Temperature and Curing Degree Field of Composite Laminate During Bonding Repair Process

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Abstract

In order to study the temperature field and curing degree field of resin matrix composite laminates with different thicknesses, a physical model of the laminates with different thicknesses was established, which included patch, adhesive layer and motherboard. The finite element model of bonding repair was established based on the 3d heat conduction theory and the curing kinetics theory of AS4/3501-6 prepreg. The temperature field, curing degree field and curing rate of the patching structure with different thicknesses were calculated. The varying processes of the temperature and curing degree with time at different points located at the middle position along the patch thickness direction, along the patch radius direction and along the adhesive layer radius were analyzed. According to the analysis, within the thickness range involved in this study, the larger the patch thickness is, the larger the peak value of heat release in the patch and adhesive layer is. The patch and adhesive layer with different thickness can be completely cured at almost the same time. The higher the thickness is, the higher the curing rate peak is, while the curing rate decreases to the minimum at almost the same time. During the curing heat releasing process, the temperature at the middle position along the patch thickness direction is higher than that of other parts, especially, when the temperature reaches the peak value.

Keywords

Adhesively Bonded Repair; Temperature Field; Curing Degree; Curing Rate.

1. Introduction

The composite structure repaired by the bonding repair method has the advantages of light weight, high structural efficiency and flexible component connection design [1]. Bonding repair can make the repaired surface be more smooth [2], with good aerodynamic performance, and restore the structural strength to a large extent. Bonding repair is the most common and efficient repair method. The research on bonding repair of composite materials is of great significance to the development and application of composite materials.

Many researchers have studied the mechanical properties of bonded repair composite structures. Alexander T Dee [3] studied the strain rate and compressive mechanical properties of single-layer AS4/3501-6 composite laminates, and obtained the compressive mechanical properties of single-layer AS4/3501-6 composite laminates. The study of Kumar S B [4] shows that when the bonding Angle is less than 2°, fiber fracture and being pulled out are the main failure modes, while when the bonding Angle is greater than 2°, the damage of the film is mainly caused by shear failure. Chun H Wang [5] studied the local plastic strain peak caused by the uneven shear strain distribution on the

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beveled joint, and proposed that the stress concentration factor is largely depended on the lay-up order and thickness of the laminates. Campilho R [6] validated the mixed mode cohesion damage model, which was applied to composite material repair and was suitable for different overlap lengths and repair thicknesses. The simulation results show that the equivalent stiffness and failure load increase with the increase of patch thickness. Kwon Y W [7] showed that the effects of stiffening parameters and plate thickness on the composite patch were significantly different. Tao tao Zhang's research [8] shows that harder and thicker patches can withstand higher loads. Their research narrowed the range of configuration parameters in bonding repair, and also mentioned that thickness would have a certain influence on the strength and stiffness of composite repair.

During the curing process of composite materials, the residual stress caused by the uneven distribution of temperature is also an important factor affecting the quality of composite materials, so it is necessary to study the temperature distribution during the curing process of adhesive bonding repair structures. Therefore, the temperature and curing degree field of bonding repair laminated plate with different thickness is simulated with the finite element method in this article, and the effects of bonding repair thickness on the temperature and curing degree during the curing process were explored.

2. Physical model

As shown in Figure 1, the bonding repair structure consists of patch, adhesive layer and motherboard. The motherboard represents the damaged parts in the actual use of AS4/3501-6 composite product. In the repair process of composite components, the repaired area should be grinded and sanded to be a groove with a certain taper. The patch is made of circular prepreg with different radii in accordance with the repair area. The adhesive layer is the adhesive between the patch and the motherboard, and is made of the mixture of a certain proportion of adhesive and resin. The thickness δ of the laminated plates involved in the analysis is 2.7mm, 6mm and 10mm respectively, the damage diameter is 10mm, the bonding Angle is 6°, and the thickness of the adhesive layer is 0.13mm.

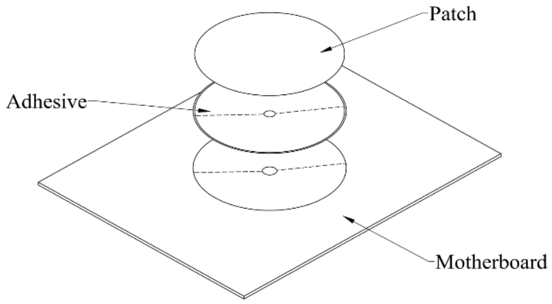

Figure 1. Schematic diagram of bonding repair structure

3. Mathematical model

3.1 Thermo-chemical model

The curing process of composites can be regarded as a nonlinear heat conduction problem with internal and external heat sources. Transient heat conduction equation of three-dimensional anisotropic materials is [9]:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + \dot{q} = \rho c_p \frac{\partial T}{\partial t} \tag{1}$$

Where k_x, k_y and k_z are respectively the thermal conductivity of the composite material in three directions x, y, z, and x is the direction along the fiber of the composite material, y is the direction perpendicular to the fiber, and z is the direction of the layer thickness of the composite material; ρ, c_p respectively are the density and specific heat of the composite material; T is the instantaneous

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temperature of the cell node; t is the curing time. Heat generation rate $\dot{q}$ is the heat generated by curing reaction of resin in unit volume and time, it is related to the curing reaction rate as follows [10]:

$$\dot{q} = \rho_m(1 - V_f)H_R\frac{d\alpha}{dt} \tag{2}$$

Where ρ_m is the resin density, determined by formula (3), V_f is the volume fraction of composite fiber; H_R is the total heat release of the resin per unit mass during curing reaction; α is curing degree, which is the integral of curing rate with respect to curing time [10] and can be determined by formula (4):

$$\rho_m = \begin{cases} 0.09\alpha + 1.232 & \alpha \le 0.45 \\ 1.272 & \alpha > 0.45 \end{cases} \tag{3}$$

$$\alpha = \int_0^t \frac{d\alpha}{dt}dt \tag{4}$$

Where $\frac{d\alpha}{dt}$ is the curing rate, which is expressed as [11]:

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \tag{5}$$

Where, $f(\alpha)$ is the function of curing degree, $k(T)$ is the function of curing rate, which follows Arrhenius formula (7). For AS4/3501-6 composite system, its curing rate is a piecewise function [11]:

$$\frac{d\alpha}{dt} = \begin{cases} (k_1 + k_2\alpha)(1-\alpha)(0.47-\alpha) & (\alpha \leqslant 0.3) \\ k_3(1-\alpha) & (\alpha > 0.3) \end{cases} \tag{6}$$

$$k_i = A_i exp(\frac{-\Delta E_i}{RT}) \qquad (i = 1,2,3) \tag{7}$$

Where k_i is the reaction rate constant; A_i is the frequency factor; E_i is the activation energy of the resin; R is the molar gas constant. The physical property parameters and curing kinetics parameters of AS4/3501-6 composite material selected in this study are listed in the literature [10].

3.2 Boundary conditions

Boundary conditions are set according to the environment [12] of the repair area in aircraft maintenance. Since the motherboard is a part of the aircraft body, fixed constraints and adiabatic boundary conditions are applied on the four sides and bottom surface of the motherboard. The curing process of composite material is applied to the upper surface of the patch, the adhesive layer and the motherboard.

According to the composite Materials manual [14], the curing process curve of AS4/3501-6 prepreg is shown in Figure 2. The temperature is increased from 293K to 390K at the heating rate of 2.5K/min, and then held in 3600s. For the second time, the temperature is raised to 450K at the rate of 2.5K/min, and the temperature is kept at this temperature for 7200s. Finally, the temperature is reduced from 450K to the room temperature at the rate of 2.5K/min, and held for 3000s before the repaired laminate is used.

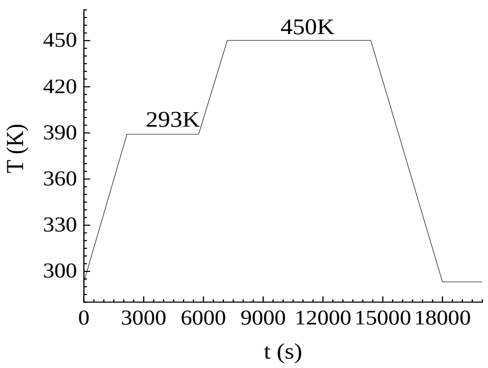

Figure 2. Cure cycle

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The boundary condition can be expressed as:

$$T(\pm\frac{a}{2},\pm\frac{b}{2},t)=T_s(t) \tag{8}$$

$$\frac{\partial T(\pm\frac{a}{2},Y,Z,t)}{\partial X}=0 \tag{9}$$

$$\frac{\partial \mathrm{T}(X,\pm\frac{b}{2},\mathrm{Z},\mathrm{t})}{\partial Y}=0 \tag{10}$$

$$\frac{\partial T(X,Y,0,t)}{\partial Z}=0 \tag{11}$$

Where, a and b are the length and width of the motherboard respectively.

Initial temperature and initial curing degree can be expressed as [13]:

$$\mathrm{T}(\mathrm{X},\mathrm{Y},\mathrm{Z},\mathrm{t})|t=0=\mathrm{T}_0 \tag{12}$$

$$\alpha|t=0=\alpha_0 \tag{13}$$

Where T_0=293K, and $\alpha_0=10^{-4}$.

4. Calculation results and discussions

4.1 The temperature and curing degree at the middle position along the direction of patch thickness

The temperature at the middle position along the direction of patch thickness for different patch thickness is shown in Figure 3. The temperature variation trend of the middle point is consistent with the curing process curve of AS4/3501-6 prepreg. Curing reaction exothermic peaks appear in both the first and second holding stages, and the larger the patch thickness is, the higher the temperature peak at the middle point is. In the first holding stage, the temperature peak value is smaller. The difference of the temperature peak between 2.7mm and 10mm patch thickness patch is about 3K, and that between 2.7mm and 6mm patch thickness patch is about 1K. At the end of the first temperature holding stage, the temperature peak disappears completely, and the temperature is consistent with the curing process temperature curve. In the second holding stage, the peak value is larger. The difference of the temperature peak value between 2.7mm and 10mm patch thickness is about 10K, and the difference of the central peak temperature of 2.7mm and 6mm patch thickness is about 4K. In the middle of the second holding stage, the temperature peak completely disappears, and the temperature is consistent with the curing process temperature curve.

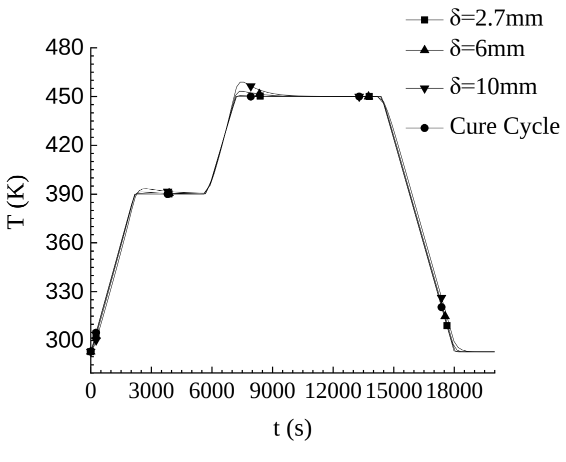

Figure 3. The temperature at the middle position along the direction of patch thickness

The curing degree at the middle position along the direction of patch thickness for different patch thickness is shown in Figure 4. As can be seen from this figure, the curing degree at this position is in the same varying trend for different patch thickness, and the values are also very close. The curing is in a pre-curing stage, in the time of 0-6000s, and is in rapid curing stage from 6000s. The curing process completes at about 15000s. In general, the cure is in slower rate when the curing degree is less than 0.3, and is in faster rate when the curing degree is larger than 0.3.

The curve of curing rate varying with time is shown in Figure 5., There are two peaks in the curing rate curve. The first peak is smaller than the second peak. For patches with different thickness, the higher the patch thickness, the higher the curing rate peak is, for the middle position along the patch thickness direction, which means the maximum curing rate increase with the patch thickness. The curing rate peak occurs later with patch thickness increase. However, as can be seen from Figure 5., the curing rate is nearly close except at peak time.

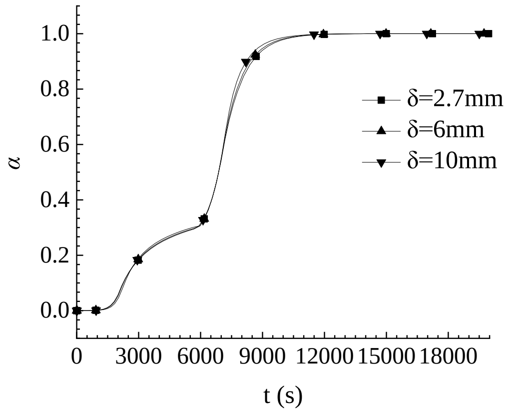

Figure 4. The curing rate at the middle position along the direction of patch thickness

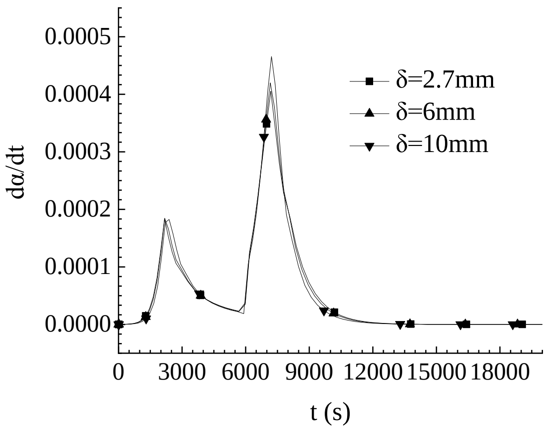

Figure 5. The curing degree at the middle position along the direction of patch thickness

4.2 The temperature and curing degree at the middle position along the direction of patch radius

The temperature varying with curing time at the middle position along the direction of patch radius is shown in Figure 6. The temperature at this position varies nearly along the curing process curve of AS4/3501-6 prepreg for different patches thickness, except near the time when the temperature reaching the peak value. At the time when the temperature reaching the peak value, the larger the patch thickness is, the higher the peak temperature is. The peak value appearing in the first holding stage was small. For the thin patch of 2.7mm, the temperature curve at this position is only slightly different from the curing process temperature curve. The peak temperature difference between 2.7mm and 10mm thickness patch is about 2K, while the peak temperature for 2.7mm and 6mm thickness patch is nearly close. In the second insulation stage, the peak value is larger. The peak temperature difference between 2.7mm and 10mm thickness patch is about 12K, and that between 2.7mm and 6mm thickness patch is about 2K.

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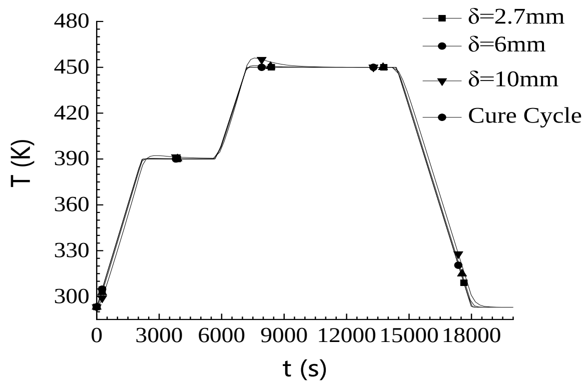

Figure 6. The temperature at the middle position along the direction of patch radius

The curing degree varying with time at the middle position along the direction of patch radius is shown in Figure 7. The curing degree curves nearly coincide for different thickness patch except the beginning and ending of curing. So the patch thickness less than 10mm has little effect on the curing time for the patch side surface.

The curing rate curves varying with time at the middle position along the direction of patch radius is shown in Figure 8, there are two peaks in the curing rate curve. For patches with different thickness, the higher the patch thickness is, the higher the curing rate peak is. The curing rate peak occurs later with patch thickness increase.

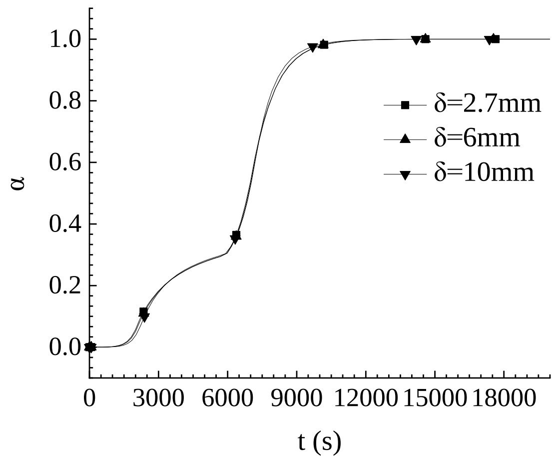

Figure 7. The curing degree at the middle position along the direction of patch radius

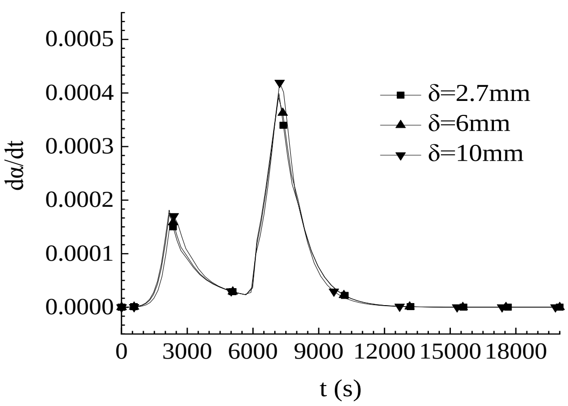

Figure 8. The curing rate at the middle position along the direction of patch radius

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4.3 The temperature and curing degree of the middle position along the direction of adhesive layer radius

The temperature and curing degree of the middle position along the direction of adhesive layer radius of the bonding surface was taken for research. It can be seen from Figure 9, the exothermic peaks are not easy to be seen in the first temperature holding stage, while the temperature peaks are obvious in the second temperature holding stage. They also become higher with patch thickness increasing. It can be seen from Figure 10, the curing degree curves nearly coincide for different thickness patch except the beginning and ending of curing. It can be seen from Figure 11, The higher the thickness is, the higher the curing rate peak is.

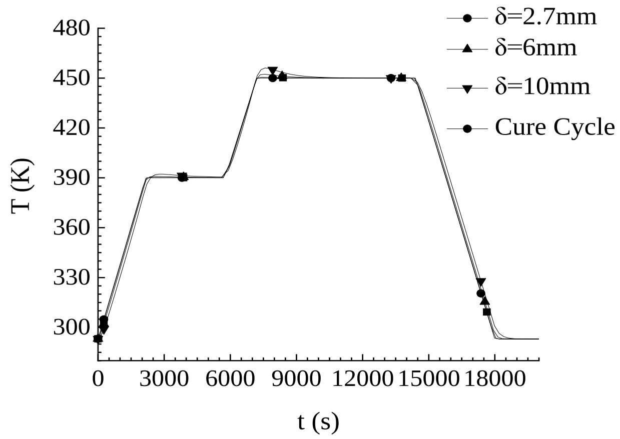

Figure 9. The temperature of the middle position along the direction of adhesive layer radius

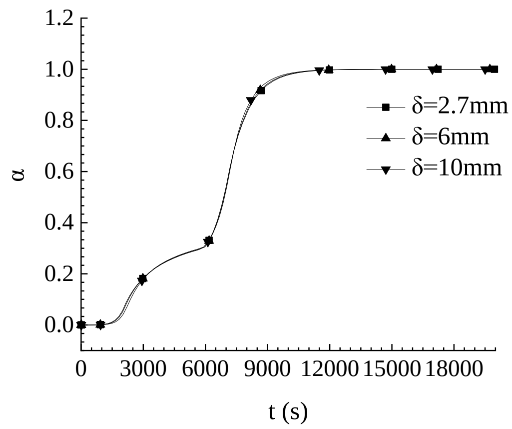

Figure 10. The curing degree of the middle position along the direction of adhesive layer radius

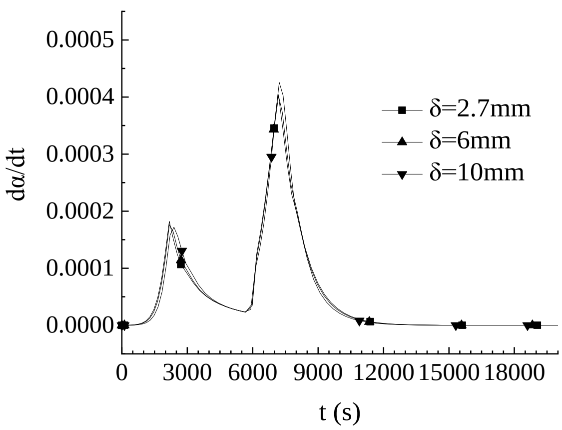

Figure 11. The curing rate of the middle position along the direction of adhesive layer radius

4.4 The temperature and curing degree of different position in 10 mm thick patches

The temperature varying with curing time at the middle position along the patch thickness direction, the patch radius direction and the adhesive layer radius direction in 10 mm thick patches is shown in Figure 12, It can be seen that the temperature at the middle position along the patch thickness direction is largest. The maximum peak value difference of temperature is about 3K. Since the middle positions along the patch radius direction and the adhesive layer radius direction are close to each other, the temperature curves of the two positions are almost in coincidence. In general, the temperature distribution of each part of the adhesive repair structure with this thickness is relatively uniform during the curing process, and a better curing quality can be obtained. It can be seen from Figure 13, that the curing degree at three different positions is relatively close at all times, and reaches full curing at almost the same time.

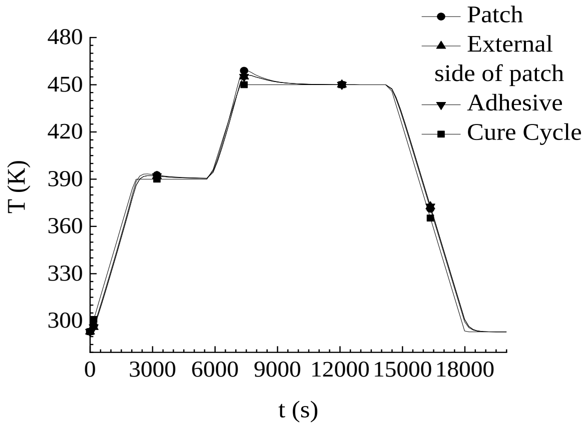

Figure 12. The temperature of different position in 10 mm thickness patches

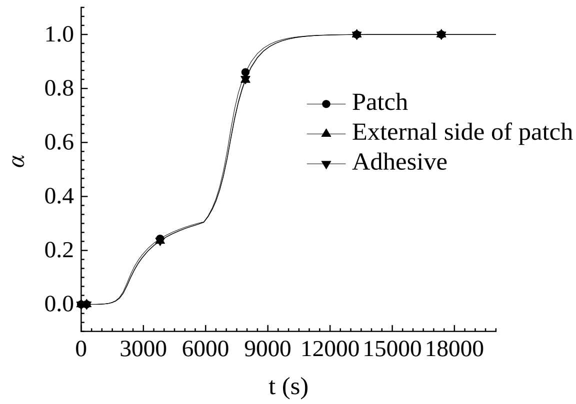

Figure 13. The curing degree of different position in 10 mm thickness patches

5. Conclusion

(1) Within the thickness range involved in this study, the peak value of temperature in the patch and adhesive layer becomes higher with increasing the patch thickness in the bonding repair structure.

(2) The patch and the adhesive layer with different thickness involved in this research can be cured completely with the same time.

(3) In the bonding repair structure with different thicknesses, the higher the thickness, the higher the curing rate peak, while the curing rate is nearly close except at peak time.

(4) Within the thickness range studied, the peak value of temperature at the middle point of the patch in the thickness direction is higher than that of other parts, while the curing time for complete curing is close for different part.

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