

Resin Flow of an Advanced Grid-Stiffened Composite Structure in the Co-Curing Process

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Abstract The soft-mold aided co-curing process which cures the skin part and ribs part simultaneously was introduced for reducing the cost of advanced grid-stiffened composite structure (AGS). The co-curing process for a typical AGS, preformed by the prepreg AS4/3501-6, was simulated by a finite element program incorporated with the user-subroutines ‘thermo-chemical’ module and the ‘chemical-flow’ module. The variations of temperature, cure degree, resin pressure and fiber volume fraction of the AGS were predicted. It shows that the uniform distributions of temperature, cure degree and viscosity in the AGS would be disturbed by the unique geometrical pattern of AGS. There is an alternation in distribution of resin pressure at the interface between ribs and skin, and the duration time of resin flow is sensitive to the thickness of the AGS. To obtain a desired AGS, the process parameters of the co-curing process should be determined by the geometry of an AGS and the kinds of resin.

Keywords Simulation · Co-curing process · Resin flow · Advanced grid-stiffened composite structure (AGS) · Manufacture technique

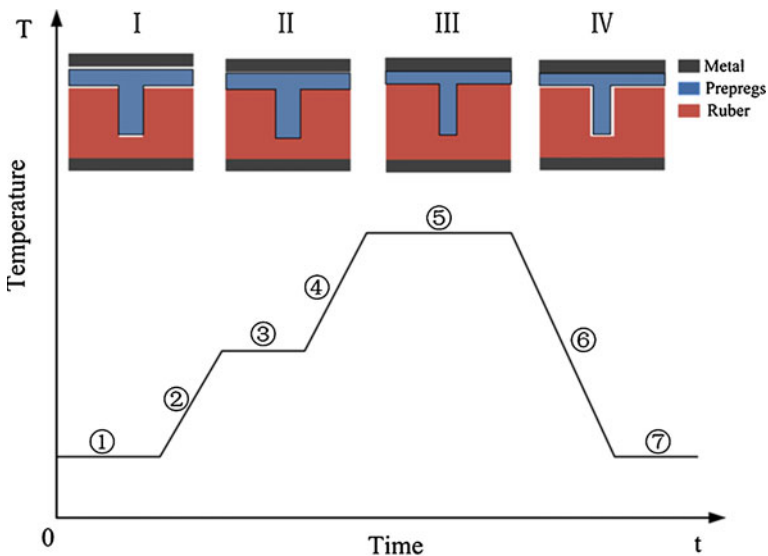
1 Introduction

Advanced grid-stiffened composite structure (AGS) is one of the advanced lattice structures and has been widely applied in aerospace, military, marine and civil structures, due to the advantages of light weight, high strength and stiffness, fatigue resistance, designable properties, etc. [1, 2]. Traditionally, there are two steps during the manufacture for an AGS; firstly, the skin part and the grids part with designed pattern are manufactured individually, secondly, the cured skin part and the grids part are joined together by resin and re-cured in an autoclave. During the process, the excessive resin would flow owing to the low viscosity and pressure gradient and result in non-uniform resin content which affects the performance of product. Although, the quality of product could be improve by adjusting

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some process parameters such as temperature and pressure by a trail-and-error technique, it is a high-cost and time-consuming process which hinders the application of AGSs relative to competitive materials.

Some novelty manufacturing techniques have been proposed for reducing the cost and time of AGSs [3–5]. The novelty manufacturing techniques reducing the two steps into one step would cure the skin part and ribs part simultaneously in a hybrid mold. A hybrid mold is made up of a plate and some expansion blocks which provide desired pressure on product during a curing process. It is a daunting task to align the appropriate expansion blocks into a suitable position caused the quality of ribs is determined by the expansion blocks. To overcome the drawbacks, a promising manufacture technique is proposed, that is, the soft-mold aided co-curing process which replaces the expansion blocks by a replaceable silicon rubber mold with desired grooves. The principle of the soft-mold aided co-curing process is given in Fig. 1. It is seen that the soft-mold made of silicon rubber with a higher coefficient of thermal expansion (CTE) would expand and provide desired pressure on the AGS in the process. Therefore, the skin part and ribs part would be cured simultaneously by the technique, i.e. the co-curing process. The soft-mold would also squeeze excessive resin, evaluate fiber volume fraction and facilitate de-molding. Multi-coupled fields such as temperature field, cure degree field, pressure field, resin flow field, are involves in an AGS in the co-curing process. The resin flow is the primary mechanism for removing the excess resin and voids entrapped inside the AGS and obtaining a desired fiber volume



- I : ① lay up prepregs on the soft-mold for forming an AGS and assemble it with assistant materials in an autoclave;
 II : ②, ③ heat up the assembly and result in the soft-mold contact on prepregs;
 III : ④, ⑤ heat up the assembly continually that initiate the cross-linking reaction and squeeze the excessive resin out of the molds while the soft-mold expanding;
 IV : ⑥, ⑦ cool down the assembly when the prepregs was cured fully and de-mold the AGS product.

Fig. 1 The principle of the co-curing process

fraction and size. Although, the quality of AGS can be improved by determining a series of appropriate process parameters based on a trial-and-error procedure, it is a daunting and cost-consuming task since the adequate process parameters are only suit for a specific AGS.

Numerical technique is an effective solution to save the time and cost by employing a predictive mathematical model includes thermal transfer, cure kinetics, resin flow, fiber compaction. A curing process would be optimized by simulating the process with several candidate process parameters. Modeling the curing process of composites has been the focus of increasing number of research articles over 2 decades, and a number of increasingly complex and capable computational models for the autoclave process have been developed to simulate the curing process [6–14]. Telikicherla et al. [15] considered a two dimensional time-dependent heat conduction equation with a heat generation term and employed an Alternating Direction Explicit (ADE) finite difference procedure, addressing the effects of the heating rate, the laminate thickness, bleeder material, and convective heating. Hojjati and Hoa [16] used a control-volume method combined with an ADE method to solve a one-dimensional heat conduction equation coupled with the flow equations. Combining the present models or methods, the resin flow in a composite cured by advanced manufacture techniques such as resin transfer molding [17], liquid composite molding [18], resin infusion molding [19], etc. is investigated. However, the resin flow in a composite with complex geometry in a curing process such as an AGS in the co-curing process is still unknown. It is important to investigate the resin flow in AGS for ensuring the quality, since the size and cost of an AGS are greater than others.

There are kinds of numerical techniques for simulating the resin flow in prepregs by now. However, the finite element technique would be an effective solution than the others due to the geometrical pattern of AGSs and the co-curing process. Attempts were made to utilize a commercial finite element software ANSYS to solve the present issue. Unfortunately, special features such as variable viscosity, permeability and a general fiber constitutive law are not implemented in the software. Therefore, two user-subroutines the ‘thermo-chemical’ module and the ‘chemical-flow’ module are incorporated in ANSYS which with excellent pre- and post-processor properties. The variations of temperature, cure degree, pressure and resin flow in an AGS in the co-curing process are investigated. Based on the simulation results, some advices are proposed for improving the product quality by modifying the processing parameters. A parametric study for the resin flow in the AGS will also be presented.

2 Models Development

2.1 Assumptions

An AGS can be described by a representative volume element as shown in Fig. 2, owing to the periodically geometry pattern. The skin part and ribs part are fabricated with a lay-up sequence by prepreg sheets and prepreg tapes, respectively. The coordinates indicates that the skin part is laid on the x-y plane while the z axis indicates the thickness of the AGS. Performing the analysis on a 2-D section (gray plane in Fig. 2) is believed to be adequate and appropriate for the AGS, as at least one dimension is usually much larger than the other [20]. Gradients in the in-plane direction are correspondingly small and can safely be ignored. The present model is made in the following assumptions:

1. a plane strain condition is assumed to prevail as the size of the AGS is great enough
2. the AGS is idealized as a void free fiber bed fully saturated with a curing resin

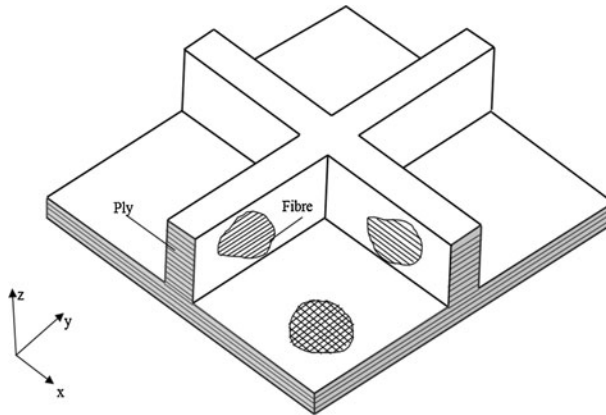


Fig. 2 The AGS representative volume element

3. the resin is assumed to behave as an incompressible Newtonian fluid
4. the thermal properties of the AGS and molds are constant during the whole co-curing process.

2.2 Governing Equations

2.2.1 The Thermo-Chemical Module

In the co-curing process, the prepregs are heated and initiate the cross-linking reaction of resin which would generate amounts of heat. Based on a physical law, the temperature is assumed to be in local equilibrium at any time due to its slow processing speed. The heat transfer differential equation with an interior heat source during the co-curing process could be expressed as [21]

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} \left(\lambda_{ij} \frac{\partial T}{\partial x_j} \right) + \dot{Q} \quad (1)$$

where \dot{Q} is an interior heat source ratio, λ_{ij} is the effective thermal conduction, ρ and c are, respectively, effective bulk density and effective bulk specific heat of prepregs, and t is the time.

The interior heat source caused by the chemical reaction of resin can be calculated with the cure degree law of composite materials. It is expressed as

$$\dot{Q} = \rho H_r \frac{d\alpha}{dt} \quad (2)$$

where $d\alpha/dt$ is the rate of cure determined by the cure kinetics of resin; H_r is the total released heat of reaction. A simple and effective cure kinetic is derived from the phenomenological theory and could be expressed by the Arrhenius equation and the law of cure degree variation [22]. The cure kinetics for Carbon/Epoxy AS4/3501-6 is expressed as

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

$$K_i = A_i \exp\left(-\frac{\Delta E_i}{RT}\right) \quad i = 1, 2, 3$$

where K_i is the Arrhenius equation associated with the temperature; A_i is pre-exponential factor; ΔE_i is activation energy. These values are determined by the differential scanning calorimetry (DSC) experiment. R is the universal gas constant; T is the Kelvin temperature.

Owing to the variations of temperature and cure degree of resin, the resin viscosity is varied and it could be taken as proposed in Lee et al. [23]:

$$\mu = \mu_\infty \exp\left(\frac{U}{RT} + K_\mu \alpha\right) \tag{4}$$

where μ_∞ is the resin viscosity in infinity, U is the activity energy and K_μ is a constant.

2.2.2 The Chemical-Flow Module

At present, a phenomenological model derived from a series of experiments by Dave [8] has been widely used for the discretion of resin flow. In the model, the action of resin flow is regarded as a viscous fluid flow in a porous fiber bed under a pressure. The applied pressure is shared by the resin and the fiber bed simultaneously. The pressure taken by the resin will drive the excessive resin to flow out in directions both normal and parallel to the tool surfaces, and the flow depends on the resin viscosity and the fiber permeability. Because the fiber bed acts as a non-linear spring [7], as the skin and ribs thickness gradually decreases, more and more pressure is taken by the fiber bed. At the end of co-curing process, the pressure is completely supported by the fiber bed if gelation does not occur before that. Since the applied pressure is shared by the resin and the fiber bed, the equilibrium equation can be written as [8]

$$P = P_r + P_f \tag{5}$$

The equation of the resin pressure in a 2D model in the co-curing process is expressed as [9],

$$\frac{\partial}{\partial x} \left(\frac{k_x}{\mu} \frac{\partial P_r}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{k_y}{\mu} \frac{\partial P_r}{\partial y} \right) = m_v \frac{\partial P_r}{\partial t} \tag{6}$$

where k_x and k_y are the fiber bed permeability in the direction of fiber and perpendicular to the fiber direction, respectively, μ is the viscosity of the resin, and m_v is the coefficient of volume compressibility [9]

$$m_v = -\frac{1}{1+e} \frac{de}{dP_r} \tag{7}$$

where e is the void rate (volume of voids per unit volume of fibers in the prepregs), expressed as

$$e = \frac{1 - V_f}{V_f} \tag{8}$$

where V_f is the fiber volume content. In Eq. (7), the de/dP_r can be obtained from the stress–strain relationship of the porous fiber bed. In the co-curing process, the void ratio of the AGS will vary according to the change of the effective stress. One relation used in the following simulations between the effective stress and the void ratio was derived by Young [11] based on the curing experiments conducted by Gutowski [7]:

$$e = \begin{cases} -1.552 \times 10^{-6} P_r + 0.81 & \text{for } 0 \leq P_r \leq 68.95 \times 10^3 Pa \\ -0.247 \log P_r + 1.899 & \text{for } P_r > 68.95 \times 10^3 Pa \end{cases}$$

The fiber permeability k_x and k_y used in the following simulations is given by [16]

$$K_x = \frac{r_f^2(\pi + 2.15V_f)(1 - V_f)}{48V_f^2} K_y = \frac{r_f^2(1 - V_f^*)\left(1 - \sqrt{V_f^*}\right)^2}{24(V_f^*)^{1.5}}$$

where

$$V_f^* = \begin{cases} V_f & V_f < 0.5 \\ 2.2V_f^2 - 1.22V_f + 0.56 & V_f \geq 0.5 \end{cases}$$

Obviously, the pressure transfer differential Eq. (6) and the boundary conditions are, respectively, similar to the heat transfer differential equation and the associate boundary conditions in a transient heat transfer analysis. In view of that, the pressure transfer simulation could be simulated in the transient heat transfer simulation module with the pressure represented by the temperature. Since the velocity of resin flow is small, the flow action could be expressed by the Darcy's law [9]. The law used for a fluid flowing through an orthotropic material whose coordinate axes are aligned with the principal axes of material can be expressed as:

$$q_i = -\frac{k_i}{\mu} \frac{\partial P_r}{\partial x_i} \quad (9)$$

where q_i is the flow velocity of resin in direction i .

3 Results and Discussion

Based on the aforementioned equations, a user-subroutine combined with the 'thermo-chemical' module and the 'chemical-flow' module was developed for simulating the resin flow of the AGS during the co-curing process. The simulation of the co-curing process for an AGS was conducted by a 2D finite element model (as shown in Fig. 3) for a cross section in this section. The AGS is made of AS4/3501-6 prepregs with a lay-up sequence (0/90)_{8s} and (0)₁₀₀ for skin and rib, respectively. Since the unique characteristic of the co-curing process, the components of the finite element model should be three parts, the metal part, composite part and rubber part. For simplify, a bleeder between the top surface of skin and the metal mold wasn't modeled. However, the effect of it was considered by a parameter of contact thermal resistance about 20. The size of the assembly is also shown in Fig. 3. The AGS would be under a compacting pressure 1.379 MPa on the top of skin in the co-curing process, and is subjected to a cure cycle as shown in Fig. 4. The pressure in the bleeder is taken to be 0.0167 MPa, which is a typical bleeder pressure in the commercial composite material processing by using vacuum bagging procedures [6]. The material parameters required in the simulation are given in Table 1 and Table 2.

The boundary conditions of assembly for the simulation of the 'thermo-chemical' module are assumed that on the top and bottom boundary are first condition with the temperature equal to the cure cycle (shown in Fig. 4) while the left and right boundary are adiabatic, due to the symmetry. Based on the simulation results of the AGS in the co-curing process, the variations of temperature and viscosity of resin could be investigated with the 'thermo-chemical' module and the aforementioned boundary.

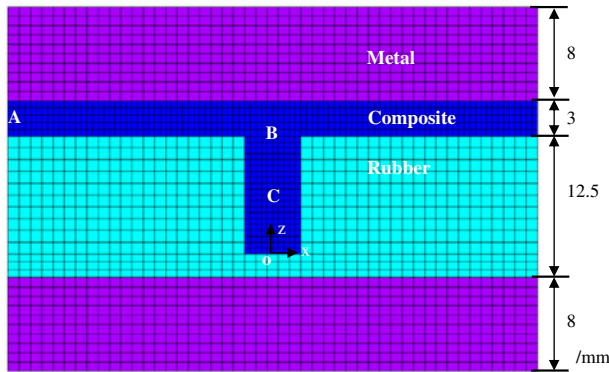


Fig. 3 The 2D finite element model of a cross section in the AGS specimen

Figure 4 shows the variations of temperature and cure degree at the positions A, B and C (skin center, interface center and rib center, as shown in Fig. 3) in the co-curing process, and the cure cycle. It can be seen that there is a uniform distribution of temperature and cure degree in the AGS, an obvious ‘overshoot’ appears at the second dwell stage of cure cycle, the cure degree is increasing while the temperature over 100°C and the chemical action of resin is mostly accomplished at the second heating stage of cure cycle. According to the Eq. (4), the variation of viscosity of resin associates with the temperature and cure degree. Figure 5 illustrates the variation of viscosity of resin at the position A, B and C in the co-curing process. It can be seen that there is a synchronous variation of viscosity in the AGS. The viscosity is decreased before initiating the cure reaction, increase gradually during the cure degree varying, and increase dramatically at the cooling stage of cure cycle.

Based on the ‘thermo-chemical’ module, the resin flow in the co-curing process was simulated by the 2D finite element model. To squeeze the excessive resin and entrapped void effectively, an autoclave pressure 1.379 MPa is applied at a specific time when the viscosity of resin achieves the lowest, i.e. the autoclave pressure is applied at the time that the AGS has been cured for 3000 s. Figure 6 shows the variation of resin pressure at specific time along the thickness direction at position $x=0$ (as shown in Fig. 3). It can be seen that the distance between the location in the AGS and the bleeder is an important factor which

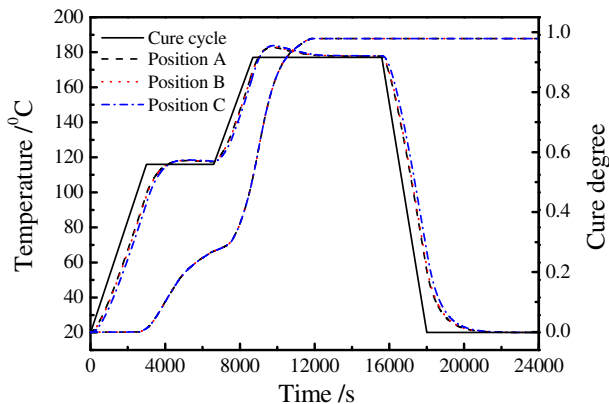


Fig. 4 Simulation results of temperature and cure degree in the AGS by the ‘thermal-chemical’ module

Table 1 Thermal parameters of composite and molds [22]

	ρ (kg/m ³)	C/KJ/(mol·K)	$K/W \cdot (m \cdot K)^{-1}$	
			K_{33}	K_{11}/K_{33}
Silicon rubber	1.23e3	1.53	1.23	1
45# Steel	7.85e3	0.46	50.24	1
Graphite/Epoxy	1.52e3	9.42e-1	4.457e-4	10

influence the resin flow rate in it, the resin flow accomplishes mostly in 6000 s since the autoclave pressure applied, and the gradient of resin pressure is decreasing along the thickness direction at position $x=0$ as the co-curing process proceeding. Besides, there is an alteration of the gradient of resin pressure at the position of the interface between rib and skin. It is shown that the profile of resin pressure is quadratic in rib zone while that of resin pressure is nearly liner in skin zone.

Figure 7 shows the variations of resin pressure and fiber volume fraction at position A B and C in the AGS in the co-curing process. It is seen that the variations of resin pressure and fiber volume fraction would be finished in 6000 s since the autoclave pressure applied, and there is the same variation progress between the position A and B. The fiber volume fraction in skin zone increases from 55 % to about 71.5 % which is great than in rib zone 70 %. It can be concluded that the flow of resin is mostly affected by the distance from the bleeder, owing to the geometry pattern the resin flow in the skin part is different from that in the rib part and the prepregs would be compacted completely in 6000 s in the AGS in the co-curing process.

Based on the aforementioned modules, the resin flow in the AGS in the co-curing process has been simulated and some valuably results have been obtained. However, there are still some inexplicit phenomena, such as whether the resin flow would be finished in 6000 s and

Table 2 The parameters used in the resin flow simulation for the AS4/3501-6 prepregs [23]

Parameter	Value
Pre-exponential factor A_1 (/min)	2.102e9
Pre-exponential factor A_2 (/min)	-2.014e9
Pre-exponential factor A_3 (/min)	1.960e5
Activation energy ΔE_1 (J/mol)	8.07e4
Activation energy ΔE_2 (J/mol)	7.78e4
Activation energy ΔE_3 (J/mol)	5.66e4
Heat of reaction H_r (KJ/Kg)	473.6
Viscosity constant μ_∞ (Pa s)	7.93e-14
Activity energy for viscosity U (J/mol)	9.08e10
Viscosity constant k_μ	14.1
Fiber radius r_f (m)	3.8e-6
Fiber volume fraction V_f (%)	55
Fiber density ρ_f (kg/m ³)	1.79e3
Resin density ρ_y (kg/m ³)	1.26e3
Specific heat of fiber c_f (J/(kg K))	7.12e2
Specific heat of resin c_y (J/(kg K))	1.26e2

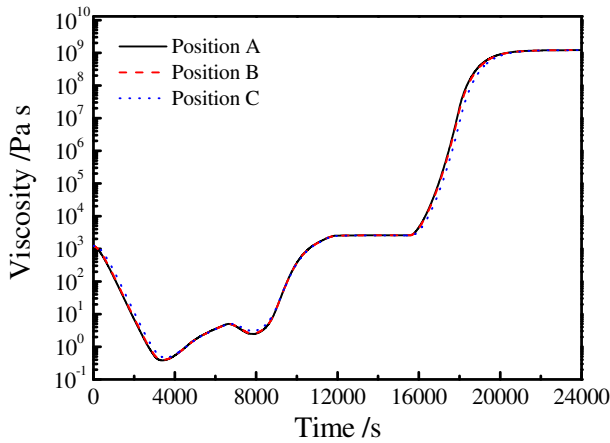


Fig. 5 Resin viscosity variation of the AGS by the ‘chemical-flow’ module

the resin pressure would be alternation at the interface between the skin and the rib. To verify these phenomena, a parametric study has been conducted based on two modified models with the same initial conditions and boundary conditions. The models for the parametric study are shown in Fig. 8. The modified model I just increase the thickness of skin one time and the modified model II increases the thickness of skin and rib one time. The simulation results obtained from different models are shown in following figures.

The variations of temperature and resin viscosity at the position C (rib center) of the models in the co-curing process are shown in Fig. 8. It shows that there are almost the same variation progresses of temperature and the resin viscosity between the original model and the modified model I, there is a much more visible hysteresis of temperature and resin viscosity in modified model II, there are more apparent overshoot at the second dwell stage of cure cycle in both of the modified model I and II. The reason is that, the lower thermal conductivity of composite prepregs and the more distance of composite prepregs from the

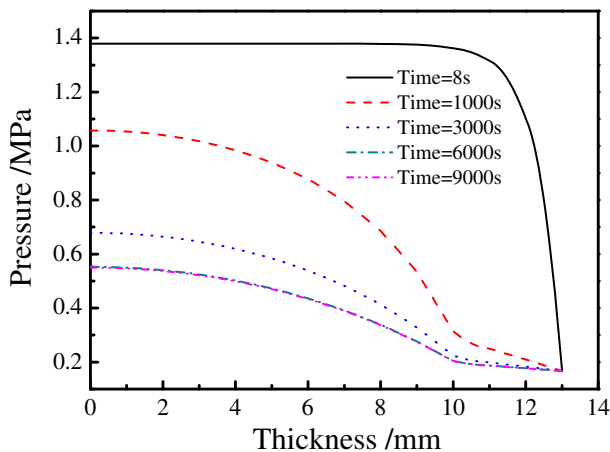


Fig. 6 Distribution of resin pressure in the AGS during the co-curing process

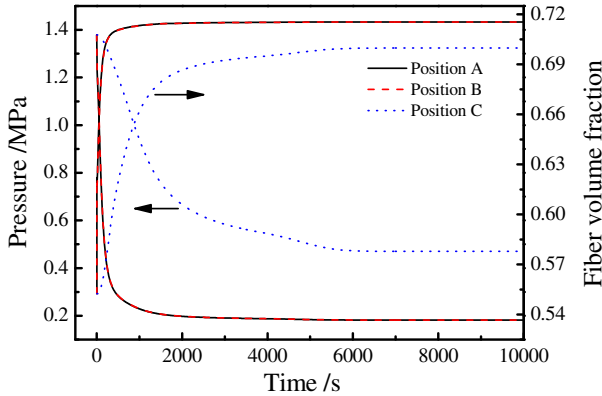


Fig. 7 Variation of resin pressure and fiber volume fraction in the AGS during the co-curing process

boundary, the more time is required to achieve the desired temperature. The hysteresis of temperature and cure degree in composite prepregs results in the hysteresis of resin viscosity.

The distribution of resin pressure along the thickness direction at position $x=0$ in the AGS at the specific time (3000 s and 6000 s since the autoclave pressure applied) are shown in Fig. 9. It can be seen that there is a significant difference of distribution of resin pressure between the original model and the modified models. In the original model, the applied autoclave pressure is mostly carried by the fibers bed at the rib part where the resin takes the mostly autoclave pressure at the rib part of modified models. The degradation of resin pressure basically appears in the skin part in modified models while it appears in both of parts in the original model. Though the sizes of models are different, there is an alternation in the distribution of resin pressure at the interface between the skin and rib. It is due to that the distribution of resin viscosity is non-uniform and the unique geometric pattern of the AGS, that is, the deeper part in the AGS, the more postponed variation of resin viscosity in the co-curing process, and the hysteresis of resin viscosity hinders the resin flow. It can be concluded that the dwell stage of cure cycle for a thicker AGS should be longer and the time of applying autoclave pressure should be postponed, i.e. an appropriate cure cycle

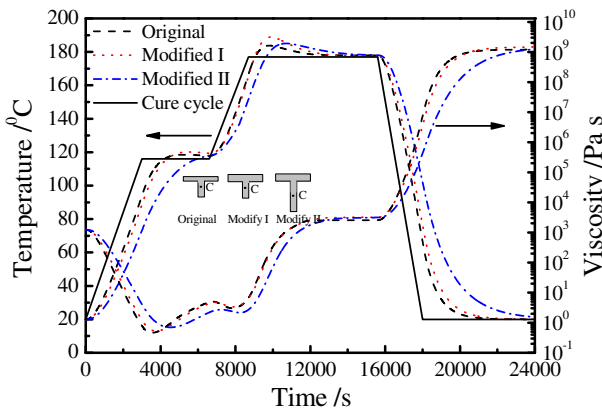


Fig. 8 Variation of temperature and resin viscosity in rib center of models during the co-curing process

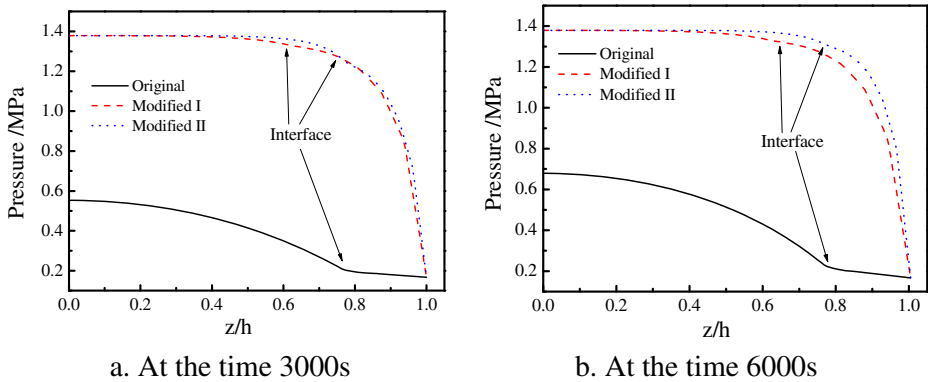


Fig. 9 Distributions of resin pressure along the path $x=0$ in the models at the time 3000 s and 6000 s since the autoclave pressure been applied

should be designed with the size of product. For the resin 3501–6, the resin flow would be finished in 6000 s since the autoclave pressure been applied.

4 Conclusions

An innovative manufacture technique i.e. the soft-mold aided co-curing process is introduced. The process would reduce the time and cost by simultaneously cure the skin part and ribs part using a specific silicon rubber mold. Two user-subroutines for describing the curing process in composite were developed according to the thermal-chemical model and the chemical-flow model. The variation of multi-coupled fields in an AGS could be investigated by the user-subroutines during the soft-mold aided co-curing process.

Based on the simulation results, the variations of temperature, cure degree, resin pressure and fiber volume fraction in the AGS are illustrated during the co-curing process, respectively. It can be concluded that in the co-curing the resin flow in an AGS is non-uniform even there are uniform distribution of temperature and cure degree in it, the distance between the bleeder and the location in the AGS, and the time of applying autoclave pressure affect the resin flow significantly. Due to the geometry of AGS, there is an alternation of the distribution of resin pressure at the interface between rib and skin. The variations of resin pressure and fiber volume fraction during the compacting illustrates that the duration of resin flow in an AGS is limited and the resin flow would be weak quickly since the viscosity of resin increasing rapidly.

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