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The Variation Patterns of Resin Modulus in Composite under Different Curing Process Parameters

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Abstract

To investigate the effects of curing process parameters on the elastic modulus and shear modulus of resin in the composite, a finite element model for the scarf repair of curved laminated plates was established based on the thermochemical and mechanical models of composite materials, as well as the linear elastic constitutive relation. Simulation calculations were conducted for different heating and cooling rates. The variation process and development patterns of the resin's elastic modulus and shear modulus were investigated. The results indicate that the onset of the increase in resin elastic modulus and shear modulus is advanced with increasing the heating rate and the resin modulus under a heating rate of 3.5 K/min begins to change approximately 3000 seconds earlier than at a heating rate of 1.5 K/min, reducing the total curing time by about 20%. And the cooling rate has no impact on the variation patterns or the development process of the resin's elastic modulus and shear modulus.

Keywords

Composite Materials; Thermal Curing; Elastic Modulus; Shear Modulus.

1. Introduction

Compared to traditional metallic materials, composite materials offer advantages such as higher specific strength, higher specific stiffness, lower weight, and superior corrosion resistance, making them widely used in the aerospace industry. In civil aviation, their application has evolved from initial load-bearing structures, such as fuselage components, to their use in engines. For example, the inner wall panel of the thrust reverser in the Turbo-fan engine is composed of a curved composite laminated plate with an aluminum honeycomb core. During the operation of civil aviation engines, due to the influence of mechanical loads and environmental conditions, damage to composite laminated plates is inevitable. For the damaged areas, scarf repair is typically employed to ensure that the thrust reverser inner wall panel can meet the operational performance requirements prior to the damage. Scarf repair is the primary method for repairing damaged composite components in civil aviation. During the repair and curing process, the distribution of residual stress and the curing-induced deformation in the repair patch are key parameters for evaluating repair quality. These factors are closely related to the variations in the elastic modulus and shear modulus of the resin within the composite material.

Many scholars have conducted research to explore the variation patterns of resin modulus during the curing process. Wang Yuantao[1] investigated the influence of various factors on residual stress, including transverse shear stress, gradient layer thickness, material parameter characteristics, and fiber type. Ding Anxin[2] explored the relationship between resin modulus and curing shrinkage, analyzing the development process of residual stress in composite materials. Ding Zhenyuan[3] used

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a dynamic analysis method for resin modulus to study the effect of different curing regimes on residual stress. Yan Dengjie[4] combined the variation characteristics of resin elastic modulus and shear modulus with finite element secondary development techniques to study the effect of different heating methods on residual stress in the adhesive layer during the curing process. Tian Keke[5], H.P. Kirchner[6], and others considered the variation patterns of resin modulus during the thermosetting process, investigating the prestress transfer relationship between resin and fiber, and analyzing the connection between resin modulus variation and curing deformation at the scarf repair interface.

At present, most scholars, when setting parameters for composite materials, typically assign fixed thermal and mechanical properties, overlooking the fact that parameters such as elastic modulus and shear modulus undergo dynamic changes during the curing process. This article focuses on the finite element model of scarf repair for curved laminated plates made of AS4/3501-6 composite material, considering the time-varying characteristics of composite material parameters during the curing process. It investigates the variation patterns of the elastic modulus and shear modulus of 3501-6 resin during curing and analyzes the effects of different heating rates and cooling rates on the elastic modulus and shear modulus of the resin in the composite.

2. Theoretical Model

2.1 Thermochemical Model

AS4/3501-6 is a thermosetting composite material, and its heat conduction governing equation is[7]:

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

In the equation, k_i(i=x, y, z) represents the thermal conductivity, and $\dot{q}$ denotes the heat generation rate, which is expressed as[8]:

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

In the equation, V_f is the fiber volume fraction, H_R represents the heat of reaction per unit mass of the composite material, and α, $d\alpha/dt$ denote the degree of cure and the curing rate.

The degree of cure and curing rate of AS4/3501-6 can be calculated using the cure kinetics equation[9]:

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

In the equation, $K_i = A_i \exp\left(-\frac{E_i}{RT}\right)$,$(i = 1, 2, 3)$, K_i,E_i,A_i represent the reaction rate constant, activation energy, and frequency factor, respectively. For detailed curing kinetics parameters of AS4/3501-6, refer to the reference [4].

2.2 Thermal and Mechanical Parameter Governing Equations

Considering the time-varying characteristics of the thermal properties of resin and fiber, the specific heat capacity of AS4 fiber(C_f) and the thermal conductivities along the fiber direction(k_{fL}) and perpendicular to the fiber direction(k_{ff}) are linearly correlated with temperature[10-12].

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$$C_f = 750 + 2.05T \tag{4}$$

$$k_{fL} = 7.69 + 0.0156T \tag{5}$$

$$k_{fT} = 2.4 + 0.00507T \tag{6}$$

The density of 3501-6 epoxy resin (ρ_r) is related to the degree of cure[13]:

$$\rho_r = \begin{cases} 90\alpha + 1232 & (\alpha \leqslant 0.45) \\ 12729 & (\alpha > 0.45) \end{cases} \tag{7}$$

The specific heat capacity (C_r) and thermal conductivity (k_r) of 3501-6 epoxy resin are linear functions of temperature and the degree of cure[14]:

$$C_r = 4184[0.468 + 5.975 \times 10^{-4}T - 0.141\alpha] \tag{8}$$

$$k_r = 0.04184[3.85 + (0.035T - 0.141)\alpha] \tag{9}$$

The density, specific heat capacity, and thermal conductivity of AS4/3501-6 composite material can be calculated using the following mixture rule equations[15]:

$$\rho_c = V_f\rho_f + (1 - V_f)\rho_r \tag{10}$$

$$C_c = \frac{V_f\rho_f C_f + (1 - V_f)\rho_r C_r}{\rho_c} \tag{11}$$

$$K_L = K_f V_f + K_r(1 - V_f) \tag{12}$$

$$K_r = K_r\left(1 - 2\sqrt{\frac{V_f}{\pi}}\right) + \frac{K_r}{B}\left[\pi - \frac{4}{\sqrt{1 - \frac{B^2V_f}{\pi}}}\tan^{-1}\frac{\sqrt{1 - \frac{B^2V_f}{\pi}}}{1 + B\sqrt{\frac{V_f}{\pi}}}\right] \tag{13}$$

In the equation, $B = 2(K_r/K_{fT} - 1)$。

The 3501-6 epoxy resin can be described by the CHILE (α) linear elastic constitutive model, where its elastic modulus and shear modulus exhibit instantaneous variation with the degree of cure during the curing process as follows[16]:

$$E_r = \begin{cases} E_r = E_{r0} & (\alpha \leqslant \alpha_{gel}) \\ E_r = (1 - \alpha_{mod})E_{r0} + \alpha_{mod}E_{r\infty} & (\alpha > \alpha_{gel}) \\ G_r = E_r/2(1 - v_r) & \end{cases} \tag{14}$$

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In the equation, $\boldsymbol{\alpha_{mod} = (\alpha - \alpha_{gel})/(1 - \alpha_{gel})}$, $\boldsymbol{\alpha_{gel}}$ is the degree of cure at the resin gelation point, with a value of 0.57. $\boldsymbol{E_{r0}}$ and $\boldsymbol{E_{r\infty}}$ represent the modulus of the resin in its viscous state and glassy state.

For detailed mechanical property parameters of 3501-6 epoxy resin, refer to reference [4].

3. Verification of the Calculation Method

Based on the aforementioned thermochemical model and linear elastic mechanical model, a three-dimensional thermo-mechanical-chemical coupled finite element model was established. To verify the accuracy of the computational model and method, the case study from reference [14] was used for validation. In the case study, the model dimensions are 15.24 × 15.24 × 2.54 cm, representing a planar composite laminated plate. The boundary conditions were set to be identical to those in the reference case. The calculated results for the composite's modulus parallel to the fiber direction ($\boldsymbol{E_1}$) and perpendicular to the fiber direction ($\boldsymbol{E_2}$) were compared with the numerical results from the reference case. The comparison is shown in Fig. 1. It can be observed that the variation curves of the composite material parameters are generally consistent with the results from the literature, with an error margin of less than 2%. Therefore, the computational model and secondary development program used in this study are validated as accurate.

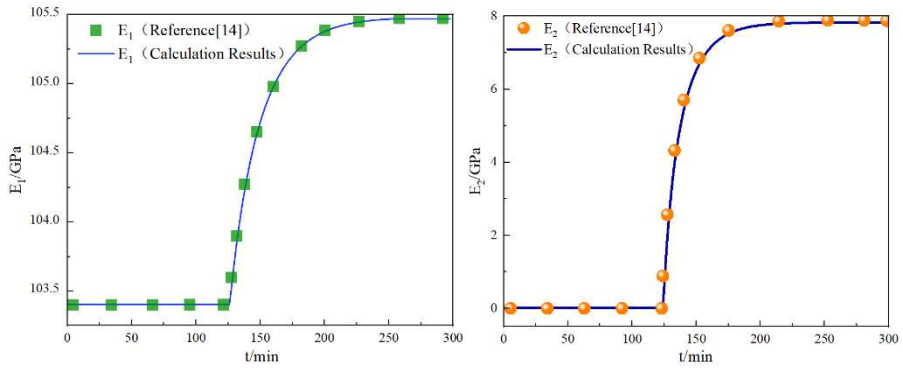


Fig.1 Comparison of computational results with literature

4. Geometric Model and Boundary Conditions

4.1 Geometric Model

The geometric model consists of three components: the composite parent plate, the repair patch, and the adhesive layer. The composite parent plate has dimensions of 300 mm × 300 mm × 3 mm. The scarf repair section is designed with a width-to-thickness ratio of 20:1, with the upper and lower surface diameters of the repair patch calculated to be 150 mm and 30 mm, respectively. The adhesive layer has a thickness of 0.4 mm. Both the parent plate and the repair patch are made of AS4/3501-6 resin, with the same fiber orientation of 0°, as shown in Fig. 2.

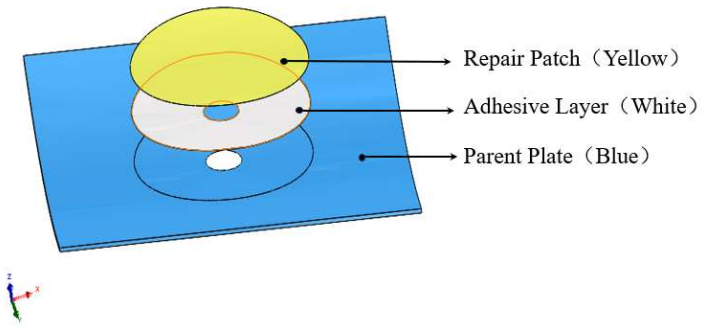


Fig.2 Geometric Model

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4.2 Boundary Conditions

The initial boundary conditions for the calculation are set as follows:

$$T(x,y,z)|_{t=0} = 293\text{K}, \alpha|_{t=0} = 1 \times 10^{-4} \tag{15}$$

The heating method uses a thermal repair device, where the concave surface of both the parent plate and the repair patch are in direct contact with the electric heating blanket, ensuring uniform temperature across these surfaces. The other surfaces are treated with thermal insulation to prevent heat loss and maintain a consistent curing environment.

$$T_S(t) = T_H(t) \tag{16}$$

In the above equation, $T_S(t)$ represents the surface temperature of the concave side of the parent plate and the repair patch, while $T_H(t)$ is the temperature of the heating blanket, which is determined by the curing process temperature curve.

At the same time, during the calculation process, a displacement constraint is applied to the concave surface of both the parent plate and the repair patch. This constraint ensures that the surfaces remain fixed in position, preventing any unwanted movement during the curing process simulation.

$$\frac{\partial u(t)}{\partial x} = 0, \frac{\partial u(t)}{\partial y} = 0, \frac{\partial u(t)}{\partial z} = 0 \tag{17}$$

In the equation, $u(t)$ represents the displacement of the concave surface on the parent plate and the repair patch.

5. Results and Discussion

5.1 Effect of Heating Rate on Resin Elastic Modulus and Shear Modulus

Five different heating rates were set for the curing process parameters: 1.5 K/min, 2 K/min, 2.5 K/min, 3 K/min, and 3.5 K/min, while all other parameters remained consistent. The corresponding process curves are shown in Fig. 3.

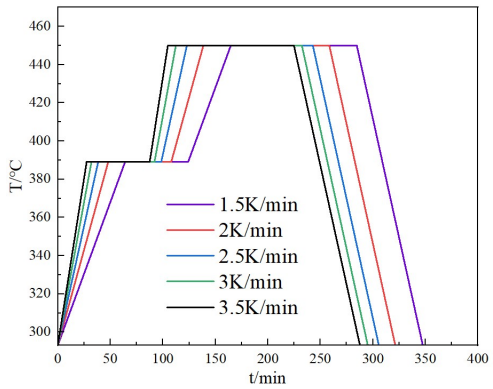


Fig.3 Curing process curves under different heating rates

Fig. 4 (a) and (b) show the variation of the resin's elastic modulus (E_r) and shear modulus (G_r) under different heating rates. The variation of both the elastic modulus and shear modulus follows a "step-like" curve pattern. The higher the heating rate, the more heat is absorbed by the resin per unit time,

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leading to a more intense curing reaction, and thus the earlier the changes in elastic and shear moduli occur. At a heating rate of 3.5 K/min, the resin modulus begins to change approximately 3000 seconds earlier than at a heating rate of 1.5 K/min, with the total process time reduced by about 20%.

Since the curing temperature is the same, the total heat absorbed by the resin during the curing process remains unchanged. Therefore, the heating rate has little effect on the overall variation patterns and final values of the elastic modulus and shear modulus. The final values of the elastic modulus and shear modulus remain approximately 3.5 GPa and 2.5 GPa, respectively.

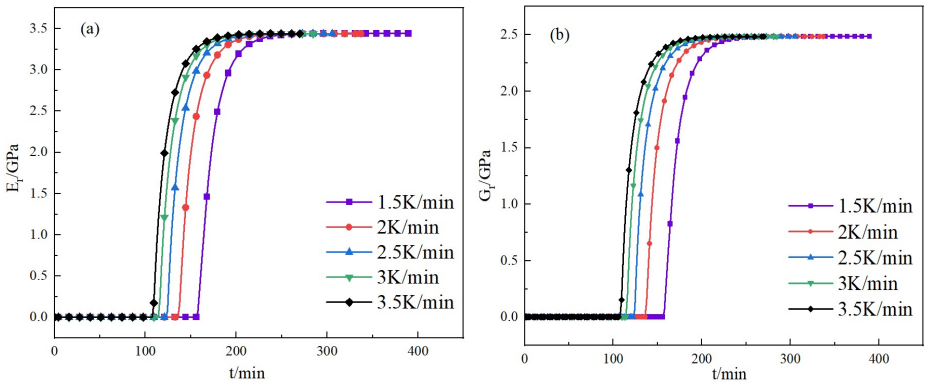


Fig.4 Resin's Elastic Modulus (a) and Shear Modulus (b) Curves under Different Heating Rates

5.2 Effect of Cooling Rate on Resin Elastic Modulus and Shear Modulus

Five different cooling rates were set for the curing process parameters: 1.5 K/min, 2 K/min, 2.5 K/min, 3 K/min, and 3.5 K/min, while all other parameters remained consistent. The corresponding cooling curves are shown in Fig. 5.

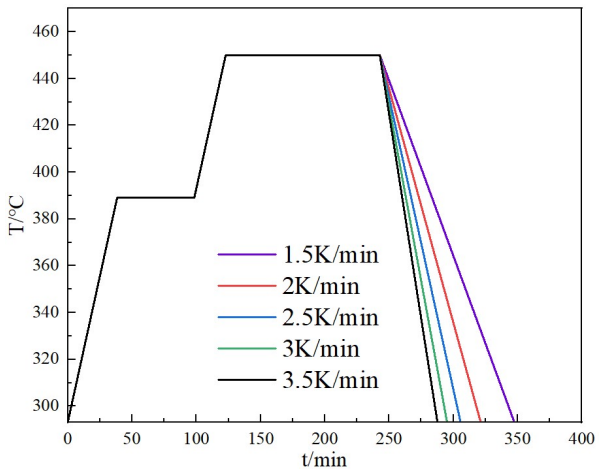


Fig.5 Curing process curves under different cooling rates

Fig. 6 (a) and (b) show the variation of the resin's elastic modulus ($\boldsymbol{E_r}$) and shear modulus ($\boldsymbol{G_r}$) under different cooling rates. The analysis indicates that the variation of elastic and shear moduli still follows a "step-like" curve pattern. Since only the cooling rate is changed, the heat absorbed by the resin during the heating and holding phases remains the same, leading to the same degree of cure and curing rate. Additionally, the resin is fully cured before the cooling phase begins, so the variation in elastic modulus and shear modulus during the heating and holding phases remains consistent.

As a result, the change in cooling rate has no impact on the development of the elastic modulus and shear modulus. The resin's modulus curves under the five different cooling rates overlap entirely.

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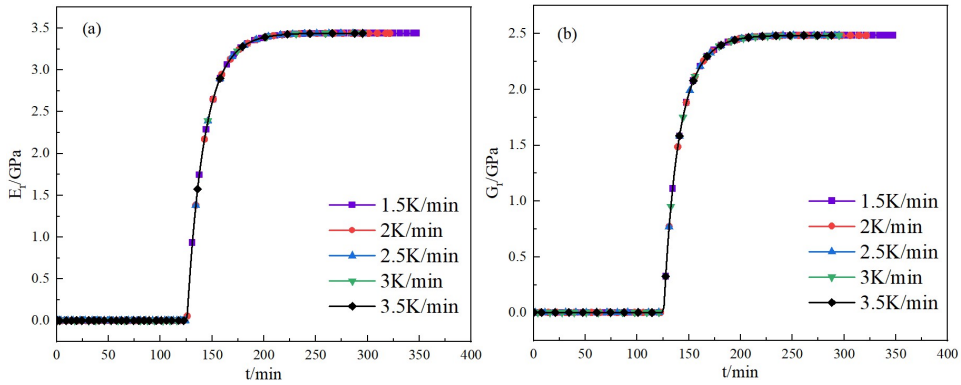


Fig.6 Resin's Elastic Modulus (a) and Shear Modulus (b) Curves under different cooling rates

6. Conclusion

(1) Based on the thermochemical model and the linear elastic mechanical constitutive model ,the finite element model for the scarf repair of curved laminated plates was established, the model was used to calculate and analyze the variation and development patterns of resin's modulus under heating rates and cooling rates.

(2) The onset of the increase in resin elastic modulus and shear modulus is advanced with increasing the heating rate and the resin's modulus under a heating rate of 3.5 K/min begins to change approximately 3000 seconds earlier than at a heating rate of 1.5 K/min, reducing the total curing time by about 20%.

(3) The cooling rate has no impact on the variation patterns or the development process of the resin's elastic modulus and shear modulus.

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