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Thermo Mechanical Analysis of Composite Material Exposed to Fire

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Abstract: A large amount of research has been performed to characterize the combustion properties and reduce the flammability of composite materials, although less is known about the structural behavior of composites in fire. Several studies have examined the effect of high temperature or fire on the load-bearing properties of polymer laminates and sandwich composites. This paper presents thermo-mechanical models for predicting the strength of polymer laminates loaded in tension or compression exposed to one-sided radiant heating by fire. The models predict the temperature rise and through-thickness temperature profile in a hot decomposing laminate exposed to fire. The models assume that one side of a laminate beam is evenly heated at a constant radiant heat flux. Calculation of the fire resistance demands determination of temperature distribution in the cross-section (heat-exposure model) and analysis of mechanical responses of the structure exposed to increased temperature (structural response model). Space division of temperatures, which rises in probable fire, could be expressed through of fire-driven fluid flow or FDS (Fire Dynamics Simulator). The temperature field of the laminate was calculated by using COMSOL Heat Transfer Module. The surface recession rate is specified with a moving mesh boundary condition enabled through the "Moving Mesh" interface of the COMSOL Multiphysics software.

Keywords: Polymer matrix, Fire, Pyrolysis, Charred material, Thermo-mechanical properties, Heat Transfer, COMSOL, Heat Transfer Module, FDS code, Strength analysis.

1. Introduction

Fiber reinforced composite structures have become very competitive engineering materials in recent years and have successfully replaced conventional metallic and other polymeric materials in many important sectors of industry.
Epoxy resin matrix based composites because of their favourable mechanical, physico-chemical properties and high strength to light weight ratios are used in load-bearing structures such as aircraft, military vehicles, ships, building and offshore structures. In order to increase the market penetration and because of current stringent aviation and other legislation to increase safety, improvements in flame retardancy have been given significant priority. The organic matrix components are susceptible to combustion and fire damage because of their chemical structures [1–3]. This leads to concerns about the structural integrity of composite laminates during and after exposure to fire. Many composite materials are layered and hence, each glass layer acting as an insulator, affects the burning of underlying resin [3–6]. The heat impinging on the surface causes degradation of the resin leading to its ignition. Further penetration of the heat below the first glass layer causes degradation of the underlying resin. The degradation products migrate to the burning zone through the glass and any char retained in the glass reinforcement. This process goes on until all layers of the resins are burnt. However, if the char formation can be enhanced which can then act as a thermal barrier, it can slow down this migration resulting in stopping or slowing down burning. As the composite is heated, the original virgin material (or rather one or more *components* of the original composite virgin material) pyrolyzes and yields a pyrolysis gas, which percolates away from the pyrolysis zone, and a porous residue, which for most materials *of* interest is a carbonaceous char, possibly

reinforced with refractory fibers or cloth (see Figure 1). Superimposed on this basic problem may be a number of even more complex events. The pyrolysis gases percolating through the char may undergo further chemical reactions among themselves, and may react with the char, either eroding it or depositing additional residue upon it ("coking"). The char itself may collapse or fragment from mechanical or thermal stresses, and the refractory reinforcements may melt or suffer mechanical damage. Finally, various constituents of the residue structure may react chemically with each other, changing the nature of the char, and various mechanical forces may remove material from the surface [7].

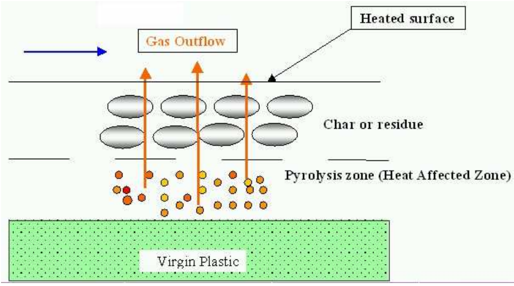

Figure 1. Composite degradation process

Despite these complexities, it is found that the "simple physics" described by:

$$\text{Virgin plastic} \rightarrow \text{char} + \text{gas}$$

This reaction underlies a wide range of problems of technical interest, and for a great many materials, such as carbon phenolic, graphite phenolic, and wood, constitute all the events of interest. Such events as coking, mechanical erosion, melting, and subsurface reactions (other than pyrolysis) are less common and generally characterize specific problems. Therefore in any effort to compute the in-depth response of pyrolyzing materials is to characterize the heat conduction and the primary pyrolysis reaction, which have useful generality. Particular details of special char chemical systems can then be superimposed upon this general computational scheme as required. The present effort has been mostly devoted to the general conduction-pyrolysis problem [7].

2. Proposed Concurrent Fire Structural (CFS) Modeling Approach

In this modeling approach, analysis of structures under combined mechanical and fire loads are carried out using the FDS and empirical codes. The FDS code is first used in order to solve for the temperature or heat flux on the surfaces as a function of time. The nonlinear structural analysis is sequentially carried out once the temperature distributions are obtained as a function of time within all points in the structure. The proposed approach can be divided into three simulation parts. The first part is the fire simulation where the FDS model is utilized. The FDS model generates a solution of several state variables, such as pressure, temperature, heat, velocity vector. However, our framework is interested in the heat and temperature solution part that are related to the structure performance and response. The temperature and heat flux of the interior structural surfaces profiles are used and applied to subsequent simulation parts. In the second part, COMSOL heat transfer module was used in order to compute the temperature profiles for the composite through their thickness using the heat flux or surface temperature results from the FDS model. In the third part, the mechanical properties of the composite were evaluated.

2.1 Fire Dynamic Simulator (FDS)

The fire dynamics simulator (FDS) has been developed at the Building and Fire Research Laboratory (BFRL) at the National Institutes of Standards and Technology (NIST), e.g. McGrattan et al. [8]. The program calculates the temperature, density, pressure, velocity, and chemical composition within each numerical grid cell at each discrete time step. It computes the temperature, heat flux, and mass loss rate of the enclosed solid surfaces. The FDS code is formulated based on Computational Fluid Dynamics (CFD) of fire-driven fluid flow. The FDS numerical solution can be carried out using either a Direct Numerical Simulation (DNS) method or Large Eddy Simulation (LES). The latter is relatively low Reynolds numbers and is not severely limited in grid size and time step as the DNS method. In addition to the classical conservation equations considered in FDS, including mass species momentum and energy, thermodynamics based state equation of a perfect gas is adopted along with chemical combustion reaction for a library of different fuel sources. The latter is used in the case where the fire heat release rate is unknown. FDS also has a visual post-processing image simulation program named "smoke-view" This study develops different software for post-processing the FDS results and generating the temporal and spatial numerical data needed for the proposed temperature approximation functions.

3. Use of COMSOL Multiphysics

In this work, we have assumed that the composite degraded to a gas plus char. The reaction scheme is shown:

$$P \rightarrow \alpha G + (1-\alpha)C \tag{1}$$

During the pyrolysis reaction, mass of the polymer is consumed and produces a fraction, α, of gas and the remaining char. The first order reaction rate for the composite is:

$$\frac{dr_p}{dt} = -k_0 r_p \tag{2}$$

where r_p is the thickness of the polymer in [m], t is the time in [sec] and k_0 is the rate constant for pyrolysis reaction in [1/sec].

The rate constant in for the pyrolysis reaction, k_0, is a function of temperature and is better described by the Arrhenius relationship:

$$k_0 = A_0 \cdot \exp\left[-\frac{E_{A0}}{R \cdot T}\right] \tag{3}$$

Where A_0 is the pre-exponential factor of pyrolysis reaction [1/sec]. E_{A0} is the activation energy of pyrolysis reaction [kJ/kmol], R is gas constant [J/mol/K] and T is the temperature in [K]. The pre-exponential factor and activation energy can be found by thermogravimetric analysis.

A 1D heat conduction equation for the composite temperature $T_s(x,t)$ is applied in the direction x pointing into solid (the point x=0 represents the surface) [8]

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T_s}{\partial t}\right) + \dot{q}_s \tag{4}$$

The source term, $\dot{q}_s$, consists of chemical reactions, radiative absorption and convective heat transfer.

$$\dot{q}_s = \dot{q}_{s,c} + \dot{q}_c \tag{5}$$

The convective heat flux is calculated by using the following equation:

$$\dot{q}_c = h(T_g - T_w) \tag{6}$$

In Large Eddy Simulation (LES) calculation, the convective heat flux to the surface is obtained from combination of natural and forced convection correlations:

$$h = \max\begin{bmatrix} C\left|T_g - T_w\right|^{\frac{1}{3}} \\ \frac{\lambda_g}{L} 0.037\, Re^{\frac{4}{5}}\, Pr^{\frac{1}{3}} \end{bmatrix} w/m^2/K \tag{7}$$

Where C is the coefficient for natural convection (1.52 for horizontal surface and 1.31 for vertical surface), L is characteristic length related to the size of the physical obstruction, λ_g is the thermal conductivity, and the Reynolds Re and Prandtl Pr numbers are based on the gas flowing past the obstruction. The chemical source term of the heat conduction equation consists of the heat of the reaction

$$\dot{q}_{s,c} = -\rho_s k_0 \Delta H_r \tag{8}$$

ΔH_r is the heat of reaction. The thermophysical properties (thermal conductivity, heat capacity and density) and the rate constants of the composite used in the calculation of FDS and COMSOL are shown in Table 1.

Table 1: Thermo-physical and thermo-chemical Properties of composite used in calculations.

Parameter	Value	Unit
ρ_s	1,140	kg/m^3
$c_{p,s}$	760	$J/kg\ K$
λ_s	0.43	$w/(m \cdot K)$
E_{A0}	2.13E+05	$kJ/kmol$
A_0	5.59E+13	$1/s$

Figure 2 shows the predicted thickness of the composite as a function of time.

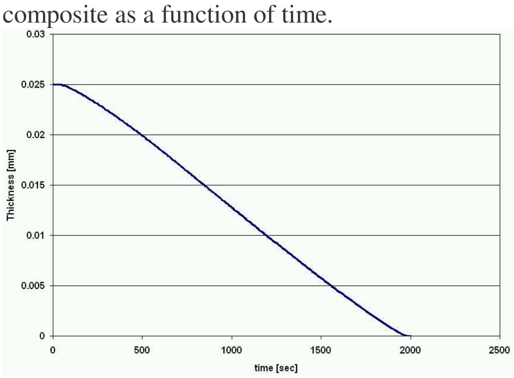

Figure 2. Predicted thickness of the composite as a function of time.

From Figure 2 it can be seen that the composites ablated completely after 2000 sec. The recession output results, which was obtained by FDS software, has been transferred to COMSOL model. In COMSOL model, the composite external surface recession is specified with a moving mesh boundary condition enabled through the "Moving Mesh Application Mode" of the COMSOL Multiphysics software. The program has a pre-packaged feature described as the Arbitrary Lagrangian-Eulerian (ALE) method; it permits moving boundaries without the need for the mesh movement to follow the material [9].

Figure 3 shows the temperature field of the composite after 900 sec from the beginning of fire.

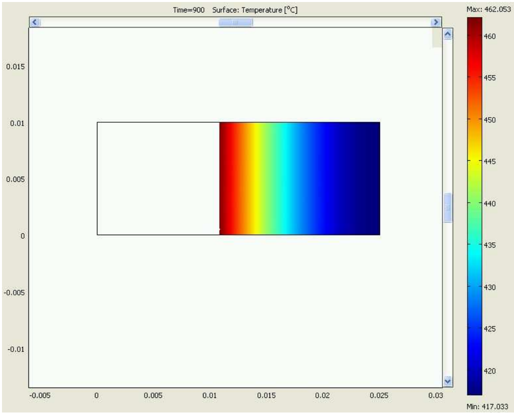

Figure 3. Temperature field of the composite after 900 sec.

4. Mechanical properties degradation

The temperature dependence of mechanical properties can be expressed as the hyperbolic tangent function temperature. For Young's modulus, the degradation law is written as [10]:

$$E(T) = \frac{E_1 + E_2}{2} + \frac{E_1 - E_2}{2} \tanh[\Phi(T - T_k)] \quad (9)$$

Here E_1 is the Young's modulus at initial temperature in [MPa], E_2 is the residual modulus in [MPa], Φ is 0.026 [1/K], and $T_k = 88^o C$. Figure 4 shows the Young's modulus as a function of the temperature at t=50, 100, 150, 200 and 300 sec.

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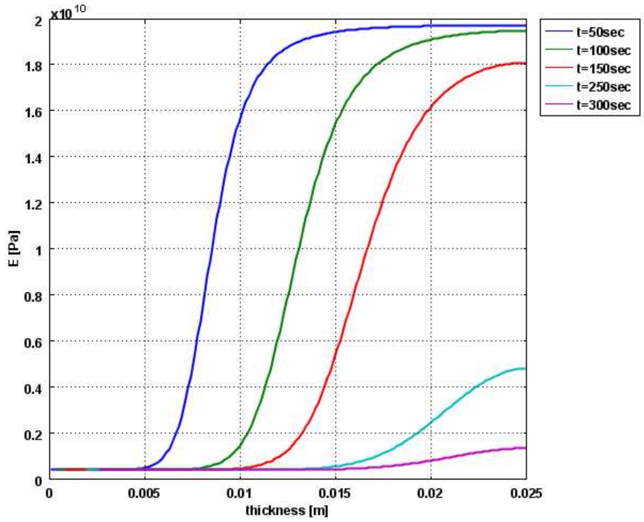

Figure 4. Young's modulus of the composite at several temperatures

From figure 4 it can be seen that the Young's modulus decreases at higher temperatures.

7. Summary and Conclusions

This paper presents thermo-mechanical models for predicting the strength of polymer laminates loaded in tension or compression exposed to one-sided radiant heating by fire. The models predict the temperature rise and through-thickness temperature profile in a hot decomposing laminate exposed to fire. The models assume that one side of a laminate beam is evenly heated at a constant radiant heat flux. The proposed approach can be divided into three simulation parts. The first part is the fire simulation where the FDS model is utilized. The FDS model generates a solution of several state variables, such as pressure, temperature, heat, velocity vector. However, our framework is interested in the heat and temperature solution part that are related to the structure performance and response. The temperature and heat flux of the interior structural surfaces profiles are used and applied to subsequent simulation parts. In the second part, COMSOL heat transfer module was used in order to compute the temperature profiles for the composite through their thickness using the heat flux or surface temperature results from the FDS model. In the third part, the mechanical properties of the composite were evaluated. It has been shown that the Young's modulus decreases at higher temperatures.

8. References

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