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Three-dimensional Cure Simulation of Stiffened Thermosetting Composite Panels

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Stiffened thermosetting composite panels were fabricated with co-curing processing. In the co-curing processing, the temperature distribution in the composite panels was nonuniform. An investigation into the three-dimensional cure simulation of T-shape stiffened thermosetting composite panels was presented. Flexible tools and locating tools were considered in the cure simulation. Temperature distribution in the composites was predicted as a function of the autoclave temperature history. A nonlinear transient heat transfer finite element model was developed to simulate the curing process of stiffened thermosetting composite panels. And a simulation example was presented to demonstrate the use of the present finite element procedure for analyzing composite curing process. The glass/polyester structure was investigated to provide insight into the nonuniform cure process and the effect of flexible tools and locating tools on temperature distribution. Temperature gradient in the intersection between the skin and the flange was shown to be strongly dependent on the structure of the flexible tools and the thickness of the skin.

KEY WORDS: Thermosetting composite; Stiffened panels; Co-curing; Numerical simulation

1. Introduction

The use of resin matrix composites in aircraft structures has the potential to decrease the structural weight because of high stiffness-to-density and high strength-to-density ratios of the composites. New fabrication techniques result in fewer parts and reduce the assembly time and costs of aircraft structures[1,2]. Stiffeners are integrally cured with the skin in one cure cycle, which is called co-curing. Co-curing techniques are used to make aircraft composite components[1–4], such as vertical fins, tail cones, and horizontal stabilizers. And stiffened thermosetting composite panel is primary aircraft structure. As shown in Fig. 1, the panel is composed of skin, flange and web. Different from other processes, flexible tools and locating tools are used in co-curing processing[5].

Thermosetting resins are polymerized by applying temperatures for some time. The heat required for the polymerization in resins causes chemical changes in the molecular structure. Resins have cross-linked structures with covalent bonds between molecules, and the cross-linking reaction is strongly dependent on the applied temperature. Additionally, internal heat is also generated by chemical reactions. The mechanical properties of the thermosetting matrix composites strongly depend on the curing process and the highly exothermic nature of the cure reaction. The investigation into the curing temperature distribution is important for assuring processability of the thermosetting composites. And the curing temperature distribution of the panel during the co-curing processing is more complex than that during other processing because of the influence of flexible tools and locating tools.

Pusatcioglu *et al.*[6] investigated the temperature gradient developed during the casting of unsaturated polyester by solving the one-dimensional heat transfer equation using the experimentally determined reaction kinetics and thermal conductivities. Loos and Springer[7] developed a one-dimensional model to simulate the curing process of a flat-plate by solving the

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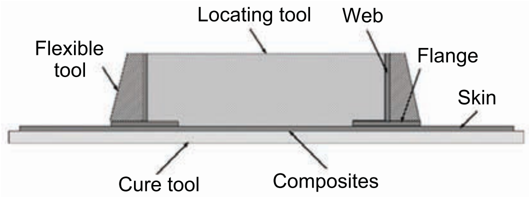

Fig. 1 Schematic diagram of co-curing processing

governing equation using an implicit finite difference method. Bogetti and Gillespie Jr[8,9] also studied two-dimensional anisotropic cure simulations of thick thermosetting composites laminates using a finite difference method. Yi *et al.*[10,11] developed a nonlinear transient heat transfer finite element model to simulate the curing process of polymer matrix composites laminates. Zhu *et al.*[12] developed a three-dimensional coupled thermo-chemo-viscoelastic model to simulate the heat transfer, curing, residual stresses and deformation of a composite part during the entire cure cycle. And they investigated the temperature gradient developed of U-shaped composite parts. Guo[13] investigated the influence of auxiliary materials on the temperature distribution. The previous works have taken finite element approaches and three-dimensional simulations. However, for those especial fabrication techniques, for example co-curing processing, the influence of auxiliary tools must be considered and fewer people have studied it. In the intersection between the web and the skin, the strength was the lowest as shown in the work by Huang[14]. So cure induced residual stresses in the intersection between the web and the skin would influence the strength of the stiffened panels.

In the present work, a nonlinear transient heat transfer finite element model, in which the influence of auxiliary tools was considered, was developed to simulate the co-curing process of the stiffened thermosetting composite panels. It was assumed that no resin flow or thickness reduction occurred during the co-curing process. Temperatures inside the composites were evaluated by solving the nonlinear anisotropic heat conduction equations including the internal heat produced by chemical reactions. Material parameters were assumed to be constant. Different structures of the flexible tools and different thicknesses of the skin were investigated during the same co-curing processing.

2. Model Description

2.1 Degree of cure and cure kinetics

The degree of cure rate can be expressed as a function of the rate of heat generation:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t}=\frac{1}{\rho H_{\mathrm{u}}}\dot{q} \tag{1}$$

where ρ is the polymer density, H_{u} is the amount of heat generated during dynamic scanning until completion of the chemical reactions, and $\dot{q}$ is the rate of heat generation.

Two empirical schemes, the nth order and binodal models[13,15], were widely used for modeling cure kinetics of thermosetting materials. The nth order kinetics can be expressed as

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t}=k_0(1-\alpha)^n \tag{2}$$

and the binodal model is

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t}=(k_1+k_2\alpha^m)(1-\alpha)^n \tag{3}$$

where k_0, k_1 and k_2 and are rate constants, which depend on temperature, and m and n are constants obtained by DSC[15–21]. The rate constants k_0, k_1 and k_2 are usually assumed to be of the Arrhenius form[13]. And Arrhenius equation can be expressed as

$$k(T)=A\exp(-E/RT) \tag{4}$$

where A is frequency factor, E is activation energies, R is the universal gas constant and T is absolute temperature. A and E can be obtained by DSC, too. There are different kinetics models for different kinds of polymer. Cure kinetics model for glass-polyester system can be described as follows[8].

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t}=A\exp(-E/RT)\alpha^m(1-\alpha)^n \tag{5}$$

2.2 Thermo-chemical model

Based on the energy balance principle and the Fourier heat transference law, thermo-chemical model is given by

$$\rho_{\mathrm{c}}c\frac{\partial T}{\partial t}=k_{xx}\frac{\partial^2 T}{\partial x^2}+k_{yy}\frac{\partial^2 T}{\partial y^2}+k_{zz}\frac{\partial^2 T}{\partial z^2}+\dot{q} \tag{6}$$

where T and t are the temperature and time; ρ_{c}, c, k_{ii} are the density, the specific heat and the anisotropic thermal conductivity of the composites, respectively; and $\dot{q}$ is the heat flow rate per unit area. According to Eq. (1), $\dot{q}$ can be expressed as

$$\dot{q}=\rho H_{\mathrm{u}}\frac{\partial\alpha}{\partial t} \tag{7}$$

2.3 Finite element formulation

According to variation approach, virtual temperature δT is introduced. The integral expression of Eq. (6) can be shown as

$$\int_V(\rho_{\mathrm{c}}\frac{\partial T}{\partial t})\delta T\mathrm{d}V=\int_V(k_{xx}\frac{\partial^2 T}{\partial x^2}+k_{yy}\frac{\partial^2 T}{\partial y^2}+ k_{zz}\frac{\partial^2 T}{\partial z^2}+\dot{q})\delta T\mathrm{d}V \tag{8}$$

In discrete Eq. (8) by finite element method, the temperature and the degree of cure at arbitrary position

Table 1 Material properties of the glass/polyester plate

ρ_c/kg·m^{-3}	c/J·kg·K^{-1}	K_{33}/W·m^{-1}·K^{-1}	K_{11}/K_{33}
1890	1260	0.2163	2

Table 2 Cure kinetics parameters for the glass/polyester composites

A/min^{-1}	m	n	ΔE/J·mol^{-1}	H_u/J·kg^{-1}	R/J·mol^{-1}·K^{-1}
3.7×10^{22}	0.524	1.476	1.674×10^5	77500	8.3143

Table 3 Material properties of auxiliary tools

	Density/kg·m^{-3}	Specific heat/J·kg^{-1}·K^{-1}	Thermal conductivity/W·m^{-1}·K^{-1}
Rubber	1350	1400	0.756
Steel	7800	502	16.3

in an element can be expressed as nodes temperature and the degree of cure:

$$T=\sum_{i=1}^{m}N_iT_i \tag{9}$$

$$\alpha=\sum_{i=1}^{m}N_i\alpha_i \tag{10}$$

where T_i and α_i are the node temperature and the node degree of cure, respectively, and N_i is the element form function. The finite element procedure CURESIMULATION was developed based on the above formulations, which has three-dimensional isoparametric elements.

3. Numerical Results

Firstly, a simulation example was presented to demonstrate the use of the present finite element procedure CURESIMULATION for analyzing composite curing processes. A glass/polyester composite laminate was analyzed, and thermal properties and equations for the rate of curing were reported as shown in Tables 1 and 2 from the work by Bogetti and Gillespie[8]. The composite laminate was 15.24 mm×15.24 mm×2.54 mm. And the boundary conditions were the same as ones in the work by Bogetti and Gillespie[8]. Figure 2 shows the node temperature in the center of the laminate *vs* the manufacturer's recommended cure cycle (MRC). The simulated results shown in Fig. 2 are in good agreement with the work by Bogetti and Gillespie. And in the present solution, the peak value of cure temperature was 125°C at 170 min after heating began. In the work by Bogetti and Gillespie[8] the peak value of cure temperature was 126°C at 164 min.

Cross section scale of stiffened thermosetting composite panels is shown in Fig. 3. The length is 0.5 m. The flexible tools were composed of silicon rubber and fiber, and the locating tools were made up of steel. Thermal properties of auxiliary tools were listed in Table 3.

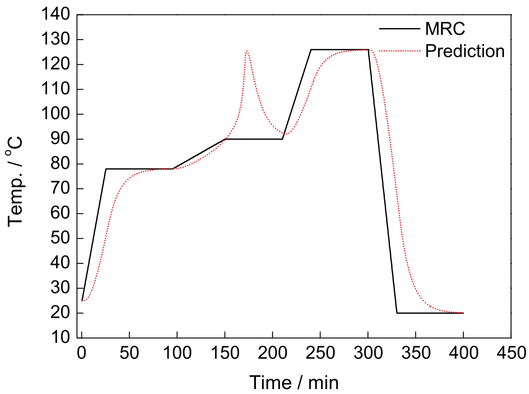

Fig. 2 Temperature for glass/polyester composite laminate

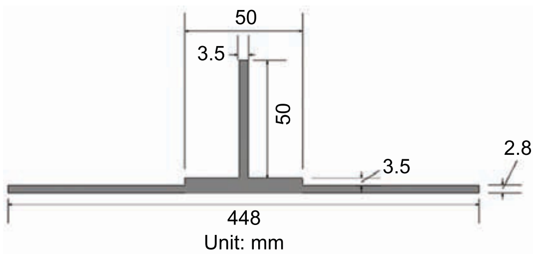

Fig. 3 Cross section scale of stiffened thermosetting composite panels

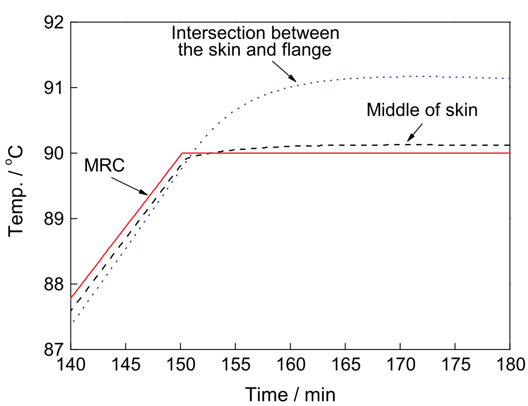

Fig. 4 Temperature in different positions of glass-polyester stiffened panels

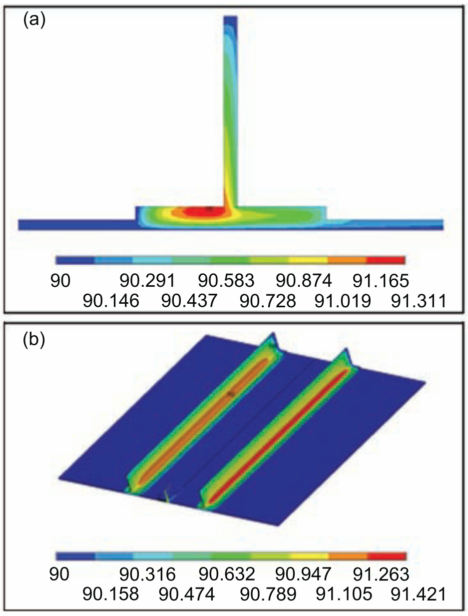

Fig.5 Temperature distribution in the stiffened panel at 165 min

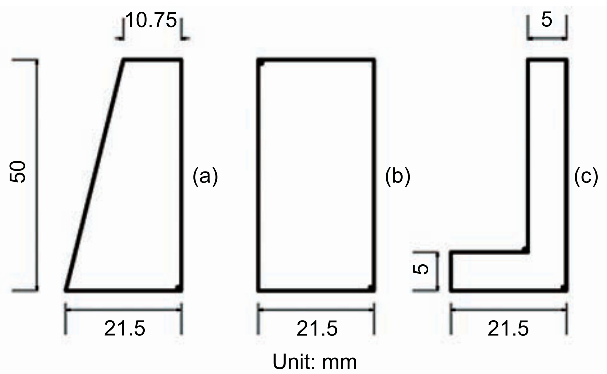

Fig. 6 Different structure forms of flexible tools

We introduced auxiliary tools to the simulation of cure temperature. The relationship between temperature in different positions of the stiffened panel and the curing time is shown in Fig. 4. And the temperature in the interface between the skin and the flange was the highest. The peak value of curing temperature was 91.4°C at 165 min. It was 1.4°C above the temperature of MRC. The temperature distribution in the stiffened panel at 165 min is shown in Fig. 5 and the highest temperature was present in the middle of composite parts throughout the length. In the intersection between the skin and the flange, the temperature gradient along direction y was higher. It was about 257.

Figure 6 shows the flexible tools with different structures. And the temperature gradient distributions using different flexible tools are illustrated in Fig. 7. Temperature gradients along direction y in the intersection between the skin and the flange for (a)–(c) were 257, 259 and 197, respectively. The structures of flexible tools influenced temperature distribution during co-curing processing. And the structure (c) was better for temperature distribution.

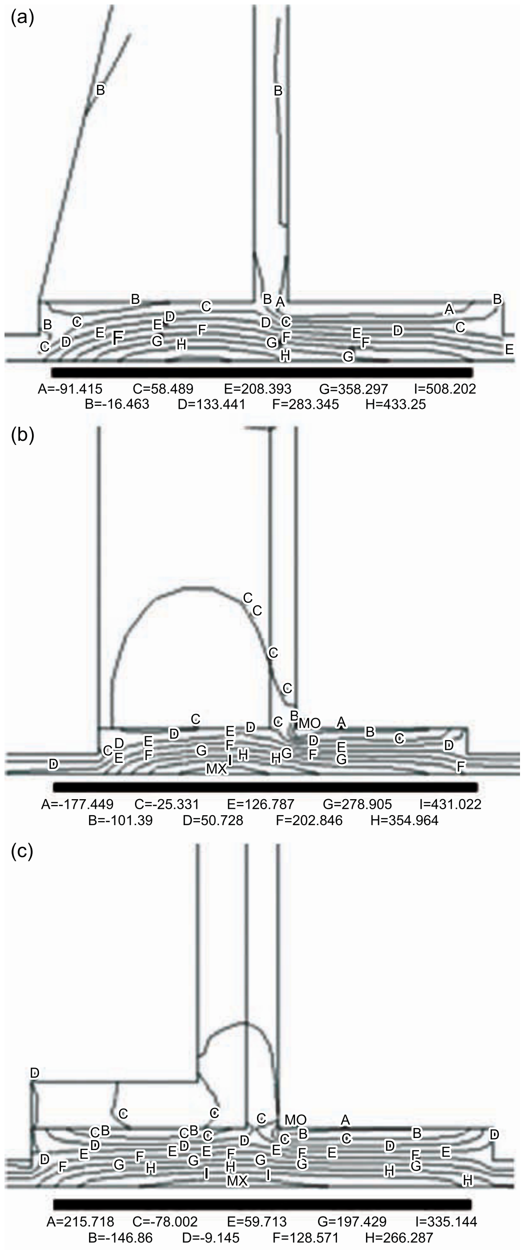

Fig. 7 Distributions of temperature gradients along direction y during co-curing processing for using different flexible tools. (a)–(c) correspond to (a)–(c) in Fig. 6, respectively

In fact, the thickness of the skin influenced the cure temperature distribution during co-curing processing, too. The peak value of the cure temperature *vs* the thickness of the skin is illustrated in Fig. 8. And when the thickness of the skin increased, the temperature in the intersection between the skin and the flange also increased. When the thickness of the skin was 10 mm, the peak value of temperature was 94.3°C.

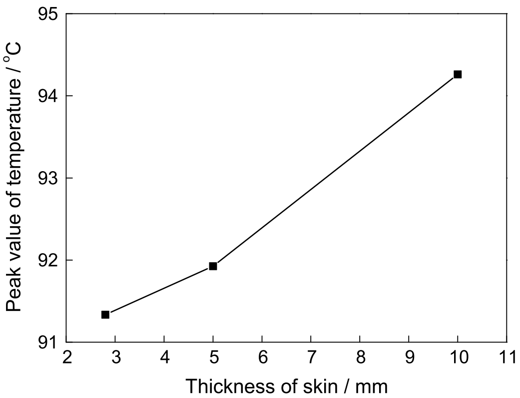

Fig. 8 Peak value of temperature versus the thickness of skin

4. Conclusions

(1) A transient finite element model has been established successfully to simulate the cure temperature distribution of T-shape stiffened thermosetting composite panels.

(2) By using the code CURESIMULATION, the temperature distribution of stiffened composite panel during co-during processing was obtained. The temperature gradient was higher in the intersection between the skin and the flange. And different temperature distributions were obtained by using different flexible tools or different thicknesses of the skin.

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