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Thermo-mechanical damage modeling of polymer matrix sandwich composites in fire

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ABSTRACT

The objective of this research is to develop a modeling and simulation approach for predicting the thermo-mechanical damage of composite materials subjected to fire environments. A 3D thermal damage model is developed for glass-reinforced polymer composite materials subject to high temperature and radiative environments. Homogenization methods are used to formulate the damaged material in terms of fiber, resin and char. The thermal damage model is implemented in Abaqus via an overlaid element approach. The solution of the mechanical response uses the existing functions in Abaqus for large-displacement analysis. Composite sandwich panels with balsa core are examined. Reasonable agreement in temperature is obtained between predictions and available experimental data. For the sandwich panels, delamination failure is predicted at the sandwich interface – consistent with the experiments. Comparisons of time-to-failure of the sandwich panel show the predictions are reasonable.

1. Introduction

Existing models for describing the thermal response of decomposing composite materials have been proposed by Henderson [1–3], Dimitrienko [4–9], Feih [10–12], Zhang and Case [13,14], Summers [15], and Luo and DesJardin [16,17]. A one-dimensional transient thermal model for a glass-phenolic system was developed by Henderson and Florio et al. [1–3]. They modeled the composite as composed of virgin and burnt (char) material. Dimitrienko has systematically developed more advanced thermo-mechanical models for high-temperature composites over a series of studies [4–9]. In his approach, the matrix is assumed to consist of fiber, resin, char and gas. The formulation of the system of thermal and mechanical equations are derived using asymptotic averaging yielding a hierarchy of linearized equations [7]. Feih et al. developed a thermo-mechanical model based on Henderson's model, laminate theory and temperature-dependent strength to estimate the time-to-failure of composite structures under compressive loading and one-sided heating [10–12]. The thermal model is a 1D equation that only considers the conductive heat transfer and mass transport of decomposed gases in the through-thickness direction. The time-to-failure is determined by comparing the average compressive strength of the laminate with the compressive force. Summers developed an analytical model using beam bending analysis to study the compression failure of polymer composite laminate [15]. Zhang and Case developed a 3D thermal and mechanical finite element model by extending Henderson's 1D thermal model and including the viscoelastic effects of composite materials in fire [13,14]. The model considers original and decomposed materials, and does not study the debonding of laminate skins.

Luo and DesJardin developed a constituent based thermal decomposition model based on a homogenized system of thermal and mechanical equations using phase-averaging concepts [16,17]. The result of this procedure incorporates the effect of gas pressurization from resin decomposition in a self-consistent manner. The solution of the equations was obtained using a finite element method. The model was exercised for the case of a 2D clamped beam for which a plane strain assumption is imposed. Given the thermal properties at material's constituent level (fiber, resin, char and gas), a homogenization approximation is used to characterize the thermal decomposition and mass transfer for an arbitrary composite system. With this constituent based thermal decomposition model, the fire response can be simulated for a new material system without performing extensive coupon level testing.

The existing thermal mechanical damage models only examined three of the failure mechanisms for decomposing composite materials, that are charring, creation of gas from resin decomposition, and thermal degradation of elasticity properties. However, delamination has been observed to be an important mode of failure in experimental studies of composite structures in fire environments [12,15,18]. The delamination could occur between the plies of composite laminates [15] and the interface between laminate and balsa core in composite sandwich structures [12].

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The main objective of this study is to implement the thermal damage model in the commercial finite element analysis software Abaqus, and extend it to a thermo-mechanical damage model in Abaqus by enriching the capabilities simulating large deformation and delamination failure of composite structures. The model formulation is presented in Section 2 and the implementation of both thermal and mechanical response in Abaqus is discussed in Section 3.

2. Mathematical formulation

In order to model the response of a composite structure in fire, the macroscopic structural response needs to be determined from microscopic changes in fiber and resin due to local heating and pyrolysis. The modeling approach pursued in this study is based on the homogenization techniques where phase-averaged equations are derived for mass and energy transport within the structure [16,17]. The following summarizes the main results of this development. More details can be found in Ref. [19].

The initial composite material is assumed to be composed of fiber, resin and a small amount of gas void. Upon heating the resin heats up and is pyrolyzed, creating additional gas and char. Thermal equilibrium is assumed among the constituents therefore the solution of only a single energy equation is required for the determination of the local temperature field. The resulting phase-averaged equations for solid phase fraction, φ_i, gas-phase density, ρ_g, and energy (temperature) transport are summarized below [16,19]:

$$\rho_i \frac{\partial \varphi_i}{\partial t} = \dot{m}_i''' \qquad i = f, r, c \tag{1a}$$

$$\frac{\partial \rho_g \varphi_g}{\partial t} = \nabla \cdot \left[\rho_g \frac{\underline{\underline{K}}}{\mu_g} \cdot \nabla (\rho_g R_g T_g) \right] + \dot{m}_g''' \tag{1b}$$

$$(\rho c_p - \rho_g \varphi_g R_g) \frac{\partial T}{\partial t} = (\rho_g c_{p_g} + \rho_g \varphi_g R_g) \left[\frac{\underline{\underline{K}}}{\mu_g} \cdot \nabla (\rho_g R_g T) \right] \cdot \nabla T + \nabla \cdot (\underline{\underline{k}} \cdot \nabla T) - \dot{m}_g''' (\Delta h_{dec} - R_g T) \tag{1c}$$

where the subscripts f, r, c, g represent fiber, resin, char and gas phase; $\rho c_p = \varphi_g \rho_g c_{p_g} + \sum_i \varphi_i \rho_i c_{p_i}$ and the thermal conductivity is $\underline{\underline{k}} = \varphi_g k_g \underline{\underline{I}} + \sum_i \varphi_i k_i \underline{\underline{I}}$. The first terms on the right-hand side of Eqs. (1b) and (1c) account for the transport of gases assuming a Darcy flow, requiring specification of the permeability tensor, $\underline{\underline{K}}$. R_g is the gas constant, μ_g is the viscosity of decomposed gas, and Δh_{dec} is the heat of decomposition. The source/sink terms for the solid phase $(\dot{m}_i''')$ and the gas phase $(\dot{m}_g''')$ account for change in mass from pyrolysis. These terms can furthermore be expressed solely in terms of $\dot{m}_g'''$ after considering overall mass conservation,

$$\dot{m}_f''' = -\frac{\tau_2 \dot{m}_g'''}{(1-\tau_1)(1+\tau_2)} \tag{2a}$$

$$\dot{m}_r''' = -\frac{\dot{m}_g'''}{(1-\tau_1)(1+\tau_2)} \tag{2b}$$

$$\dot{m}_c''' = \frac{\dot{m}_g'''}{\frac{1}{\tau_1} - 1}. \tag{2c}$$

where two additional parameters, τ_1 and τ_2, are introduced that are defined as:

$$\tau_1 \equiv -\frac{\dot{m}_c'''}{\dot{m}_f''' + \dot{m}_r'''} \qquad \tau_2 \equiv \frac{\dot{m}_f'''}{\dot{m}_r'''}. \tag{3}$$

The physical meaning of τ_1 is the ratio of mass generation rate of char to the decomposition of fiber and resin, and τ_2 is the ratio of decomposition rate of fiber to that of resin. These two parameters can be related to ratio of the final mass ($m_e = m_{fe} + m_{re}$) to the initial mass ($m_e = m_{f0} + m_{r0}$) of the matrix, β:

$$\beta \equiv \frac{m_{f_e} + m_{ce}}{m_{f0} + m_{r0}} = \tau_1 + \frac{(1-\tau_1)(m_{f0} - \tau_2 m_{r0})}{m_{f0} + m_{r0}} \tag{4}$$

which can be measured experimentally. Substituting Eq. (4) into Eq. (3) results in an expression for τ_1 in terms of τ_2 and β:

$$\tau_1 = \frac{\beta(m_{f0} + m_{r0}) - (m_{f0} + \tau_2 m_{r0})}{(1+\tau_2) m_{r0}}. \tag{5}$$

For glass fibers the silicon does not participate in the decomposition processes, therefore $\tau_2 = 0$ and τ_1 is solely a function of β and the initial masses of the fiber (m_{f0}) and resin (m_{r0}). The decomposition of the gas is modeled using a standard Arrhenius law for pyrolysis processes given as: $\dot{m}_g''' = -A_i \rho_0 \left(\frac{\rho - \rho_c}{\rho_0}\right)^{n_i} e^{-E_i/R_g T}$. The pre-exponential factor, A_i, activation energy, E_i, and power exponent, n_i can be measured experimentally. Once the volume fractions of the solid phases are determined then the gas volume fraction, φ_g, used in Eqs. (1b) and (1c) can be determined using: $\varphi_g = 1 - \varphi_f - \varphi_r - \varphi_c$.

The thermal formulations are implemented in Abaqus, and the mechanical response of composite structures is also solved using Abaqus. The solution approach will be introduced in next section.

3. Solution approach

3.1. Thermal response in abaqus

In Abaqus, user subroutine UMATHT can be used to define the thermal constitutive behavior of the material as well as internal heat generation during heat transfer processes. It can be used for solving the temperature equation represented in Eq. (1c), as well the gas transport equation Eq. (1b). However, there is no such a type of element that has both temperature and gas pressure degrees of freedom for heat transfer or thermal-mechanical analyses. Only one user-defined thermal material behavior can be used for each material point.

In order to implement the thermal damage model in Abaqus, an overlaid element approach, shown in Fig. 2, is developed and implemented in Abaqus/Standard [20,21]. The two overlaid layers of elements are actually on top of each other, and plotted offset for illustration purpose. These elements have their displacement degrees of freedom fixed to each other at the nodes, which can reduce the unnecessary computational cost. The solution procedure employs one UMAT (if needed for mechanical field) and one UMATHT(1) applied to the first layer to define the constitutive, decomposition, and heat transfer equations. Another UMATHT(2) is applied to the second layer to solve the gas transport equation. Since both UMAT and UMATHT(1) are used for the first layer of elements, the common variables can be shared via the state variables associated with material points. These state variables include temperature, remaining solid mass, etc. To use these state variables as

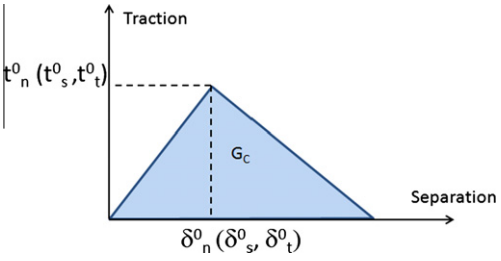

Fig. 1. Typical traction–separation response of a cohesive element. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)