Virtual Modeling of The Curing Process of Composite Aerospace Components Using Coupled Multiphysics Models

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Abstract. This work presents a multifield simulation approach using a higher-order one-dimensional model derived within the Carrera Unified Formulation framework to assess the impact of curing on the composite part's performance. The proposed approach enables coupled thermo-chemo-mechanical simulation and the simultaneous evaluation of temperature, degree of cure, process-induced deformations, and residual stresses in time and space. The advantage of this model is that it can generate a three-dimensional representation of the part while keeping computational cost low. Typical composite configurations in the aeronautical field, such as sandwich and stiffened structures, are analyzed. The results demonstrate the capability of the present numerical tool to simulate the behavior of the composite part during the process.

Introduction

The growing use of composite materials in the aerospace industry, owing to their excellent mechanical properties and high strength-to-weight ratio, has generated considerable interest in their curing processes. The complexity of the process and the stringent manufacturing specifications required to achieve high product quality have necessitated numerical modeling for the accurate and rapid study of the thermo-chemo-mechanical behavior of the composite part [1]. In recent years, more complex structural configurations, such as sandwich panels, have been increasingly used due to the excellent compromise between lightness and mechanical performance [2]. However, the presence of heterogeneous materials and complex interfaces makes the curing process even more challenging, requiring advanced numerical models that can realistically capture the three-dimensional distributions of temperature, degree of cure, and deformations.

The autoclave curing process is characterized by complex, coupled thermal, chemical, and mechanical interactions, further complicating its numerical simulation. The strong temperature and degree-of-cure gradients that develop within the laminate can lead to process-induced defects, such as residual stresses, warpage, and spring-in angles, which may significantly affect the final mechanical performance of the component [3,4]. In this context, numerical tools based on the finite element method (FEM) can be used to predict thermochemical behavior and process-induced defects; however, the inherently three-dimensional nature of the problem requires the use of solid elements, which significantly increases computational costs. For this reason, this work uses higher-order 1D models based on the Carrera Unified Formulation (CUF) [5] and finite elements to solve the coupled thermo-chemo-mechanical problem. In previous work, CUF-based models have been used to determine spring-in angles and stresses in L-shaped parts. Still, they have not accounted for the three-dimensional effects of thermal and chemical phenomena [6]. This variability is now introduced, enabling a more accurate solution for the part's temperature, degree of cure, and

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mechanical deformation. This work considers a typical aeronautical configuration of a stiffened honeycomb sandwich structure.

Thermo-chemo-mechanical model

To accurately describe the curing process, the thermochemical behavior of the composite is modeled using the 3D heat-conduction equation, coupled with the kinetic model governing the resin curing reaction [7]. The heat transfer equation is expressed as:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{\kappa}\, \nabla T) + \rho H_r \frac{d\alpha}{dt} \tag{1}$$

where ρ is the density, C_p is the specific heat and $\boldsymbol{\kappa}$ is the thermal conductivity tensor. $\partial T/\partial t$ and $d\alpha/dt$ are the two time derivatives of temperature and degree of cure, respectively, and ∇T is the gradient of temperature. H_r is the effective total heat of reaction. Curing kinetics depend on material type and are typically described by Arrhenius-type equations. For AS4 carbon fiber reinforced Hexcel 8552 resin, the cure rate is [8]:

$$\begin{aligned} \frac{d\alpha}{dt} &= \frac{K\alpha^m(1-\alpha^n)}{1+e^{C[\alpha-(\alpha_{C0}+\alpha_{CT}T)]}} \\ K &= Ae^{\frac{-\Delta E}{RT}} \end{aligned} \tag{2}$$

where A is the pre-exponential coefficient, ΔE is the activation energy, R is the universal gas constant, and the others are constant fitting parameters. The experimentally fitted cure kinetic parameters are given in [8].

During curing, the resin's mechanical properties and volumetric cure shrinkage depend on both the instantaneous temperature and the degree of cure. The fiber properties, on the other hand, are assumed to be constant and independent of the cure. Consequently, the composite's mechanical properties evolve in time and space in response to the local thermochemical behaviour. Micromechanical models, such as those presented in [8], are employed to relate the fiber and matrix properties and to derive the lamina's effective mechanical properties, thermal expansion coefficients, and cure shrinkage. The evolution of these quantities is then incorporated into the mechanical analysis to calculate the stiffness matrix and the external force vector, as described in [6].

Therefore, to solve for the unknown displacement field $\boldsymbol{u}$, a linear static mechanical equation is solved [6]:

$$\boldsymbol{k}_{uu}\boldsymbol{u} = \boldsymbol{p}_u \tag{3}$$

where $\boldsymbol{k}_{uu}$ is the [3x3] fundamental nucleus of the stiffness matrix, and $\boldsymbol{p}_u$ is the fundamental nucleus of the vector of external loads represented by the shrinkage and thermal strains. In this paper, the thermo-chemo-mechanical problem is solved using a higher-order 1D model based on CUF and finite elements. This model assumes that the displacement, temperature, and degree-of-cure fields in the cross-section are expressed as expansions of two-dimensional Lagrange functions. At the same time, along the y-axis of the beam, they are approximated using FEM, i.e., they can be written as:

$$\begin{aligned} \boldsymbol{u} &= N_i(y)F_\tau(x,z)\boldsymbol{u}_{i\tau}, \qquad \tau = 1,\dots,M;\ i = 1,\dots,N \\ T &= N_i(y)F_\tau(x,z)T_{i\tau}, \qquad \tau = 1,\dots,M;\ i = 1,\dots,N \\ \alpha &= N_i(y)F_\tau(x,z)\alpha_{i\tau}, \qquad \tau = 1,\dots,M;\ i = 1,\dots,N \end{aligned} \tag{4}$$

where $F_\tau(x,z)$ is the expansion function over the cross-section, $N_i(y)$ are the shape functions, and $\boldsymbol{u}_{i\tau}$, $T_{i\tau}$, and $\alpha_{i\tau}$ are the nodal unknowns of the displacement field, temperature, and degree of cure. M is the number of terms of the expansion function, and N is the number of nodes of the finite element. By expressing the unknowns in terms of the CUF and finite elements and substituting them into the thermo-chemo-mechanical equations, the resulting system is obtained:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & D_T & D_{T\alpha} \\ 0 & 0 & D_\alpha \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{u}} \\ \dot{T} \\ \dot{\alpha} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{k}_{uu} & 0 & 0 \\ 0 & K_T & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \boldsymbol{u} \\ T \\ \alpha \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{p}_u \\ p_T \\ p_\alpha \end{Bmatrix} \tag{5}$$

whose terms are written as fundamental nuclei [5]. The problem is partially coupled, since thermal and chemical phenomena influence mechanics but not vice versa. Because the thermochemical problem requires more iterations than the mechanical problem, the heat-transfer and cure-kinetics equations are solved first using the Newmark method [9], yielding a 3D solution for temperature and degree of cure. Starting from the solution of α, the mechanical properties of the composite are evaluated and used as input for the mechanical analysis. The mechanical problem is solved iteratively using a CHILE approach [10,6]. In this way, an accurate solution can be obtained while limiting analysis time and computational costs.

Results

The higher-order 1D model introduced in this work is used to investigate the thermochemical behavior and process-induced deformations of a substructure representative of a stiffened honeycomb fuselage structure studied in [8]. The structure consists of two 12-layer AS4/8552 composite skins with symmetrical lamination $[45/90/\text{-}45/0/45/90]_s$. Between the two skins, there is a thick HEXCEL HRP-3/16-8.0 honeycomb core. The reinforcement, located on the top surface at the center of the sandwich panel, is a pre-cured resin-transfer molded J-frame. The tool used is made of aluminum, while the tool/part interface is simulated using a shear layer. All details on the materials used, geometric dimensions, and boundary conditions are given in [8]. In the reference, some properties of the composite and J-frame are temperature-dependent, whereas in this work, they are assumed constant and calculated using the maximum curing-cycle temperature. The curing cycle used in the numerical simulation is the one that most accurately reproduces the autoclave temperature measured experimentally in [8]. It involves two holding temperatures at 107 °C and 177 °C for 100 min and 116 min, respectively. The two heating ramps have heating rates of 1.85 °C/min and 0.7 °C/min, and a cooling rate of 2.3 °C/min. The FEM model consists of 3 quadratic beam elements, while 140 Lagrange elements with nine nodes (140L9) are used in the cross-section. The total number of degrees of freedom is 22085.

Figure 1 shows the temperature and degree of cure at the same points considered in [8], i.e., at the tool/part interface, on the top surface of the sandwich panel, and on the J-shaped reinforcement. A good match is obtained between the temperature obtained from the CUF model and those reported in the literature. Significant temperature and degree-of-cure gradients develop across the thickness of the sandwich panel due to the low thermal conductivity of the core. These variations can promote the formation of high residual stresses and induce deformations.

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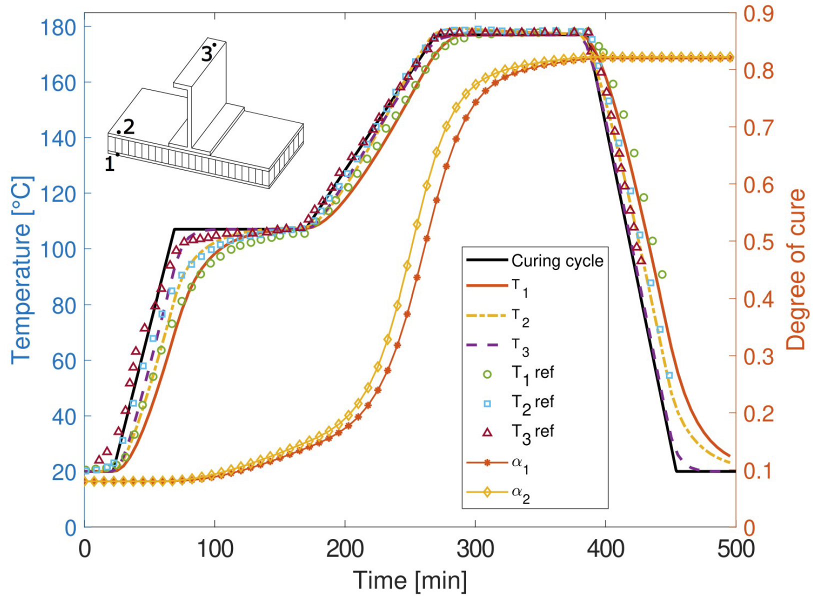

Figure 1: Temperature and degree of cure obtained using the present model and comparison with reference temperature solution [8] at points 1, 2, and 3 of the sandwich structure

Figure 2 shows the 3D deformation of the structure along the z-axis after tool removal. The structure exhibits warpage in the x–z plane. In the top plot of Fig. 2, the predicted warpage along the x-axis is compared with the fitted experimental results for three specimens reported in [8], showing good agreement.

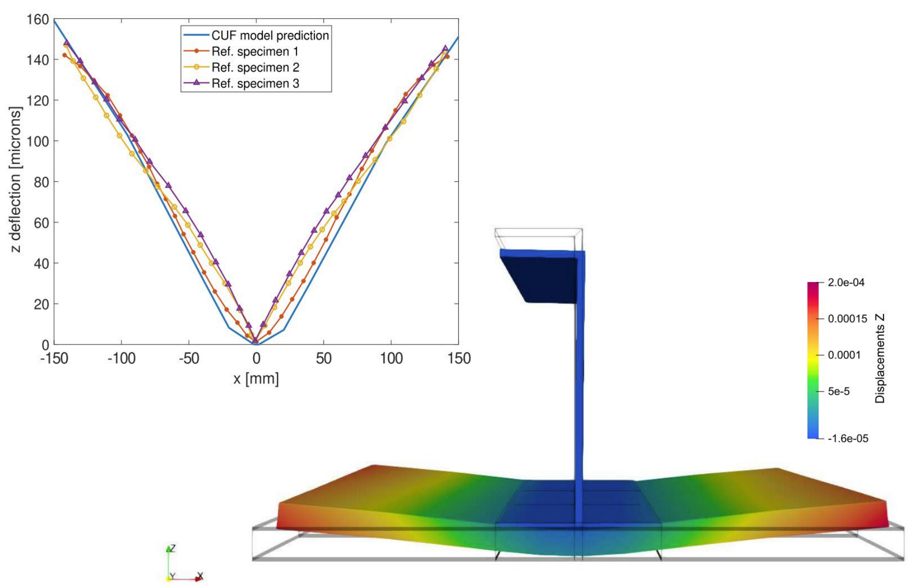

Figure 2: 3D distribution of the displacement in the z-direction (in mm) and comparison between the CUF model prediction and the experimental reference data taken from [8] of the warpage along the x-axis

Conclusion

This paper presents a numerical simulation to solve the coupled thermo-chemo-mechanical problem associated with the curing process of composite materials. The proposed model uses 1D finite elements along the beam axis and in the cross-section, higher-order distributions of temperature, degree of cure, and displacements using the Carrera Unified Formulation. The advantage of the CUF model is that it can obtain 3D solutions for temperature, degree of cure, and displacements while maintaining a 1D formulation at low computational cost. A stiffened honeycomb sandwich panel is analyzed to validate the proposed numerical model. Comparing temperature measurements at different points on the part with the experimental data in the literature shows good agreement, confirming the accuracy of this approach.

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