A Numerical Approach for Modelling of Polymer Curing in Fibre Reinforced Composites

Joshi, Sunil Chandrakant; Liu, X. L.; Lam, Yee Cheong

1999

Joshi, S. C., Liu, X. L., & Lam, Y. C. (2015). A numerical approach to the modeling of polymer curing in fibre-reinforced composites. *Composites Science and Technology*, 59(7), 1003-1013.

<https://hdl.handle.net/10356/80835>

[https://doi.org/10.1016/S0266-3538\(98\)00138-9](https://doi.org/10.1016/S0266-3538(98)00138-9)

© 1999 Elsevier. This is the author created version of a work that has been peer reviewed and accepted for publication by *Composites Science and Technology*, Elsevier. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [[http://dx.doi.org/10.1016/S0266-3538\(98\)00138-9](http://dx.doi.org/10.1016/S0266-3538(98)00138-9)].

Downloaded on 26 Apr 2023 21:31:41 SGT

A NUMERICAL APPROACH FOR MODELING OF POLYMER CURING IN FIBRE REINFORCED COMPOSITES

Joshi S.C.^{*}, Liu X.L., Lam Y.C.[#]

*Department of Mechanical Engineering, Monash University, Clayton Campus, Melbourne, Victoria
3168, Australia.*

*Cooperative Research Centre for Advanced Composite Structures, Fishermens Bend, Melbourne,
Victoria 3207, Australia.*

*[#]School of Mechanical & Production Engineering,
Nanyang Technological University, Singapore 639 798*

Abstract

This paper presents a procedure for using a general-purpose finite element package for cure modeling. In this procedure, a general-purpose finite element package is employed to carry out transient heat transfer analysis and two user programs are developed to simulate resin cure kinetics using nodal control volumes based on the finite element mesh. Theoretical background and numerical implementation of the procedure is described. Its stability with respect to the finite element mesh density and the length of the time step employed is investigated. Application of the procedure is demonstrated by modeling the curing of a thick prepreg laminate, a honeycomb sandwich panel and an I-beam. Predicted temperature profiles in the thick laminate are in excellent agreement with available experimental data.

Key Words: Polymer-matrix composites (A), Curing (B), Computational simulation (C), Finite element analysis (C), Nodal Control Volume

^{*}To whom correspondence be addressed.

1 INTRODUCTION

The manufacturing of fibre reinforced polymer composite parts is complex, requires special environment and can be costly to control. This is because a composite consists of two different material systems, namely the fibre and matrix systems. Most commonly used fibres are glass, aramid, boron and graphite while the matrices are generally thermosetting resins.

The successful production of a composite part depends upon the selection of the tooling, other auxiliary materials and, a proper cure cycle that leads to uniform curing and compaction. The curing of thermosetting resins is an exothermic reaction. Temperature profiles in the curing part depend upon not only the amount of heating power supplied to the tool but also the amount of heat generated by the resin cure reaction. The generated heat is a function of the total mass fraction of resin in the mould and the resin system used. The exothermic reaction associated with a low thermal conductivity of the resin might lead to excessively high localised temperatures in the part. This results in a non-uniform state of cure and an increase in the thermal residual stresses leading to degradation of the matrix¹⁻³. One requires knowledge of a gel point and gelation time of the resin system to effectively apply the compaction pressure. It is, therefore, necessary to study the curing of a component along with a chosen tooling assembly to obtain an optimum cure cycle.

Such studies can be performed effectively by numerical modeling, for it is more general and applicable to a wider range of problems than analytical solutions. Also the physical experiments are expensive, prone to errors and time-consuming.

For thermosetting resins, the degree of cure, the rate of reaction heat generation and the temperature are interdependent. Hence the numerical modeling of the resin cure requires an iterative procedure that couples reaction kinetics of the resin with transient heat transfer analysis. A suitable integration scheme has to be selected also for the interdependency of the above-mentioned parameters within a chosen time

step.

Different researchers have developed special-purpose numerical softwares to study resin cure process. Lee and Springer⁴ presented a one-dimensional analytical cure model for prepreg composites. A finite difference cure modeling program based on this model⁵ can analyse also the tool and the bagging. This program uses implicit method to calculate the degree of cure and, therefore, a time step of half a second or less was recommended for heat transfer calculations. Kim et. al.⁶ used an alternating direction explicit finite difference method to trace the cure front of the continuously laid prepreg composites in one-dimension. Bogetti and Gillespie Jr.⁷, modelled the curing of two-dimensional thick composites using boundary fitted co-ordinate systems with finite difference solution technique. The solution was reported to be mesh dependent. Loos and MacRae⁸ developed a special two-dimensional finite element software to simulate the resin film infusion process which also includes curing. Young⁹ developed a finite element code with six-noded wedge elements to model non-isothermal mould filling in resin transfer moulding process. In the subsequent work, he¹⁰ included the effects of heat transfer in the mould. He used finite difference technique, and solved the heat transfer in the mould and the non-isothermal flow in the cavity as separate problems using the output from one as boundary conditions for the other.

Even though many general-purpose finite element packages have a facility to perform transient heat transfer analysis, all of them do not have the facilities for resin cure simulation. However, if a general-purpose finite element package can be used for cure modeling, it has the obvious advantage that it is widely available, with well developed pre- and post-processor.

A procedure by which a general-purpose finite element package can be employed to perform cure modeling is presented in this paper. The theoretical background and numerical implementation of the procedure is described. Application of the procedure is demonstrated by modeling the cure of a thick graphite epoxy prepreg laminate, with and without considering the effect of three-dimensional heat

transfer. General-purpose finite element software LUSAS was used to perform transient heat transfer analysis and two user programs were developed to simulate resin cure kinetics using nodal control volumes based on the finite element mesh. The results obtained were in excellent agreement with the available experimental data. To highlight the versatility of the procedure, cure simulation of another two components is also presented.

2 THEORETICAL BACKGROUND

2.1 Governing equations

For simplicity, a situation where the resin is more or less evenly distributed in the lay-up and the convective heat transfer effect caused by the resin flow is negligible was considered. A compacted prepreg lay-up and a fully impregnated preform in resin transfer moulding (RTM) process are typical examples of it. It is assumed that the laminate geometry and the resin mass content remain constant. This is true with RTM processing. In the prepreg process, most of the compaction is completed when the resin is at its minimum viscosity and the curing is at its early stages. Little variation in the resin content and the thickness is expected beyond this point. It is also assumed that the resin and fibres are at the same temperature at all the time and form a macroscopically homogeneous material system for heat transfer purpose. Under these assumptions, the energy equation governing heat transfer¹¹ in the curing product is simplified as

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial T}{\partial z} \right) + \frac{\partial Q}{\partial t} = \rho_c c_{pc} \frac{\partial T}{\partial t} \quad (1)$$

Where ρ_c , C_{pc} , and $K_i (i = x, y, z)$ are lumped density, specific heat and thermal conductivity of the lay-up material in three orthogonal directions respectively and may be determined using the rules of mixture^{5,9}.

The internal heat generation source term $\frac{\partial Q}{\partial t}$ represents an exothermic effect of the resin reaction. By

ignoring the effect of resin flow on the species, the term is directly related to the rate of cure by an equation

$$\rho_c \frac{dQ}{dt} = \rho_r V_r Q_i \frac{d\alpha}{dt} \quad (2)$$

Where, α is the degree of cure which is defined as the ratio of the heat released to the total heat of reaction, Q_i is the heat of reaction per unit mass of resin, v_r is the resin volume fraction, ρ_r is the density of the resin and $\frac{d\alpha}{dt}$ is the rate of cure reaction.

2.2 Cure reaction kinetics

The reaction kinetics of a resin system can be determined by a Differential Scanning Calorimeter (DSC) experiment. Experimental data obtained from DSC is usually fitted into a semi-empirical model representing the rate of cure as a function of temperature and the degree of cure. One of the frequently used and the simplest model is the following Arrhenius relation^{5-7, 12}

$$\frac{d\alpha}{dt} = f(T, \alpha) = B(1 - \alpha)^c \exp(-\Delta E / RT) \quad (3)$$

Where R is the universal gas constant, T is the absolute temperature, B , ΔE and c are material constants to be determined experimentally. As reported by Vodicka⁵, in some cases it is more accurate to fit the data by two Arrhenius equations as

$$\frac{d\alpha}{dt} = \begin{cases} B_1(1 - \alpha)^{c_1} \exp(-\Delta E_1 / RT) & \alpha \leq A \\ B_2(1 - \alpha)^{c_2} \exp(-\Delta E_2 / RT) & \alpha > A \end{cases} \quad (4)$$

It is evident from eqn (4) that $\frac{d\alpha}{dt}$ and α vary continuously with time. Such a variation can be numerically modelled by assuming that T is constant at a sampling point within a small time increment Δt . A suitable integration scheme can be then used to evaluate $\Delta \alpha$ over a chosen Δt . The following two schemes have been commonly used by different researchers: the forward integration scheme and

Vergnaud's integration scheme.

2.2.1 Forward integration scheme

This scheme is easy to use and is independent of the form of the equation. It has been used by Bogetti and Gillespie Jr.⁷, Loos and MacRae⁸, Young^{9,10}, Advani¹⁴ and Burkhardts¹⁵. Using this scheme, the integral of eqn (3) or eqn (4) can be evaluated approximately as

$$\alpha_i = \alpha_{i-1} + \Delta t \cdot \frac{d\alpha_i}{dt} \quad (5)$$

Success of the scheme depends upon the maximum number of iterations allowed and the length of the time step employed. The most accurate way is to use the value of α evaluated at the end of the previous time step as the first approximation for α at the present time step. Temperature is obtained subsequent to the evaluation of $\frac{d\alpha}{dt}$ and $\frac{dQ}{dt}$. α is then re-evaluated based on the new value of temperature. This iteration loop is performed until the convergence requirement for T is met.

2.2.2 Vergnaud's integration scheme

The scheme was suggested by Vergnaud¹² and later on, used successfully by Brouzi et. al.¹³. This integration procedure is presented below.

With $B_T = B \exp(-\Delta E / RT)$, eqn (3) or eqn (4) can be re-written as

$$\frac{1}{(1-\alpha)^c} d\alpha = B_T dt \quad (6)$$

Integration of eqn (6) produces

$$\alpha = 1 - [1 + (c-1)S]^{\frac{1}{1-c}} \quad (c \neq 1) \quad (7)$$

Where S is the integral

$$S = \int_{t_0}^t B_T dt = B \int_{t_0}^t \exp(-\Delta E / RT) dt \quad (8)$$

Adopting an explicit scheme, the integral can be evaluated approximately as

$$S_t = S_{t_0} + B \exp(-\Delta E / RT_{t_0}) \Delta t \quad t \in [t_0, t_0 + \Delta t] \quad (9)$$

Once S is evaluated for a time step, α , $\frac{d\alpha}{dt}$ and $\frac{dQ}{dt}$ can be calculated using eqns (7), (4) and (2) respectively. Since the scheme uses a better approximation for integration than the previous scheme, it is expected to give better results. However, this scheme cannot be used when the cure kinetics model is too complex for integration.

3 NUMERICAL IMPLEMENTATION

Section 2 establishes that cure modeling may be considered as a transient heat transfer analysis by taking into account the effect of the resin cure reaction. Numerically, it can be divided into two sub-tasks: formulation and solution of the heat transfer equations, and simulation of the cure kinetics. Although most of the general-purpose finite element packages can be used to perform the first sub-task, all of them do not provide facility to evaluate the cure kinetics. A versatile and flexible solution procedure, which makes it possible to use such a general-purpose finite element package to perform the cure analysis of the practical components, is discussed below.

3.1 Solution procedure

A procedure is proposed in which a general-purpose finite element package is employed to perform transient heat transfer analysis and two user programs are developed to simulate the cure reaction using nodal control volumes based on a finite element mesh. Fig. 1 provides the flow chart of the procedure.

The available pre-processor to the finite element package is used to create a finite element model and to generate the initial input data file for the analysis.

User program - A is written to calculate nodal control volumes from the finite element mesh of the curing components. A routine is also included to define a cure kinetics model of the resin system from

the user-supplied parameters. Swap files are created in one of the directories in a hard disk to store the data required for the further analysis.

A user batch file, running in automated mode, is written for the calculation of heat transfer analysis and to simulate the cure kinetics. It consists of two steps -

- I. First, the finite element heat transfer analysis is performed and the temperature field is obtained.
- II. Subsequently, user program - B is activated to simulate the cure kinetics and to evaluate the degree and rate of cure reached in each of the control volumes. The rates of internal heat generation for all the nodal control volumes are calculated from the rates of cure. These are then applied as heat sources at the respective nodal points for the finite element transient heat transfer analysis for the next time step. Results are written onto the output file for user's reference. Irrespective of the state of the cure, the swap files are updated and the input data file for the analysis of the next time step is prepared. This makes it easy to stop and restart the analysis at any time step.

The execution of the general-purpose finite element package and user program - B is repeated until the completion of the cure cycle.

Both the user programs were written using a programming language FORTRAN 77 and a batch file was written in PC-DOS environment.

3.2 Numerical evaluation of nodal heat sources

The major computation involved in user program - B is the evaluation of the equivalent nodal heat sources derived from the cure reaction. In this paper, the evaluation is conducted based on the finite element nodal control volumes.

A control volume is a volume over which the parameters such as temperature, pressure, etc., are assumed to be constant. In this technique, initially sub-control volumes are created by connecting the

centroid of a finite element to the center-points of its surfaces. The boundary of each sub-control volume contains only one finite element node and that sub-control volume is assumed to be linked to that particular node. In this way, all the sub-control volumes surrounding the node form a nodal control volume; see Fig. 2 that illustrates the construction of control volume ‘ j ’.

The resin content of the control volume j can be determined as

$$V_r^j = V^j f_r^j \quad (10)$$

Where, V_r^j is the resin content of control volume j , V^j is the volume of control volume j calculated using the geometric data available from the finite element mesh and, f_r^j is a resin volume fraction.

Total heat generated in the control volume j is

$$Q^j = Q_t \rho_r V_r^j \frac{d\alpha^j}{dt} \quad (11)$$

This is then applied as a lumped heat source at nodal point j .

4 CASE STUDIES

In order to validate the procedure and to test its versatility, the following cases were analysed.

- Case 1 - Autoclave curing of the thick graphite epoxy laminate with (three-dimensional) and without (one-dimensional) considering the tool-edge effects.
- Case 2 - Fabrication of the honeycomb sandwich panel with graphite epoxy face skins (one-dimensional).
- Case 3 - Curing of the graphite epoxy I-beam with aluminium block moulds (two-dimensional) in an autoclave environment.

4.1 Problem definitions

The laminate under consideration for case 1 consisted of 140 plies of 0.1651 mm thick, AS4/3501-6, graphite epoxy prepreg arranged in $[0/90]_s$ sequence. The bagging consisted of one layer of release film, two of breathers and one of nylon. The geometric details of the fabrication assembly are presented in Fig. 3. The properties of the prepreg, as given in Table 1, were calculated using rules of mixture⁵ based resin volume fraction of 0.36. Reaction kinetics of Hercules 3501-6 resin system was expressed by eqn (4); table 2 lists the value of the parameters in the equation. A heat transfer coefficient of $85 \text{ W/m}^2\cdot\text{K}$ was used between the autoclave air and either the tool or the bagging materials. The same fabrication assembly and the parameters were used by Vodicka⁵, the results of which were used to validate the present procedure.

In three-dimensional heat transfer analysis, it is necessary to provide thermal conductivity of the material in three orthogonal directions. A orthotropic-material-definition card is provided in a general-purpose finite element package for this purpose. However, since no data was available, it was assumed that the resin was uniformly distributed in the whole laminate and the resin volume fraction was same (0.36) in all the directions. This resulted in a same thermal conductivity in all the three directions (ie., $K_x = K_y = K_z$), when calculated using the rule of mixture⁵. However, this does not affect the presented cure modeling approach and its numerical implementation. To demonstrate this, the orthotropic-material-definition card was used to define these values in three-dimensional cure modeling of the laminate.

The geometric details of the fabrication set-up for the sandwich panel (case 2) and the I-beam (case 3) are given in Fig. 4 and Fig. 5 respectively. The same prepreg lay-up (but with different thicknesses) as the laminate was used for the face skins of the sandwich panel and for the I-beam. Nomex honeycomb was used as a core in the sandwich panel. The tooling and bagging materials, the resin system and the convective heat transfer coefficients were the same as for the laminate. Physical properties of the tooling, core and bagging materials are given in Table 1.

The adopted one-stage autoclave temperature cycle for the laminate and the I-beam as well as the two-stage temperature cure cycle for the honeycomb sandwich panel are presented in Fig. 6.

4.2 Finite element models

In order to investigate the effect of mesh density on the results, one-dimensional models of the laminate fabrication assembly for case 1 were created using different number of 4-noded quadrilateral field elements. One of the models is shown in Fig. 7. For the three-dimensional model, only a quarter of the laminate fabrication assembly was necessary due to two planes of symmetry. The three-dimensional model consisted of 210 (49 for the tool, 80 for the laminate and 81 for the bagging), 8-noded solid field elements and is presented in Fig. 8. For case 2, the honeycomb sandwich panel, a total of 80 linear quadrilateral field elements (10 for the tool, 20 for each of the face skins and the core, and 10 for the bagging layer) were used as shown in Fig. 9. For case 3, the I-beam, only one quarter of the fabrication set-up was modelled due to two planes of symmetry, as shown in Fig. 10, using 260 of linear quadrilateral field elements.

5 RESULTS AND DISCUSSIONS

5.1 Case 1 - Modeling of the laminate fabrication assembly

One-dimensional transient thermal analysis was first carried out using a general-purpose finite element package without accounting for the effect of exothermic cure reaction. The finite element model shown in Fig. 7 was used. The heat transfer was allowed only from two surfaces: the bottom surface of the tool and the top surface of the bagging. The results are shown in Fig. 11 along with the available

experimental data⁵. At the maximum cure temperature, a temperature overshoot of more than 25°C was observed from the experimental results. Such a high temperature difference can be attributed to the effect of the heat released during the resin cure. This highlights the need for cure modeling to be conducted for thick laminate.

In practice, the tool is designed slightly larger than the component to be fabricated to get sufficient space for vacuum bagging and sealing operation. In the central region, fabrication set-up resembles the one as shown in Fig. 3. Usually, one-dimensional modeling is enough to correctly predict the cure profile in this region. However, exposed edges of the tool are likely to have heat transfer to and from the curing component and affect the uniformity of the cure in the component. These effects can be only predicted in three-dimensional modeling. Therefore, the problem was modelled both in one-dimension and three-dimensions.

Since the three-dimensional analysis is computationally expensive, it was decided to choose an integration scheme requiring no more than one iteration. With this criterion, Vergnaud's integration scheme was found to be accurate within 1% and was employed for the present computational scheme.

5.1.1 One-dimensional cure modeling

The one-dimensional cure modeling of the laminate was carried out using the present procedure under the same computational conditions as the transient heat transfer analysis. In order to study the stability of the procedure, different number of elements and different time increments were used. Fig. 12 and Fig. 13 illustrate the respective temperature responses in the central lamina of the laminate. Little variations with respect to mesh density and time increment were observed. This suggests that the results were not sensitive to both the mesh density and the size of time increment employed. Therefore, the results obtained with a 40-element mesh and a 30 seconds time step were used in the subsequent studies.

To validate the present procedure, the one-dimensional package CURE^{4,5} was used to model the same problem. As CURE uses a finite difference solution technique, a line model with the same number of elements as the finite element model was used. A time step of 0.5 seconds was selected to achieve the desired accuracy. The temperature results for the central layer by CURE and the present procedure were compared with the available experimental data⁵; see Fig. 14. The predicted temperature responses by both the numerical procedures were in good agreement with the experimental results. However, the results obtained by the present procedure followed the experimental response more closely during the temperature overshoot. The maximum temperature predicted by the present model and CURE was 207.1°C and 210.7°C respectively while the experimental value was 205.6°C.

The information on the degree of cure α is presented in Fig. 15. Very negligible cure ($\alpha \leq 0.0013$) was observed during the first 80 minutes. At this initial stage of the cure cycle, autoclave temperature was held at 55°C to allow the temperature in the tooling set-up to homogenise. Significant solidification was observed from 126.5 minute. The degree of cure at the central lamina reached a value of 0.6 (approximate gel point)⁵ at about 138.0 minute and 0.95 at 156.5 minute, see Fig. 15. Even though the chosen temperature cycle was effective in completing the cure, the temperature overshoot needs to be controlled.

5.1.2 Three-dimensional cure modeling

Since very negligible cure was observed during the first 80 minutes of cure cycle in one-dimensional simulation, that segment of the cure cycle was ignored in three-dimensional analysis for saving in computational efforts. Fig. 16 compares the temperature responses at the centre of the laminate predicted by one-dimensional and three-dimensional simulations. The two predictions match well, giving the highest temperature of 207.1°C and 207.0°C respectively. The temperature predicted by one-dimensional analysis had a slower rate of decrease after the temperature overshoot as compared to the three-dimensional results. The reason is that in one-dimensional analysis, heat could only dissipate

from the top and bottom surfaces, while in three-dimensional analysis additional dissipation occurred from the edges.

The temperature contours in the central lamina, obtained from the three-dimensional analysis, at two different times are illustrated in Fig. 17. At the early stage of curing, there was little reaction and heat was transferred from the autoclave air into the laminate through the tooling-air interface. Therefore, as seen from Fig. 17(a), temperatures at central locations were lower than those at the positions close to the interface. In the later stage of the cure cycle, significant exothermic effect of curing caused higher temperature in the laminate than that of the autoclave air. This resulted in a dissipation of heat from the laminate to the air. The phenomenon may be observed from Fig. 17(b), which shows a decreasing trend in temperature from the centre of the laminate to the interface. Maximum temperature difference observed in the plane of central lamina was 12°C.

Fig. 18 shows the temperature distribution in the thickness direction at 139 minutes. Since the bagging layer has a comparatively low thermal conductivity, dissipation of heat was difficult from the top surface. It resulted in a temperature difference of about 20°C in the thickness direction and affected the uniformity of cure. Fig. 19 gives the distribution of α at the corresponding sections. About 10% difference in α was observed from the bottom layer to the top of the laminate at these sections.

The non-uniform distribution in temperatures and the degree of cure indicates that the tool-edge and the bagging effects were significant in this set-up.

5.2 Case 2 - Modeling of the honeycomb sandwich panel

The temperature distribution in the top and the bottom face skins of the panel was almost the same as that of the autoclave temperature cycle; see Fig. 20. No exothermic effect was observed.

Fig. 21 presents the variation in the degree of cure with time. The rate of cure observed was moderate. This indicates uniform heat transfer to the part from the surrounding and negligible effect on

temperature by the exothermic reaction. Because of the relatively thin composite face skins, the amount of heat of reaction was comparatively small. It appears that the iso-thermal hold at 125°C allowed the heat from exothermic reaction to dissipate without raising the temperature levels. Nevertheless, this example demonstrates the capability of the present procedure in modeling more than one curing part simultaneously.

5.3 Case 3 - Modeling of the I-beam fabrication assembly

The distribution of temperature and the degree of cure α over the two-dimensional cross section of the I-beam is shown in Fig. 22 and Fig. 23 respectively. Variation in both the parameters was quite uniform over the section. It indicates that even heating was achieved.

As seen from Fig. 24, the gel point ($\alpha \approx 0.6$) reached after 75 minutes and complete cure ($\alpha \geq 0.95$) occurred after 150 minutes from the starting of the isothermal hold. Such a slow rate of cure may be attributed to both the large thermal mass of the tool and the inefficient cure cycle and indicates the need for modifications in the design of the tool.

6 CONCLUSIONS

A procedure is developed in employing a general-purpose finite element package for cure modeling of composite manufacturing. Thus, the costly development of a numerical cure analysis program can be avoided. The procedure was successfully used in simulating the curing of different composite components. From the results obtained, it can be concluded that

1. The procedure is numerically stable and produces accurate results.
2. The procedure can make use of all the features pertaining to a commercial finite element package. It can be employed to perform three-dimensional cure modeling. It can handle cure simulation of

complicated components such as the I-beam. It also supports simultaneous cure simulation of more than one laminate, as required in the case of sandwich construction.

3. The transient temperatures in the part not only depend upon the curing component, but also the fabrication assembly as a whole. The study of the curing process using a complete fabrication assembly is, therefore, essential to judge the quality of the end product. The present procedure provides a versatile numerical tool for such studies.

ACKNOWLEDGMENTS

Various supports from the Cooperative Research Centre for Advanced Composite Structures Limited (CRC-ACS), Australia, are appreciated. The financial assistance by Monash University, CRC-ACS and the Australian Government to the first author in the form of research scholarships is gratefully acknowledged.

REFERENCES

1. Choi, J.H. and Lee, D.G., Expert Cure System for the Carbon Fiber Epoxy Composite Materials, *J. Comp. Mater.*, 1995, **29**, 1181-1200.
2. White S.R., Hahn H.T., Cure cycle Optimisation for the Reduction of Processing-Induced Residual Stresses in Composite Materials, *J. Comp. Mater.*, 1993, **27**, 1352-137.
3. Joseph B., Hanratty W. and Kardos J.L, Model Based Control of Voids and Product Thickness during Autoclave Curing of Carbon /Epoxy Composite Laminates, *J. Comp. Mater.*, 1995, **29**, 1000-1023.
4. Lee W.I., Springer G.S., Curing of Epoxy Matrix Composites, *J. Comp. Mater.*, 1983, **17**, 135-169.

5. Vodicka R. and Evans N., User's Manual for Cure, A Computer Simulation of the Autoclave Curing Process for Composite Lay-Up, *CRC-AS report*, restricted circulation, 1994.
6. Kim C., Teng H., Tucker C. III, The Continuous Curing Process for Thermoset Polymer Composites. Part 1: Modeling and Demonstration, *J. Comp. Mater.*, 1995, **29**, 1220-1253.
7. Bogetti T.A. and Gillespie Jr. J.W., Two-dimensional Cure Simulation of Thick Thermosetting Composites, *J. Comp. Mater.*, March 1991, **25**, 239-273.
8. Loos A.C., MacRae J.D., A Process Simulation Model for the Manufacture of a Blade-stiffened panel by the Resin Film Infusion Process, *Comp. Sci. Technol.*, 1996, **56**, 273-289.
9. Young W.B., Three-dimensional Non-isothermal Mould filling Simulations in Resin Transfer Moulding, *Polym. Comp.*, April 1994, **15**, 118-127.
10. Young W.B., Thermal Behaviour of the Resin and Mold in the Process of Resin Transfer Molding, *J. Reinf. Plastics Comp.*, April 1995, **14**, 310-332.
11. Huang H.C. and Usmani A.S., *Finite Element Analysis for Heat Transfer: Theory and Software*, Springer - Verlag, London, 1994, 13-14.
12. Vergnaud J.M. and Bouzon J., *Cure of Thermosetting Resins: Modelling and Experiments*, Springer - Verlag, London, 1992, 105-107.
13. Brouzi A.E., Dursaprt M. and Vergnaud J.M., Simultaneous Determination of Torque and State of Cure of a Thermoset Composite by Experiment and Modelling of the Process, *Plastics, Rubber and Composites Processing and Applications*, 1991, **15**, 3-18.
14. Advani S.G., Bruschke M.V. and Parnas R.S., Resin Transfer Moulding in Flow phenomenon in Polymeric Composites, *CCM Report 92-48*, Centre for Composite Materials, Dept. of Mechanical Engineering, University of Delaware, 1992.
15. Burkhard F., Modelling of Three-dimensional Flow Fields in Injection and RTM, *CCM Report 93-06*, Centre for Composite Materials, Dept. of Mechanical Engineering, University of Delaware, 1993.

FIGURES

Fig. 1. Flow chart of the present cure modeling procedure.

Fig. 2. Nodal control volume based on finite element mesh.

Fig. 3. Cross-section of a 140 layer, AS4/3501-6, graphite epoxy, prepreg laminate fabrication assembly.

Fig. 4. Sectional details of the honeycomb sandwich panel.

Fig. 5. Transverse section of the tooling set-up for the I-Beam fabrication.

Fig. 6. Autoclave temperature cycles.

Fig. 7. One-dimensional finite element model of the laminate fabrication assembly.

Fig. 8. Three-dimensional outline model of a quarter of the fabrication assembly for laminate.

Fig. 9. One-dimensional finite element model of the fabrication assembly of a honeycomb sandwich panel.

Fig. 10. Finite element model of a quarter of the fabrication set-up for the graphite epoxy I-Beam.

Fig. 11. Difference between temperature responses at the central lamina of the laminate ($Y=0.0246\text{m}$) obtained by transient heat transfer analysis and the available experimental data (one-dimensional simulation).

Fig. 12. Temperature response at the central lamina of the laminate ($Y=0.0246\text{m}$) showing effect of the mesh density (one-dimensional simulation with 30 seconds time increment).

Fig. 13. Temperature response at the central lamina of the laminate ($Y=0.0246\text{m}$) showing effect of different time steps (one-dimensional simulation with the 40 finite elements mesh).

Fig. 14. Temperature response at the central lamina of the laminate ($Y=0.0246\text{m}$) obtained by different methods (one-dimensional simulation).

Fig. 15. Degree of cure at the central lamina of the laminate ($Y=0.0246\text{m}$) vs. time (one-dimensional simulation).

Fig. 16. Temperature response at the central lamina of the prepreg laminate ($Y=0.0246\text{m}$) by one-dimensional and three-dimensional cure modeling using present procedure.

Fig. 17. Temperature contours in the central lamina of the prepreg laminate (X-Z section at $Y=0.0246\text{m}$).

Fig. 18. Temperatures in the prepreg laminate after 139 minutes of curing.

Fig. 19. Degree of cure profiles in the prepreg laminate after 139 minutes of curing.

Fig. 20. Temperature at the center of face skins of the honeycomb sandwich panel (one-dimensional simulation).

Fig. 21. The state of cure at the center of face skins of the honeycomb sandwich panel (one-dimensional simulation).

Fig. 22. Temperature distribution in the I-beam fabrication assembly after 140 minutes of curing (two-dimensional simulation).

Fig. 23. The state of cure of the I-beam after 140 minutes of curing (two-dimensional simulation).

Fig. 24. Temperature and degree of cure vs. time plots obtained at the end of the extreme flange (ie. at X=77.15 mm, Y=48.14 mm) of the I-Beam (two-dimensional simulation).

TABLES

Table 1. Material Properties.

Table 2. Values of cure kinetics model parameters for Hercules 3501-6 resin system.

Fig. 1. Flow chart of the present cure modeling procedure.

Fig. 2. Nodal control volume based on finite element mesh.

Fig. 3. Cross-section of a 140 layer, AS4/3501-6, graphite epoxy prepreg laminate fabrication assembly.

Fig. 4. Sectional details of the honeycomb sandwich panel.

Fig. 5. Transverse section of the tooling set-up for the I-Beam fabrication.

Fig. 6. Autoclave temperature cycles.

Fig. 7. One-dimensional finite element model of the laminate fabrication assembly.

Fig. 8. Three-dimensional outline model of a quarter of the fabrication assembly for the laminate.

Fig. 9. One-dimensional finite element model of the fabrication assembly of a honeycomb sandwich panel.

Fig. 10. Finite element model of a quarter of the fabrication set-up for the graphite epoxy I-Beam

Fig. 11. Difference between temperature responses at the central lamina of the laminate ($Y=0.0246m$) obtained by transient heat transfer analysis and the available experimental data (one-dimensional simulation).

Fig. 12. Temperature response at the central lamina of the laminate ($Y=0.0246\text{m}$) showing effect of the mesh density (one-dimensional simulation with 30 seconds time increment).

Fig. 13. Temperature response at the central lamina of the laminate ($Y=0.0246\text{m}$) showing effect of different time steps (one-dimensional simulation with the 40 finite elements mesh).

Fig. 14. Temperature response at the central lamina of the laminate ($Y=0.0246\text{m}$) obtained by different methods (one-dimensional simulation).

Fig. 15. Degree of cure at the central lamina of the prepreg laminate ($Y=0.0246\text{m}$) vs. time (one-dimensional simulation).

Fig. 16. Temperature response at the central lamina of the prepreg laminate ($Y=0.0246m$) by one-dimensional and three-dimensional cure modeling using present procedure.

a. after 99 minutes of curing

b. after 139 minutes of curing

Fig. 17. Temperature contours in the central lamina of the prepreg laminate (X-Z section at $Y=0.0246\text{m}$).

Fig. 18. Temperatures in the prepreg laminate after 139 minutes of curing.

Fig. 19. Degree of cure profiles in the laminate after 139 minutes of curing.

Fig. 20. Temperature at the center of the face skins of the honeycomb sandwich panel (one-dimensional simulation).

Fig. 21. The state of cure at the center of the face skins of the honeycomb sandwich panel (one-dimensional simulation).

Fig. 22. Temperature distribution in the I-beam fabrication assembly after 140 minutes of curing (two-dimensional simulation).

Fig. 23. The state of cure of the I-beam after 140 minutes of curing (two-dimensional simulation).

Fig. 24. Temperature and degree of cure vs. time plots obtained at the extreme end of the flange (ie. at X=77.15 mm, Y=48.14 mm) of the I-Beam (two-dimensional simulation).

Table 1. Material Properties

Material	Aluminium	AS4/ 3501-6 graphite epoxy prepreg	Nomex honeycomb	Bagging
Density (kg/m ³)	2692.1	1555.0	192.3	355.6
Specific Heat (J/kg. K)	916.9	909.0	1226.7	1256.0
Conductivity (W/m. K)	216.3	0.556	0.203	0.069

Table 2. Values of cure kinetics model parameters for Hercules 3501-6 resin system

$Q_t(\text{J/kg})$	A	B_1	B_2	$\Delta E_1 (\text{J/mol})$	$\Delta E_2 (\text{J/mol})$	c_1	c_2
3.8×10^5	0.18	3.49×10^8	2.53×10^5	9.48×10^5	7.34×10^5	10	1.2