Modeling of mechanical response of FRP composites in fire

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ABSTRACT

A thermomechanical model is presented for predicting the time-dependent deflections of cellular FRP slab elements subjected to mechanical loading and fire from one side. The model comprises temperature-dependent mechanical property sub-models for the Young's modulus, viscosity and coefficient of thermal expansion. Two different thermal boundary conditions were investigated: with and without liquid-cooling of the slab elements in the cells. A finite difference method was used to calculate the deflection at each time step. Deflections resulting from stiffness degradation due to glass transition and decomposition of the resin dominated over those resulting from viscosity and thermal expansion. The predicted total deflections compared well with the measured results over a test period of up to 2 h. The failure mode of the non-cooled specimen could be explained.

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1. Introduction

Investigations on modeling of the thermal and mechanical responses of fiber-reinforced polymer (FRP) composites subjected to fire can be traced back to initial efforts by the defense and aerospace industries. The focus has since then shifted from mainly carbon fiber composites to glass fiber-reinforced polyester, vinylester, and phenolic composites used for marine and civil applications.

The mechanical responses (stress, strain, displacement and strength) of FRP composites under elevated and high temperatures are affected significantly by their thermal exposure [1]. On the other hand, mechanical responses almost have no influence on the thermal responses of these materials. As a result, the mechanical and thermal responses can be decoupled. This can be done by, in a first step, estimating the thermal responses and then, based on the modeling of temperature-dependent mechanical properties, predicting the mechanical responses of the FRP composites.

Thermomechanical models for FRP materials were first developed in the 1980s. One of the first thermomechanical models for FRP materials was introduced by Springer in 1984 [2], where the degradation of mechanical properties was empirically related to the mass loss. In 1985, Chen et al. [3] added a mechanical model to the thermochemical model presented by Griffis et al. [4]: mechanical properties at several specified temperature points were assembled into a finite element formulation. Griffis et al. [5] introduced an updated version of Chen's model in 1986, whereby an extrapolation process was used to obtain the data in the higher temperature range.

In 1992, McManus and Springer [6,7] presented a thermomechanical model that considered the interaction between mechanically induced stresses and pressures created by the decomposition of gases within the pyrolysis front. Again, temperature-dependent mechanical properties were determined at several specified temperature points as stepped functions. The issue of degradation of material properties at elevated temperatures was considered in Dao and Asaro's [8] thermomechanical model in 1999. The degradation curves used in the model were, once again, obtained by curve fitting of limited experimental data. Later in 2000, Dutta and Hui [9] devised a simple empirical model for temperature or time-dependent mechanical properties. In this model, the ratio of moduli at two different temperatures was determined by the density and temperature at these two points.

In 1999, a comprehensive, theoretical model for a temperature-dependent modulus was developed by Mahieux and Reifsnider [10,11]. In this model, Weibull functions were used to describe the change in modulus over the full temperature range including the glass transition temperature. Experimental validation was conducted on six different polymers. In each case, the degradation of the modulus during glass transition was successfully described by the model. A further application of this model to predict the mechanical responses of composites can be found in Burdette [12].

Gibson et al. [13] developed a thermomechanical model by combining their thermochemical model with Mouritz's two-layer post-fire mechanical model (a fully degraded region that is simplified as having little or no residual mechanical properties, and an unaffected region that is simplified as having the same properties as before the fire exposure, [14]). A remaining resin content (RRC) criterion was successfully used to identify the border between two different layers. In 2004, Gibson et al. [15] then presented an upgraded version by adding a new mechanical model.

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A function that assumes that the relaxation intensity is normally distributed over the transition temperature was used to fit the temperature-dependent Young's modulus. Furthermore, in order to consider the resin decomposition, each mechanical property was modified by a power law factor. Predictions of mechanical responses based on these thermomechanical models were also performed by Bausano et al. [16] and Halverson et al. [17]. Mechanical properties were correlated to temperatures through Dynamic Mechanical Analysis (DMA); but no special temperature-dependent mechanical property models were developed.

The above-mentioned thermomechanical models only consider material elastic behavior, viscoelastic behavior of FRP composites at elevated and high temperatures has seldom been investigated. Boyd et al. [18] reported on compression creep rupture tests performed on uni-directional laminates of E-glass/vinylester composites subjected to a combined compressive load and one sided heating. Models were developed to describe the thermo-viscoelasticity of the material as a function of time and temperature. In their work, the temperature-dependent mechanical properties were determined by fitting the Ramberg–Osgood equations. The viscoelastic effects were considered by the generalized Maxwell–Voigt equations; and the temperature profiles were estimated by a transient 2D thermal analysis in ANSYS® 9.0.

The objectives of this paper is to validate the material property models recently proposed by the authors in [19] on the structural level and, based on the modeling results, to understand the complex thermomechanical responses of FRP load-bearing structures subjected to fire. Conversion degrees in both time and space domain of the related chemical and physical transitions as well as thermophysical properties and temperature responses are calculated based on [20–21]. Subsequently the time- and temperature-dependent elastic and viscoelastic displacements are obtained and compared to experimental results from cellular FRP panels subjected to mechanical loads and fire from one side [22]. The additional deflections due to thermal expansion are also considered and the failure modes are discussed. The thermomechanical response model (comprising modeling of deformations due to elasticity, viscosity and thermal elongation as well as failure analysis) is the original part of this paper.

2. Modeling of temperature-dependent mechanical properties

Structural fire endurance experiments were performed on cellular GFRP slab elements (DuraSpan® 766 slab system from Martin Marietta Composites) as shown in Fig. 1. A detailed description of the experimental set-up and results is given in [22]. The pultruded composite material consisted of E-glass fibers (volume fraction 48%) embedded in an isophthalic polyester resin. The mechanical properties at ambient temperature of the cellular deck components (upper and lower face sheets and internal webs) are summarized in Table 1. The glass transition temperature, T_g, of the material was 117 °C and the decomposition temperature, T_d, 300 °C [19].
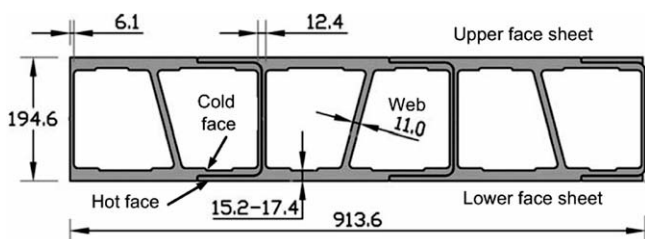

Fig. 1. Cross section of DuraSpan specimens used for fire endurance experiments.

Table 1
Mechanical properties and geometric parameters of DuraSpan deck.

Property	Face sheets	Webs	Total
E_x (GPa)	21.24	17.38	–
G_{xy} (MPa)	5580	7170	–
λ_c ($\times 10^{-6}\,K^{-1}$)	–	–	12.6
η_m (GPa h)	–	–	82.4
A (mm^2)	15350	11480	42180
Height (mm)	15.2–17.4	161	194.6
Width (mm)	913.6	71.3	913.6

2.1. Temperature-dependent Young's modulus

To describe the change in Young's modulus with temperature, the related physical and chemical processes that occur during glass transition and decomposition must be understood. Different kinetic models can be used to describe the conversion degree of each process [19,20]:

$$\frac{d\alpha_g}{dT} = \frac{A_g}{\beta} \cdot \exp\left(\frac{-E_{A,g}}{RT}\right) \cdot (1 - \alpha_g)^{n_g} \tag{1}$$

$$\frac{d\alpha_r}{dT} = \frac{A_r}{\beta} \cdot \exp\left(\frac{-E_{A,r}}{RT}\right) \cdot (1 - \alpha_r)^{n_r} \tag{2}$$

$$\frac{d\alpha_d}{dT} = \frac{A_d}{\beta} \cdot \exp\left(\frac{-E_{A,d}}{RT}\right) \cdot (1 - \alpha_d)^{n_d} \tag{3}$$

where α_g, α_r and α_d are the conversion degrees; A_g, A_r and A_d the pre-exponential factors; $E_{A,g}$, $E_{A,r}$ and $E_{A,d}$ the activation energies; and n_g, n_r and n_d the process orders for glass transition, leathery-to-rubbery transition and decomposition, respectively. R is the universal gas constant; T is the temperature; t is time; and β is the heating rate. Complex thermal loading history can be taken into account by varying β within a finite difference algorithm.

By adopting a simple mixture approach, the temperature-dependent Young's modulus, E_m, can be expressed as follows (taking into account the fact that the E-moduli in the leathery and rubbery states are almost the same [19]):

$$E_m = E_g \cdot (1 - \alpha_g) + E_r \cdot \alpha_g \cdot (1 - \alpha_d) \tag{4}$$

where E_g is the Young's modulus in the glassy state (for initial values for face sheets and webs, see Table 1) and E_r is the Young's modulus in the leathery and rubbery states, defined as being 5.8 GPa [19]. After decomposition, the material is considered as having no structural stiffness. Based on a value of $\beta = 5$ °C/min (the same as for DMA), the temperature-dependent Young's modulus results are shown in Fig. 2a. The stiffness degradation due to glass transition compares well to the DMA results given in [19], and the drop due to decomposition is also described by the model.

2.2. Temperature-dependent viscosity

The temperature-dependent viscosity, η_m, can be obtained by the same method as that used for the modeling of a temperature-dependent Young's modulus. However, since the viscosities in the leathery and rubbery states are different, the following Eq. (5) is derived [19]:

$$\eta_m = \eta_g \cdot (1 - \alpha_g) + \eta_l \cdot \alpha_g \cdot (1 - \alpha_r) + \eta_r \cdot \alpha_g \cdot \alpha_r \tag{5}$$

where η_g, η_l and η_r are the viscosities in the glassy, leathery and rubbery states. In order to obtain the viscosity in the glassy state (initial value at room temperature), creep tests at room temperature were performed on the same DuraSpan slab elements, as shown in Fig. 2d [23], and a value of $\eta_g = 82.4$ GPa h was obtained