease of assembly work, the fabricating cost using integrated formation technology is lower than the conventional process, and the structural-load-carrying capacity can make great process. Therefore, the integrative structure can be beneficial to make the application of composites extend from non-strained component to primary force-taking structure.

Co-curing technology is a major way for integrated formation, and most complex composite structures used in aircraft employ this technology in autoclave process, such as J-shaped stiffener, T-shaped stiffener, U-shaped stiffener and hat-shaped stiffener [7, 8]. Among these stiffened panels, in particular the hat-stiffened panel is extensively used in the fuselage panel due to the good structural stability and high efficiency of axial load transferring. The latest development of Boeing 787 aircraft and airbus A380 both employed this type of structure as the primary stiffened structure. To say the least, hat-stiffened panel has become one of the most typical structures in aeronautical structural components.

For the study of hat-stiffened composite panels, a number of contributions in literatures [9-14] emphasized on the buckling or postbuckling behavior and failure mechanism particularly under external compression force or tensile load both theoretically and experimentally. Also some scholars [15-17] paid close attention to the pressure transfer mechanism and nondestructive examination of internal quality for the hat-stiffened panels. However, few literatures have reported about the hat-stiffened panels fabricated integrally by co-curing process because this technology is kept secret in most companies. Moreover, in the manufacturing process of hat-stiffened panels, because two sections of hat stiffener and skin are included in the hat-stiffened panel, the bonding strength and curing quality are hard to ensure, especially in the triangle region and at the interface between the stiffener and skin in the hat-stiffened panel. Also, the reinforcement technologies for the hat-stiffened panel are rarely found in relative literatures. Therefore, it is necessary to investigate the reinforcement technology of hat-stiffened panel systematically by theoretical analysis and experimentally research, so as to provide an important experimental guidance for manufacturing

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stiffener-to-skin structures with integral forming technology in autoclave process.

The co-curing quality of hat-stiffened composite panel is determined mostly by the bonding capability between the hat stiffener and panel. Thus, how to improve the bonding strength becomes the main focus in the design of hat-stiffened panels. Filling filler in the triangle region and adding split-stopping tape between the stiffer and skin are two reinforcement technologies to improve the bonding strength of hat-stiffened panel, the schematic of which was also shown in Figure 1. The research presented in this paper aims to report an experimental investigation on the reinforcement technology of hat-stiffened composite panel fabricated by unidirectional prepreg materials in autoclave. The optimal size of filler and split-stopping tape were obtained. Results of the study can be used to develop other kinds of stiffened structures and will ultimately lead to optimized skin/stiffener designs.

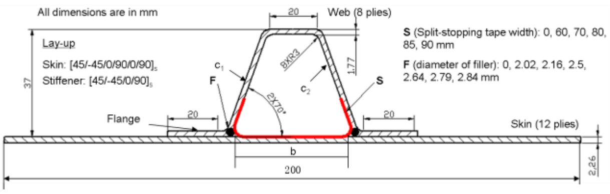

Figure 1. Geometry and dimensions of hat-stiffened composite panel

2 Experiment

2.1 Materials and manufacturing process

The composite material used in this study is epoxy prepreg CYCOM X850/T800 made by Cytec. This differentiated, exclusive primary structure capable material is optimized for wing structure ensuring COMAC maximum performance at minimum weight. The nominal ply thickness is 0.188 mm after curing. The materials of filler and split-stopping tape both choose CYCOM X850/T800 epoxy prepreg. The auxiliary materials such as vacuum bag, ventilated felt and release film are provided by the Air Tech Company. A soft tooling was set in the cavity of the hat stiffener to support the composite preform, and the soft mould material was silicone rubber, which was obtained by curing the RHODORSIL RTV 3248 A and B in accordance with the ratio of 10:1.

In the experimental process presented in this paper, the specimens of hat stiffener were 36 mm high and two ribs with a same size of 38 mm were evenly distributed on both sides. The skin specimens were 200 mm long, and were cut into pieces 30 mm in width. As the two crucial reinforcement factors, the filler diameters of 0, 2.02, 2.16, 2.5, 2.64, 2.79 and 2.84 mm as well as the split-stopping tape widths of 0, 60, 70, 80, 85 and 90 mm were tested. As shown in Figure 1. Due to the similar thermal expansion coefficient compared with the preform, a composite mould was selected as the external mould, which was used to cover the composite perform to transfer the curing pressure. While an aluminum panel was selected as the skin mould because of ease of machining and low density. For the structure of hat-stiffened panel, due to the special structure with a hat-shaped cavity, which needs an upholder to support the hat-stiffened structure so as not to be collapsed under the external curing pressure. Therefore, a silicone rubber mould was set in the cavity. The filler formed by a piece of unidirectional prepreg was rolled and filled into the triangle regions between the stiffener and skin, and various widths of split-stopping tape were added in the hat-stiffened panel, both of which were used to evaluate the reinforcement effect. A typical schematic representation of the manufacturing process for hat-stiffened composite panel was shown in Figure 2. Finally, the entire assembly was vaccum bagged and cured in an autoclave using the manufacturer's recommended cure cycle, which was presented in Figure 3.

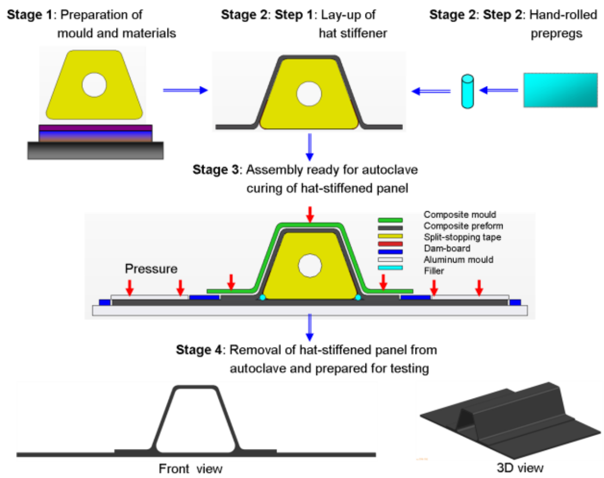

Figure 2. Schematic representation of the manufacturing process for hat-stiffened panels

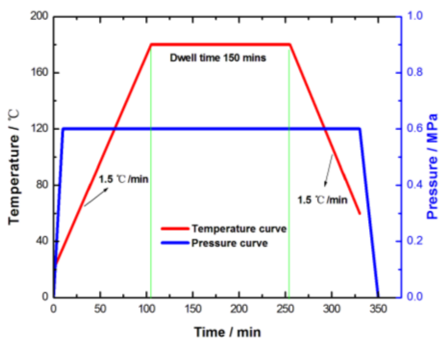

Figure 3. The manufacturer's recommended curing curve

2.2 Evaluation of mechanical properties

In order to evaluate the co-curing quality, especially the bonding capability at the stiffener-skin intersection, the tensile strength was selected as the test standard. The tensile specimen size was of 200 mm (length) × 30 mm (width) × 40 mm (height). The test of mechanical properties was conducted on CMT5105 tensile apparatus (Produced by Sansi Taijie Co., Ltd. China). The specimen was pulled upward at a crosshead speed of 0.5 mm/min until the hat stiffener was crack and debonded from the skin, and then the maximum load was obtained and used to calculate the tensile strength. Each test was conducted by three specimens, and the average value was considered as the final tensile strength. The tensile strength (MPa) at the stiffener-skin intersection was determined according to equation (1):

$$\sigma_t = F_{max}/2(a \cdot b) \quad (1)$$

Where, F_{max} is the broken load or the maximum load (N), a is the length (mm) of the bonding interface, and b is the width (mm) of bonding interface.

3 Results and discussion

3.1 Effect of filler on co-curing quality

As one of the most effective reinforcement technologies, the method of filling filler in the triangle region is very useful for the reinforcement of stiffened panels. The filler was rolled-up by unidirectional prepreg and filled into the triangle regions, which played a very important role for the co-curing quality at the stiffener-skin intersection. Compared with the situation of no filler, the filler filled the triangle cavity so as to ensure that the resin flow uniformly and the fibers distribute smoothly. Therefore, the internal stress can be weakened and the bonding capacity of the intersection can be improved. But how to determine the optimal size of filler was rarely mentioned according to the latest report. The following study was carried out to determine the optimal size of filler based on co-curing quality.

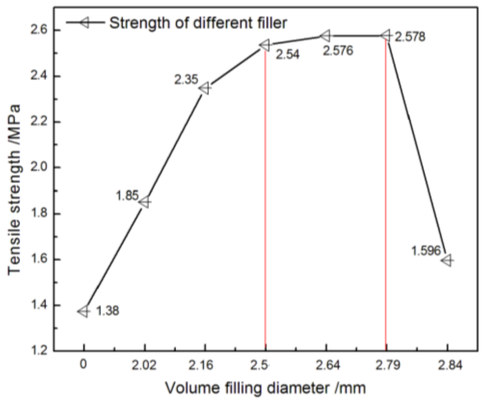

Figure 4. Tensile strengths of hat-stiffened panel with the same size of split-stopping tape for various diameters of filler

The tensile strengths of hat stiffened panels obtained by various sizes of filler were shown in Figure 4. The strength of stiffener-skin intersection increased by 87% as the filler diameter increased from 0 to 2.79 mm. However, the strength decreased significantly when the diameter of filler exceeded 2.79 mm. The optimal diameter of filler may be distributed between 2.5 and 2.79 mm. Among these test results, the hat-stiffened panel with a filler diameter of 2.79 mm got the greatest strength. Another experimental phenomenon shows that although the strength decreases sharply when the diameter of filler exceeds 2.79 mm, e.g. the filler diameter of 2.84 mm, the strength is still larger than that no filler filled in the triangle region.

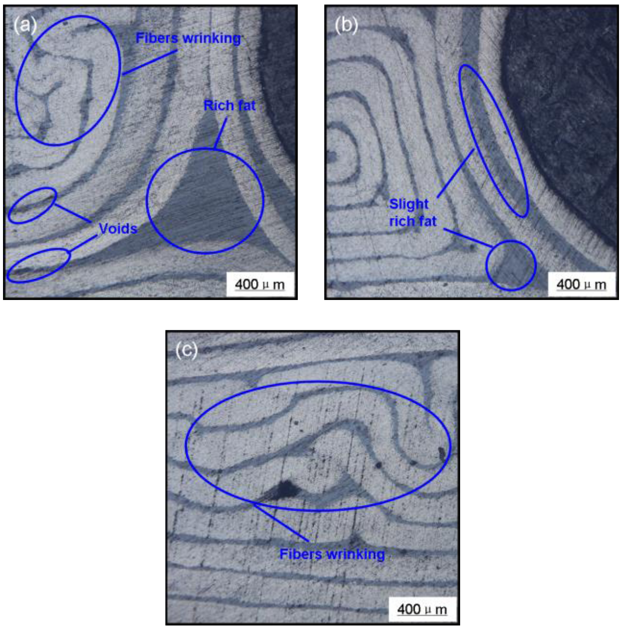

Figure 5. Microstructures of triangle region filled with various diameters of filler (a) No filler in the triangle region (b) Filler diameter of 2.79 mm (c) Filler diameter of 2.84 mm

External performance is a reflection of internal structural change. Hence, the change of bonding capacity at the intersection caused by size of filler can be studied through the microstructure of triangle regions. The specimens were cut from the intersection of triangle regions, polished and ultrasonically cleaned. The optical digital microscope (ODM, model: OLYMPUS DS × 500) and metallurgical microstructure image analysis systems were employed to study the microscopic structure. The microstructures of triangle regions obtained by various sizes of filler were shown in Figure 5. As can be seen from Figure 5(a), the fibers were seriously twisted in the triangle region where there was no filler filled in it, voids and excess resin were also existed in the triangle region. Rolled-up filler made it possible to support the triangle cavity enough. In this case, the resin can maintain relatively homogeneous flow and the fibers can keep a good compliance during curing. Therefore, the defects such as fiber wrinking and voids gradually decreased as the filler diameter increased, as shown in Figure 5(b). But when the filler diameter exceeded 2.84 mm, the defects, especially the twisted fibers were existed in the triangle region again, and the strength would decrease, as shown in Figure 5(c) and Figure 4. That is to say, too large or too small, the filler would not meet the best reinforcement effect, because even a small cross section with twisted fibers could easily break when the stiffener was subjected to an external force. Actually, the triangle region was simultaneously subjected to three aspects of effects, pressure of external composite mould, thermal inflation of internal rubber mould and resin shrinkage of its own during curing. It is difficult to completely conform to the contour of the hat stiffener and skin, causing more or less plies to bridge across the corner region during bagging and curing. But a relatively suitable process window can be determined by specific experiment. For the hat-stiffened composite panel in this paper, the more ideal tensile strength at the stiffener-skin intersection with filler diameter of 2.5 mm to 2.79 mm was obtained, and the filler diameter of 2.5 mm to 2.79 mm can be regards as the suitable process window.

3.2 Determination for universal size of filler

The optimal size of filler mentioned above is only based on the fixed volume of triangle cavity, and it is only applied to the size of hat-stiffened structure mentioned in Figure 1. In order to determine the universal size of filler, the filling coefficient was introduced to study the relationship between the size of filler and triangle cavity. The internal relation is given as follows:

$$\lambda = \frac{V_{\mathrm{f}}}{V_{tc}} = \frac{S_f}{S_{tc}} \qquad (2)$$

Where, λ is the filling coefficient, V_f is the filling volume, V_{tc} is the volume of triangle cavity, S_f is the cross section area of filler, S_{tc} is the cross section area of triangle cavity. According to elaborative geometric calculation, in this study the value of λ was 7.93 mm^2, and the value of was 4.91 mm^2 and 6.11 mm^2 respectively, corresponding to the optimal filler diameters of 2.5 mm and 2.79 mm. Therefore, the filling coefficient of 0.62 and 0.77 were calculated according to equation (2) respectively. Finally, the optimal filling volume or diameter can be determined by equation (3) or (4), which can be regarded as a universal basis of calculation used for similar structures.

$$V_{\mathrm{f}} = \left(0.62 \sim 0.77\right) V_{tc} \qquad (3)$$

Or

$$d = 2\sqrt{\frac{(0.62 \sim 0.77) S_{tc}}{\pi}} \qquad (4)$$

Where, d is the diameter of filler.

3.3 Effect of the split-stopping tape on interface strength

To some extent, filling the filler in the triangle region for the hat-stiffened composite panel can improve the interface strength between the stiffer and skin, but it is far from enough. Adding a split-stopping tape between the stiffener and skin is another effective reinforcement technology, especially for enclosed the stiffened panels with triangle areas. The split-stopping tape can enhance the connectivity between the skin and hat stiffener excellently, and can assist in solving the tearing problems in the triangle areas. But as for the size of split-stopping tape, too large or too small is not appropriate. If the size is too small, the strength between the split-stopping tape and side panel is too small to have the effect of reinforcement. If the size is too large, on the one hand, due to the increased reinforcement between the split-stopping tape and side panel, the strength between the bottom panel and split-stopping tape would decrease. On the other hand, too large size of the split-stopping tape seems adverse to weight loss and cost reduction. Therefore, there should be a suitable process window for the size of split-stopping tape. Meanwhile, the debonding mechanism should also be studied explicitly. This will aid in carrying out meaningful damage tolerance analysis later.

In consideration of the relationship between the mechanical property and weight of composite structure, split-stopping tape widths of 60, 70, 80, 85 and 90 mm with a conventional length of 30 mm and no split-stopping tape between the stiffer and skin were tested to find an optimal process window. The specific test results were shown in Figure 6. The tensile strength increased by 48% as the split-stopping tape width increased from 0 to 85 mm, and became stable when the split-stopping tape width was in the range of 70 to 85 mm. The specimen with split-stopping tape width of 80 mm can obtain the highest strength than other specimens. The results also clearly show that a split-stopping tape width of less than 70 or larger than 90 mm was not sufficient to create a strong structure. Also, a greater split-stopping tape width, which caused the weight and cost to increase, was not necessary. Therefore, for the hat-stiffened structure presented in this paper, a split-stopping tape width of 70 to 85 mm was optimum to improve the interface strength between the stiffener and skin.

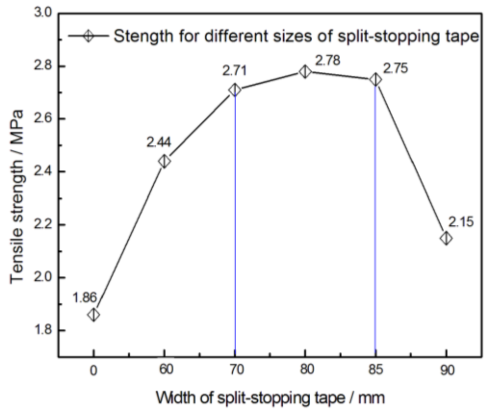

Figure 6. Tensile strength for various widths of split-stopping tape

3.4 Determination for universal width of split-stopping tape

As depicted above, the optimal split-stopping tape width of 70 to 85 mm was applied only to the fixed size for the hat-stiffened structure, and there was no universality for other sizes of similar hat-stiffened structures. To settle this issue, the width coefficient was introduced, and the meaning of it was presented as follows.

$$\eta = \frac{L}{\left(\mathrm{c}_1 + c_2 + b\right)} \qquad (5)$$

Where, L is the width of split-stopping tape, c_1, and c_2 are the rib and bottom length of the trapezoidal cavity respectively. The detailed values of them can be calculated by Figure 1. According to the experimental results, the optimal width is in the range of 70 mm to 85 mm, thus the width coefficient η of 0.56 to 0.67 was obtained, which can also be recognized as a universal dimension coefficient and can be used in the similar hat-stiffened structures.

4 Conclusions

Hat-stiffened composite panels with various diameters of filler and various widths of split-stopping tape were fabricated by autoclave process. Effect of filler and split-stopping tape on interface strength was discussed in detail, and the optimal and universal size of filler and split-stopping tape were obtained according to specific experiment and analysis. Based on this investigation the following conclusions can be drawn:

1. Filling filler in the triangle region and adding split-stopping tape between the stiffener and skin are the two important ways to reinforce the hat-stiffened structure, and adopting proper size of them can efficiently increase the interface strength between the stiffener and skin.
2. The strength of stiffener-skin intersection increased by 87% as the filler diameter increased from 0 to 2.79 mm. The strength decreased significantly when the diameter of filler exceeded 2.79 mm. The optimal diameter of filler may be distributed between 2.5 and 2.79 mm. Fiber wrinking, voids and rich fat of resin are the main reasons caused strength decrease.
3. A meaningful filling coefficient of 0.62~0.77 was obtained according to the experimental results, which can be regarded as a universal basis of calculation used for similar stiffened structures.
4. The interface strength increased by 48% as the split-stopping tape width increased from 0 to 85 mm, and became stable when the split-stopping tape width was in the range of 70 to 85 mm. The specimen with split-stopping tape width of 80 mm can obtain the highest strength compared with other specimens. A split-stopping tape width of less than 70 or larger than 90 mm was not sufficient to create a strong structure. Also, a greater split-stopping tape width, which caused the weight and cost to increase, was not necessary.
5. A universal width coefficient of 0.56~0.67 for split-stopping tape was obtained, which can also be recognized as an important dimension coefficient to determine the actual width of split-stopping tape and can be used in similar hat-stiffened structures.

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