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Modeling Thermal Residual Stresses in Composite Patch Repairs During Multitemperature Bonding Cycles

J. Cho* and C. T. Sun†
Purdue University, West Lafayette, Indiana 47907-2023

Generally, thermal residual stresses in composite patch repairs can be reduced by lowering the cure temperature of the adhesive used. However, lowering the cure temperature requires a longer curing time to achieve the fully developed performance of the repair. The total curing time can be shortened by using a multistep cure-temperature cycle. In modeling of the cure cycle, a cure kinetic model was established first based on the result of differential scanning calorimetry tests that were performed to estimate the development of the degree of cure of the adhesive. Because stress relaxation depends on the degree of cure of the adhesive, this kinetic model was used in conjunction with the Maxwell viscous model to estimate stress relaxation in the adhesive during the curing cycle. Thus, the model has the capability of estimating the thermal residual stresses in a composite patch repair undergoing a multistep curing schedule. Thermal residual stresses induced by a cure cycle were quantified by ΔT_{eff} defined as the temperature difference between the stress-free temperature and room temperature. This model was used to establish a guide for selecting an efficient two-step cure cycle, which yields a ΔT_{eff} lower than that of the cure cycle recommended by the adhesive manufacturer.

I. Introduction

ADHESIVELY bonded composite patch repairs provide an efficient and economical repair technology to extend the service life of cracked structural components in aging aircraft as a result of the many advantages of advanced fiber composites in their formability, high specific strength and stiffness, and immunity against corrosion or fatigue.[1]

However, because most high-performance adhesives used in the repair require elevated cure temperatures, as the repaired structure cools from the cure temperature to the ambient temperature, high thermal residual stresses in the repair result from the mismatch of thermal expansion coefficients between the composite patch and the cracked structure. Because thermal residual stresses are tensile in the cracked plate and tend to open the crack, they cause an adverse effect on the fatigue performance of the patching repair.[2] Hence, it is desirable to minimize these thermal residual stresses. A typical mismatch in thermal expansion coefficients of the AS4/3501-6 carbon/epoxy composite and 2024-T3 aluminum alloy, both of which were used in this study, is shown in Table 1.

Composite patches can be cured before bonding to or cocured with the cracked structure using adhesives. The former procedure was employed in the present study. In this procedure the composite patch is cured separately following the cure cycle for the composite. Subsequently, the composite patch is bonded to the cracked structure using the cure cycle for the adhesive.

During bonding of the composite patch to the cracked plate, the development of thermal residual stresses in the repair is dependent on the curing cycle of the adhesive. Thus, in general, the reduction of residual stresses in the adhesively bonded composite patch repair can be achieved by lowering the curing temperature. However, lowering cure temperature requires a longer cure time to achieve the 100% degree of cure of the adhesive as well as the fully developed mechanical performance of the repair. Moreover, lowering cure temperature without a sufficient cure time yields under cured adhesive and, as a result, produces poor mechanical performance of the repair.[3]

In the study of polymeric composite laminates by some reseachers,[4,5] it was shown that the total curing time could be shortened without sacrifice of the degree of cure and mechanical performance by using two-step cure-temperature cycles. This two-step cure cycle consists of a low cure temperature preceding a high cure temperature. The purpose of the first step is to reduce the residual stress, and the second step plays a role in completing the degree of cure. In applying this two-step cure cycle to composite patch repairs, Cho and Sun[3] demonstrated significant extended fatigue life of the repair by reducing 40% of thermal residual stresses with a selected efficient two-step cure cycle.

In Ref. 3 the selection of the two-step cycle was based on a trial-and-error procedure. It is conceivable that finding an optimal two-step cycle for an adhesive with such a procedure might require expensive experiments. Thus, it is highly desirable that the development of thermal residual stresses during the cure cycle be understood and modeled.

Because the precured composite patch and the aluminum plate basically remain elastic during the bonding process, thermal residual stresses in the repair are mainly dependent on the mechanical properties of the adhesive in the curing cycle. In view of the foregoing, the viscoelastic behavior of the adhesive during curing appears to play the dominant role in the development of thermal residual stresses. In addition, because of the change of adhesive properties with respect to the degree of cure the viscoelastic response of the adhesive must be related to the degree of cure for different temperatures. Such a relation is not easy to obtain without conducting a formidable experimental program. Thus, in the present study an empirical viscoelasticity model for the adhesive is developed based on some experimental data. With this model in conjunction with a simple thermoelastic analysis, stress relaxation in the adhesive is estimated, and thermal residual stresses are obtained. To correlate the model prediction with experimental observations, the effective ΔT_{eff} is used, which is defined as the temperature difference between the stress-free temperature and room temperature.[3]

II. Cure Kinetic Model

To predict the degree of cure of FM73M at any given time at a given temperature, it is necessary to understand the cure kinetics of the adhesive. Because the nature of the polymer reactions

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*Graduate Student, School of Aeronautics and Astronautics.
†Neil Armstrong Distinguished Professor of Aeronautical and Astronautical Engineering, School of Aeronautics and Astronautics. Fellow AIAA.

Table 1 Material properties used in study

Properties	AS4/3501-6	Al. 2024-T3	FM73M
E_1 (E) (GPa)	142	72	2.28
E_2 (GPa)	10.3	——	——
G_{12} (GPa)	7.2	——	——
$\nu_{12}(\nu)$	0.27	0.3	0.34
$\alpha_1(10^{-6}/^\circ\mathrm{C})$	−0.9	23	——
$\alpha_2(10^{-6}/^\circ\mathrm{C})$	27	23	——

is very complex to capture the behavior of the individual components, phenomenological models are commonly used.[6] In this study a phenomenological model is adopted to describe the curing of the adhesive, FM73M.

Based on the autocatalytic reaction of epoxide and amine groups, one of the most common forms of autocatalytic type kinetic model can be given by[7]

$$\frac{da}{dt} = ka^m(1-a)^n \tag{1}$$

where a is the degree of cure, t is time, k is an Arrhenius-type reaction rate constant, and m and n are reaction orders. In addition, the cure kinetic parameters k, m, and n are the function of temperature T. The parameter k is given as

$$k = Ae^{(-\Delta E/RT)} \tag{2}$$

where A is a constant, R is the universal gas constant, and ΔE is the activation energy.

To obtain the cure kinetic parameters, differential scanning calorimetry (DSC) scans were performed with several isothermal temperatures (isothermal scanning) and a programmed temperature (dynamic scanning). From the cure rate histories of the DSC scans, the cure kinetic parameters were determined, and the temperature dependence of the cure kinetic parameters was developed. With the obtained cure kinetic parameters the degree of cure can be predicted using Eq. (1).

A. DSC Test

To determine the cure kinetic parameters for a given cure temperature, isothermal scans were performed with five cure temperatures of 121, 104, 94, 82, and 77°C with a TA-Instrument DSC 2910. Samples of 8.7–9.5 mg of the uncured adhesive were encapsulated in DSC aluminum pans. The pan containing the sample was loaded into the DSC with a reference pan. Scanning was started with holding the sample at 30°C until equilibrium was achieved between the sample and reference temperatures. Subsequently, the sample was heated to the selected temperature at 50°C/min. Heat flow (milliwatts) and the corresponding time (minutes) were recorded until the scanning was over. To ensure the completion of curing, the curing times for the cure temperatures of 121, 104, and 94°C lasted at least one hour longer than those recommended by the adhesive manufacturer. For the temperatures of 82 and 77°C, the curing time was chosen to be 10 h. A typical DSC trace is shown in Fig. 1. Note that the manufacturer's recommended curing times for cure temperatures of 121, 104, and 94°C are 1 h, 1 h, and 4 h, respectively.

As shown in Fig. 1, a baseline was taken as the final steady-state signal of the DSC output, which indicates the absence of reaction. Therefore, the total area under the curve from the baseline represents the total heat of reaction H_t, and the area up to a time t indicates the heat of reaction $H(t)$ by that time. Horizontal intersection between the initial DSC signal and the baseline was taken as zero time for the reaction. The degree of cure is defined as the ratio of the heat of reaction $H(t)$ to the total heat of reaction H_t:

$$a(t) = H(t)/H_t \tag{3}$$

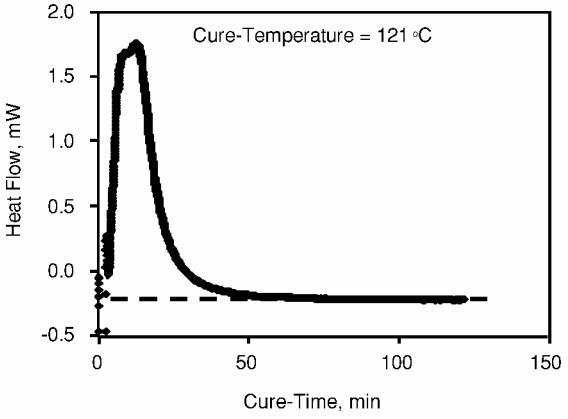

Fig. 1 Typical trace of DSC isothermal scanning and a baseline.

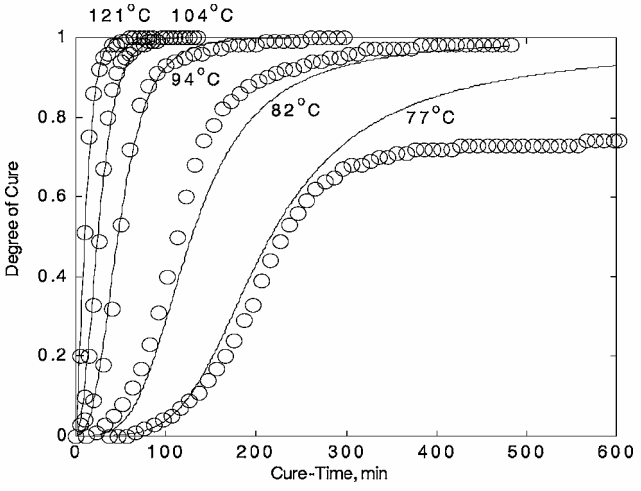

Fig. 2 Degree of cure by DSC scanning and model simulation. Symbols indicate the experimental results.

Similarly, the cure rate at time t can be obtained as

$$\frac{da}{dt}(t) = \frac{dH(t)/dt}{H_t} \tag{4}$$

Dynamic scanning was performed to estimate the total heat of reaction with a constant heating rate of 10°C/min. Similar to the isothermal scans, the sample of 9.2 mg of the uncured adhesive was loaded into the DSC at 30°C. After equilibrium was achieved, the sample was heated at 10°C/min until no heat flow was observed. The total heat of reaction was calculated by measuring the area under the curve from the baseline.

B. Temperature Dependence of Cure Kinetic Parameters

The degree of cure and the cure rate of each isothermal temperature were obtained by analyzing the histories of the DSC scans according to Eqs. (3) and (4). The degree of cure results for 121, 104, 94, 82, and 77°C are shown in Fig. 2. Symbols indicate the experimental results. By the least-squares method the obtained cure kinetic parameters for each isothermal cure temperature were obtained and are summarized in Table 2.

In determining the Arrhenius constant k according to Eq. (2), it is necessary to plot the natural log of k vs the inverse of the cure temperature for constant A, the universal gas constant R, and the activation energy ΔE. A straight line was made with slope of $-\Delta E/R$ and intercept of $\mathrm{Log}(A)$. The temperature dependence of the Arrhenius constant is shown in Fig. 3. For parameters m and n the temperature dependence was modeled by plotting the values of m and n vs the corresponding cure temperatures. The least-squares fit was performed on the data. The parameter m was modeled to be linearly dependent on the cure temperatures. For the parameter n a

Table 2 Summary of cure kinetic parameters for each cure temperature

	Cure temperature, °C				
Parameter	121	104	94	82	77
k	0.105	0.082	0.05	0.036	0.023
m	0.281	0.547	0.62	0.745	0.83
n	0.971	1.046	1.15	1.502	1.8

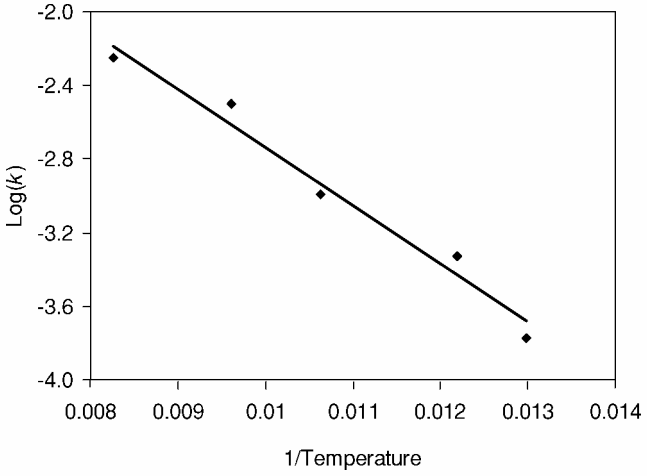

Fig. 3 Modeling of temperature dependence of cure parameter k.

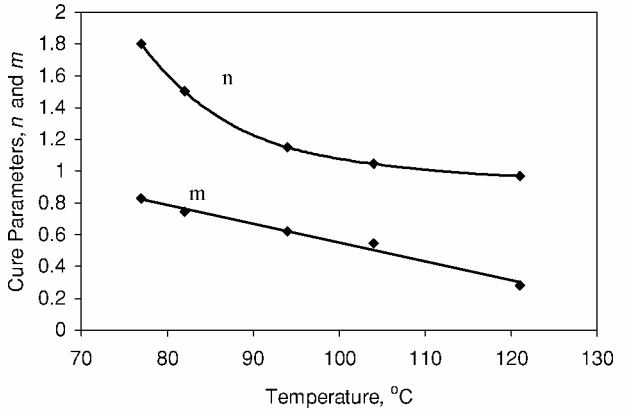

Fig. 4 Modeling of temperature dependence of cure parameters m and n.

fourth-order polynomial was used. The cure kinetic parameters thus obtained are listed in Eqs. (5a–5c), and the curve fits for parameters m and n are shown in Fig. 4.

$$k = (1.542)e^{-316.81/T} \tag{5a}$$

$$m = (-1.187 \times 10^{-2}) \cdot T + 1.739 \tag{5b}$$

$$n = (4.020 \times 10^{-7}) \cdot T^4 - (1.776 \times 10^{-4}) \cdot T^3 + (2.952 \times 10^{-2}) \cdot T^2 - 2.194 \cdot T + 62.661 \tag{5c}$$

In the preceding equations T is temperature (Celsius). These parameters were plugged into Eq. (1), and the degree of cure was evaluated by the Runge–Kutta fourth-order numerical method. The simulated degree of cure for various cure temperatures are shown in Fig. 2 and compared with experimental data.

As seen in Fig. 2, the cure kinetic model shows good agreement with the experimental results except for the 77°C cure temperature, particularly after five hours of curing time. Because the primary focus of the present work is on modeling efficient two-step cure cycles, which should last no more than five hours, the cure kinetic model thus established is adequate for the present purpose.

III. Viscoelastic Stress Relaxation Model

During the bonding process, the adhesive undergoes stress relaxation, which would affect the buildup of thermal residual stresses in the composite patch as well as the host aluminum structure. In this study a simple viscoelsticity model is used to describe this relaxation behavior. The viscoelasticity model to be developed here is not a true physical model that describes the temperature and time-dependent behavior of the adhesive. This behavior in addition to material shrinkage during the curing process is extremely complex. We attempted to develop an effective viscoelasticity model that can account for the effect of stress relaxation on the development of thermal stresses in the adherends during curing. With the foregoing objective in mind, the material constants (functions) of the viscoelasticity model were determined based on the measured thermal residual stresses for a number of composite patched specimens subjected to one-step cure cycles.

For the application of a constant-step shear strain, the shear stress–strain relationship of a linear viscoelastic model is expressed as[8]

$$\tau_{sr}(t) = \Phi(t - t')\gamma(t') \tag{6}$$

where $\tau_{sr}(t)$ is the shear stress after relaxation at time t; the function $\Phi(t - t')$ is the relaxation function that specifies the stress response to a step change of strain from time t' and is defined to be zero when $t < t'$; and $\gamma(t')$ is the applied step shear strain at time t'.

In the Maxwell model the relaxation function is given as

$$\Phi(t - t') = g(t')e^{-\int_{t'}^{t} \frac{g(k)}{\eta(k)}\,dk} \tag{7}$$

where g and η are the time-dependent shear modulus and the viscosity of the adhesive, respectively. The total relaxation time in the Maxwell model is limited by the curing time of the cure cycle. For simplicity, the heating rate and cooling rate in the cure cycle are kept constant in the model as those recommended by the adhesive manufacturer.

Note that the composite patch is placed on the aluminum panel so that the fiber direction is perpendicular to the crack surface. It is obvious that thermal expansion and thermal stresses in the fiber direction in both the aluminum and composite patch are of interest. Because of the mismatch in thermal expansion in the patch and aluminum, shear strains and, thus, shear stresses are induced in the adhesive during cooling from the elevated bonding temperature. Strictly speaking, the adhesive/composite and adhesive/aluminum mismatches in thermal expansion can cause thermal residual stresses in the composite patch as well as in the aluminum. However, the level of these stresses is relatively low in view of the thin bond line. In the present study this effect is neglected.

The shear stress and shear strain in the adhesive are not uniform. For simplicity, we consider the average shear stress and shear strain in the adhesive resulting from the thermal mismatch between the composite patch and the aluminum plate. During bonding, the patched laminate specimen was kept flat until the cure of the adhesive was completed. A sketch of the thickness section of the specimen is given in Fig. 5. The top and bottom molding surfaces in making the specimen are assumed to be frictionless. Thus, the shear strain in the adhesive is produced by the differential thermal expansions of the two adherends. Hence, the average shear strain induced

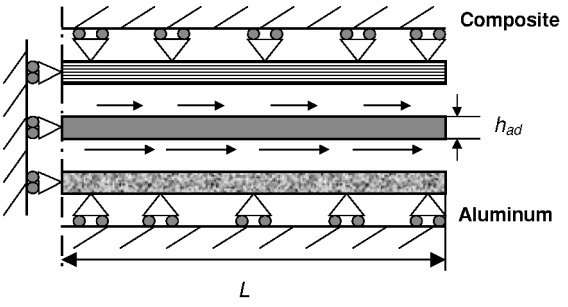

Fig. 5 Illustration of a half-specimen and boundary condition.

by a temperature change dT in the adhesive can be expressed approximately by

$$d\bar{\gamma} = \frac{\int_0^L \gamma(x)\,dx}{L} = \left(\frac{L}{2h_{ad}}\right)(\alpha_p - \alpha_{al})\,dT \tag{8}$$

where $d\bar{\gamma}$ is the average shear strain increment by dT, $\gamma(x)$ is the distribution of shear strain, L indicates the half-length of the laminate, h_{ad} is the thickness of the adhesive layer, and α_p and α_{al} are the thermal expansion coefficients of the composite patch in fiber direction and the aluminum plate, respectively.

The average shear stress corresponding to the average shear-strain increment $d\bar{\gamma}$ given by Eq. (8) can be obtained from Eq. (6). Further, by using the Boltzmann superposition principle,[8] the average shear stress in the adhesive resulting from a cure cycle of a prescribed temperature history can be evaluated numerically by breaking down the cure temperature history into small increments. The average shear stress in a cure cycle can be obtained from Eqs. (6–8) as

$$\bar{\tau}_{sr}(t) = \sum_{t'}\left[g(t')\left|e^{-\int_{t'}^{t}\frac{g(k)}{\eta(k)}\,dk}\right]\left(\frac{L}{2h_{ad}}\right)(\alpha_p - \alpha_{al})\,dT(t') \tag{9}$$

where dT is the temperature increment at the corresponding step of t'. In this study each time step was taken to be 60 s.

Curing-process induced stresses in laminated plates are usually evaluated through thermoelastic analysis using the laminated plate theory with a temperature drop ΔT_{eff}, which is defined as the temperature difference between the stress-free temperature and room temperature. In addition, it is also assumed in the analysis that the material properties of the laminate remain the same as those at room temperature. In determining the value of ΔT_{eff}, curvatures or/and residual strains of unsymmetric laminates resulting from curing stresses are measured.[3] It was shown in Ref. 3 that ΔT_{eff} is not affected by the dimensions and elastic properties of the aluminum panel and composite patches. It is obvious that using ΔT_{eff} makes it easy to provide the experimental correlation with the model prediction.

Using the conventional thermoelatic analysis in conjunction with the simple average shear model of Fig. 5, the thermal residual shear stress in the adhesive induced by a temperature drop after curing from the stress-free state is

$$\bar{\tau} = G_a\bar{\gamma} = G_a(L/2h_{ad})(\alpha_p - \alpha_{al})\Delta T_{eff} \tag{10}$$

where $\bar{\tau}$ and $\bar{\gamma}$ are the average shear stress and strain, respectively, and G_a is the shear modulus of the adhesive measured after curing. Comparing Eqs. (9) and (10), we obtain ΔT_{eff} as

$$\Delta T_{eff} = \sum_{t'}\left[g(t')e^{-\int_{t'}^{t}\frac{g(k)}{\eta(k)}\,dk}\right]dT(t')\Big/G_a \tag{11}$$

It is easy to see from Eq. (11) that ΔT_{eff} can be calculated for any given curing temperature history if $g(t)$ and $\eta(t)$ are known. In Eq. (11) g and η are to be expressed as functions of time. However, it is more convenient to determine g and η as functions of the degree of cure a of the adhesive. Subsequently, the degree of cure a can be obtained as a function of time by solving numerically the nonlinear cure kinetic model of Eq. (1) for any selected curing temperature history, that is,

$$a(t) = f[t, T(t)] \tag{12}$$

Then, the shear modulus and the viscosity can be expressed by

$$g(t) = g_a[a(t)], \qquad \eta(t) = \eta_a[a(t)] \tag{13}$$

where g_a and η_a are the shear modulus and the viscosity of the adhesive as functions of the degree of cure, respectively.

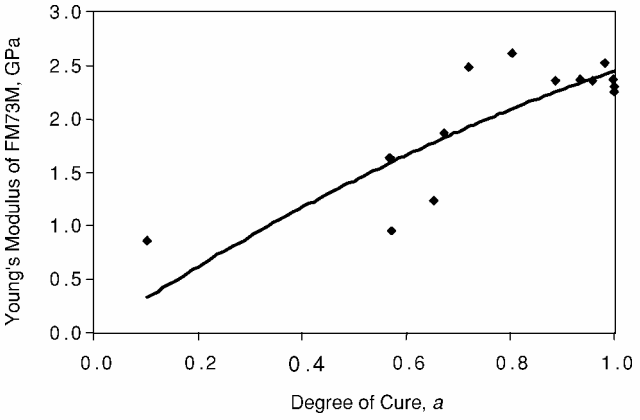

Fig. 6 Young's modulus vs degree of cure.

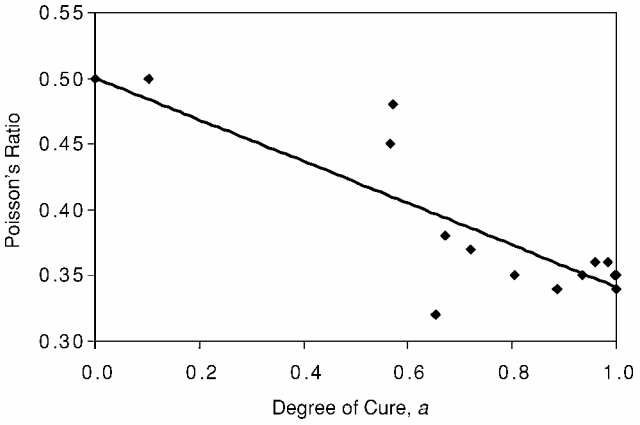

Fig. 7 Poisson's ratio vs degree of cure.

The shear modulus function g_a was obtained by measuring the Young's modulus and Poisson's ratio of a 10-layered FM73M coupon specimen of 25.4×203.2 mm in dimension. To relate the shear modulus to the degree of cure, specimens were cured with a number of one-step cure-temperature cycles based on the degree of cure calculated by the cure kinetic model. Quasi-static tensile tests were performed at room temperature with a strain rate of 10^{-4}/s. Longitudinal and transverse strains were measured in order to determine the Young's modulus and Poisson's ratio. The results are shown in Figs. 6 and 7, from which the following functions were obtained:

$$E = (-7.99 \times 10^{-1})a^2 + (3.25)a$$
$$\nu = (-1.86 \times 10^{-3})a^2 - (1.57 \times 10^{-1})a + 0.5 \tag{14}$$

Assuming isotropy, the shear modulus was obtained with respect to the degree of cure as

$$g_a(a) = \frac{E(a)}{2[1 + \nu(a)]} \quad \text{(GPa)} \tag{15}$$

The effective viscosity function $\eta_a(a)$ of the Maxwell model was determined from the relation provided by Eq. (11) with experimentally determined ΔT_{eff} with a one-step cure cycle of a composite patch/aluminum laminate specimen. However, because the functional form of $\eta_a(a)$ is not known a direct evaluation is not feasible. Instead, we made some simplifying assumptions based on physical phenomena and were able to simplify the integration involved in Eq. (11).

During the initial temperature rise period in a one-step cure cycle, the adhesive is assumed to flow, and no significant thermal stresses are produced. In the subsequent hold time during which there is no increase in temperature, stresses produced by cure shrinkage strains in the adhesive are considered to be small as compared to the

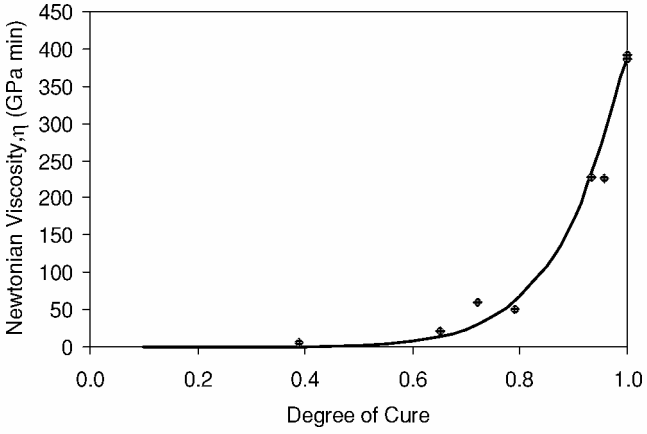

Fig. 8 Newtonian viscosity of the Maxwell model vs degree of cure.

stresses resulting from mismatch in thermal expansion. Meanwhile, the shear modulus and the viscosity of the adhesive develop during the hold time under a constant temperature. On the other hand, thermal residual stresses develop accompanied by stress relaxation in the adhesive layer once cooling begins. We further assume that the degree of cure of the adhesive does not change after cooling begins. Numerically, the preceding assumptions can be achieved by adopting a very small value for η for the period before cooling in Eq. (11) in order to annihilate the thermal stresses. As a result of the last assumption, $\eta_a(a)$ remains constant in the cooling period with the given degree of cure at the end of period of a constant cure temperature. Thus, $\eta_a(a)$ can be determined with the obtained $g_a(a)$ and the experimentally determined ΔT_{eff} from a one-step cure cycle using Eq. (11).

A one-sided patch repair was fabricated using a prescribed curing history. The 50.8 × 152.4-mm composite patch consisted of six unidirectional AS4/3501-6 composite plies. The carbon/epoxy composite patch was bonded to an uncracked 2024-T3 aluminum plate of 3.1 mm thick using the FM73M film adhesive. After the curing cycle the curvature of the specimen was measured and used in a thermoelastic analysis with the laminated plate theory. From this analysis the value of ΔT_{eff} corresponding to the cure cycle was determined.[3] The change of curvature was observed for three weeks to ensure that there was no significant stress relaxation in the specimen after bonding. For a given cure cycle, the degree of cure can be obtained from the cure kinetic model given by Eq. (1).

The viscosity $\eta_a(a)$ thus obtained is shown in Fig. 8 as a function of degree of cure. By the least-square curve fitting, the viscosity can be expressed in the form

$$\eta_a(a) = (3.89 \times 10^2)a^{7.8} \qquad (\text{GPa} \cdot \text{min}) \quad (16)$$

IV. Results and Discussion

The established model was used to predict ΔT_{eff} resulting from a number of two-step cure-temperature cycles. Table 3 lists both ΔT_{eff} determined empirically and predicted for several two-step cure cycles. It is seen that the predicted ΔT_{eff} are in fairly good agreement with the experimental results. Based on this model, ΔT_{eff} for other combinations of cure temperatures and cure times were predicted. The numerically predicted results are presented in Fig. 9. For practical interest the first step cure temperatures considered are 88, 82, and 77°C. For the second-step cure temperature, temperatures 121, 104, and 93°C, which are above the fully developed Tg[3] of 93°C, were initially considered. However, according to the cure kinetic model it was estimated that at 93°C it would require four hours to achieve 100% degree of cure with one-step cure-temperature cycle. Moreover, as seen in Table 3, the two-step cure cycle of 77°C/5 hr + 121°C/1 hr resulted in a higher level of thermal residual stresses than that of the 77°C/5 hr + 104°C/1 hr cycle. Consequently, in this study the temperature of 104°C was taken as an efficient second-step cure temperature in consideration of curing time and lowering thermal residual stresses.

Table 3 Comparison of ΔT_{eff} determined by experiment and model prediction

Two-step cure cycle	ΔT_{eff} experiment, °C	ΔT_{eff} prediction, °C
77°C/5 hr + 121°C/1 hr	−65	−66
77°C/5 hr + 104°C/1 hr	−61	−62
82°C/3.5 hr + 104°C/1 hr	−57	−61
82°C/4 hr + 104°C/0.5 hr	−53	−59
82°C/5 hr + 104°C/1 hr	−53	−59
88°C/3.5 hr + 104°C/1 hr	−62	−64
88°C/4 hr + 104°C/1 hr	−62	−64

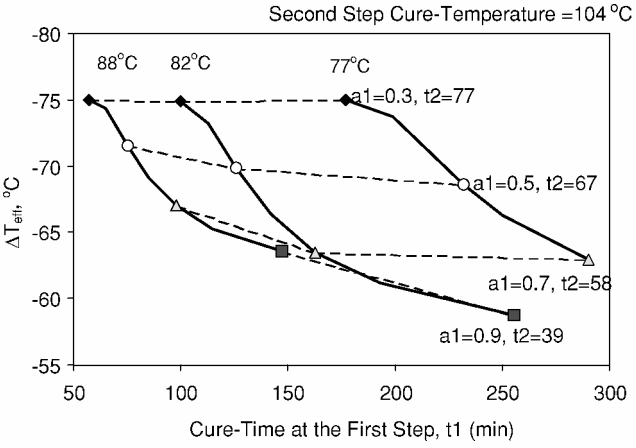

Fig. 9 Predicted ΔT_{eff} for two-step cure cycles with the second-step cure temperature at 104°C: a1, degree of cure after the first-step cure; t1 (min), cure time spent at the first-step cure; and t2, minimum cure time to achieve 100% degree of cure for the second step with 104°C. Temperatures 88, 82, and 77°C are the cure temperatures for the first step.

In Fig. 9 the horizontal axis indicates the cure time (t1) for the first-step cure. The symbol a1 in Fig. 9 denotes the degree of cure at the end of the first-step cure. For each of the first-step cure temperatures, the cure times (t1) for four different degrees of cure are marked with symbols: a diamond is for a1 = 0.3, a circle is for a1 = 0.5, a triangle is for a1 = 0.7, and a square indicates a1 = 0.9. The cure time required to complete the degree of cure after each a1 is denoted by the t2 shown next to it. As an example, consider the case of a cure cycle with the first cure temperature of 77°C. After 180 min under the first-step cure, the adhesive would achieve a 30% degree of cure. If the curing process stops at that point, the resulting residual stresses would correspond to $\Delta T_{\text{eff}} = -75$°C. To complete the cure at temperature 104°C would require 77 min after that. If the first-step cure under 77°C lasts for 230 min, then it would achieve a 50% cure. Another 67 min under 104°C afterward, the adhesive would be fully cured, and the corresponding ΔT_{eff} would be −67°C.

The curves in Fig. 9 can be used for selecting a two-step cure cycle. For example, the triangular symbol on the second curve indicates that $\Delta T_{\text{eff}} = -63$°C could be obtained from the two-step cure cycle of 82°C/160 min(t1) + 104°C/58 min(t2). One can also tell that the degree of cure at the end of the first-step cure is equal to 0.7. The results for other two-step cure cycles can be estimated by extrapolations.

Some interesting results can be observed from Fig. 9. It is seen that the first-step cure has negligible effect on ΔT_{eff} when $a1 < 0.3$ is chosen at the end of the first-step cure. To get any benefit from the two-step cure cycle, the degree of cure during the first-step cure must be larger than 0.3. In general, higher degrees of cure achieved in the first-step cure leads to lower thermal residual stresses at the expense of longer curing times.

V. Summary

In the study a cure kinetic model for FM 73M film adhesive used for bonding composite patch repairs has been established using

differential scanning calorimetry tests. Thermal residual stresses in composite patch repairs were predicted by modeling the viscoelastic response of the adhesive during the cure cycle with the aid of the cure kinetic model. Stress relaxation in the adhesive during the curing cycle was described with the Maxwell model and the average shear stress and strain in the adhesive were used in the formulation. The shear modulus and Newtonian viscosity of the adhesive were experimentally determined as functions of the degree of cure. The model predictions of thermal residual stresses in a composite patched specimen for several two-step cure cycles were in fairly good agreement with experimental data. This procedure has been used to establish a diagram for selection of efficient two-step cure cycles.

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