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Compression creep rupture behavior of a glass/vinyl ester composite subject to isothermal and one-sided heat flux conditions

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Abstract

Given the expanding applications of polymer matrix composites to civil infrastructure, the marine industry, and the military, we examine the compression creep rupture behavior of a glass/vinyl ester composite subject to combined load and one sided heating simulating fire exposure. We focus on *reversible* non-linear viscoelastic effects which dominate delayed failure at lower temperatures in the vicinity of the glass transition temperature. A compression strength model which predicts local compression failure due to micro-buckling is extended to include viscoelasticity. Times to failure under combined mechanical load and one sided heating are estimated to within an order of magnitude.

Keywords: A. Polymer–matrix composites (PMCs); B. Creep; C. Analytical modeling; Fire

1. Introduction

Polymer matrix composites (PMC's) are growing in popularity as a replacement to conventional materials in civil infrastructure, construction, and marine applications. Many navies as well are exploring the possibility of applying glass/polyester and glass/vinyl ester systems to the construction of topside structures such as radar/communications mast, helicopter hangers, and structural bulkheads and flooring on larger naval ships and as structures on patrol boats and mine hunting vessels. PMC's offer benefits over conventional materials due to their high specific strength, excellent corrosion resistance, low electromagnetic signature, overall improved operational performance and low heat conductivity. Specifically, the United States Navy is currently investigating Vetrotex 324/Derakane 510A-40, an E-glass/vinyl ester system, for use in topside structures on its naval vessels.

Before PMC's can be implemented on board naval and marine ships, questions regarding the fire performance and structural integrity of the organic polymer matrix with fire exposure must be investigated. To this point much research has been performed to characterize the flammability, toxicity and fire resistance of PMC's with fire exposure [1–3]; however, an understanding of the structural response of sandwich structures and laminates under combined mechanical load and fire is still incomplete. As the PMC is exposed to fire, it first undergoes *reversible* changes to its properties in the vicinity of the glass transition temperature T_g such as a precipitous drop in stiffness. At these elevated temperatures the structural integrity is compromised due to thermal softening which could lead to compression failure and possible collapse even though the polymer matrix has not been degraded.

The main goal of the modeling effort to characterize the structural response under fire loading conditions is to

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develop analytical models and finite element analysis methods and tools to predict laminate level limit state variables such as deflection, local compression failure due to micro-buckling, thermo-mechanical evolution of properties with temperature, and estimated times to failure. Given the importance of compressive loading at elevated temperatures in the structural response of composite structures exposed to fire, we focus on:

(a) Characterizing the non-linear creep response of the E-glass/vinyl ester composites at and above the glass transition temperature.
(b) Describing compression strength mechanics as a function of fire exposure (resulting in a non-uniform temperature profile) and mechanical loading based on a micromechanics model (Budiansky and Fleck [4]). This model is extended to include viscoelasticity.
(c) Integrating the viscoelastic characterization into the compression strength model to predict times to failure.

As mentioned much work has been conducted in the area of quantifying the smoke, toxicity and flammability of an organic matrix composite subject to fire exposure ([1–3] and flame spread and smoke density standard ASTM E 84). However, relatively little work has been done that evaluates the structural response and residual properties and strength of a composite structure compromised by fire exposure. Of the work that is currently available, Henderson and Wiecek [5], McMannus and Springer [6], and Gibson et al. [7] have lead in developing a thermodynamic polymer decomposition model that estimates degraded composite properties and residual strength as a function of fire exposure. Their collective work has focused on laminate property degradation at temperatures well above the glass transition temperature T_g high enough to cause thermal decomposition of the matrix. Gibson et al. [8,9] and Seggewiss [10,11] have also done work in the area of developing models and methods that mechanistically estimate the structural performance and residual properties of fire damaged composites. Gibson et al. [8] has developed a two-layer laminate mechanics model for estimating the post fire response and lifetimes of glass/polyester systems subject to a heat flux simulating fire exposure up to 75 kW/m^2. Seggewiß has shown a comparison of the tensile and compressive lifetimes for carbon/polyester systems in their principle orientations with heat fluxes up to 280 kW/m^2.

Most of these studies have been concerned with the very high temperature response of glass or carbon fiber reinforced composites subject to fire exposure. These high temperatures (heat fluxes greater than 50–75 kW/m^2) cause *irreversible* damage to the composite in the form of thermal decomposition of the matrix and typically a quick temperature controlled failure. As a continuation of the overall work to characterize the structural response under fire loading conditions, the current research effort seeks to study lower temperature failures which typically occur with lower heat fluxes (5–20 kW/m^2) and temperatures in the vicinity of T_g where viscoelastic creep and creep rupture effects control delayed failure.

Many researchers over the years have developed methods and models to predict delayed failure of general laminated composite systems at elevated temperatures where a viscoelastic process is the dominant factor for failure. The two most relevant to the current research are given by Miyano et al. [12–14] and Dillard et al. [15]. Miyano et al. have forwarded models predicting creep rupture behavior based purely on time–temperature equivalence. Miyano collected rupture times at different temperatures and stresses and shifted the data to form temperature master-curves. The resulting shift factors were modeled using an Arrhenius relationship and corresponding activation energies calculated. Miyano then used the master-curves to successfully predict rupture strengths. Dillard et al. utilized an elevated temperature viscoelastic characterization and extended the Tsai–Hill failure criterion to include viscoelastic effects to predict delayed failure of carbon reinforced epoxy laminates. These models have been successfully applied to glass and carbon fiber reinforced composites to predict tensile creep rupture behavior in the vicinity of T_g.

The work presented in this manuscript builds on previous work that characterizes the non-linear thermo-viscoelastic response of an E-glass/vinyl ester composite [16]. Isothermal creep and recovery tests were conducted on shear coupons ($[\pm 45°]_{2S}$) and the results indicated that the non-linear thermo-viscoelastic response of the composite was dominated by temperature and was significant at and above T_g and in the area of yield for a given temperature. In an effort to simulate the structural fire response of composites, Bausano et al. [17] conducted one-sided heat flux compression creep rupture tests on a pultruded nearly quasi-isotropic laminate of Vetrotex 324/Derakane Momentum 411-350 ($[0°/90°\pm 45°/CSM]_S$). Bausano et al. used thermally modified micromechanics together with classical lamination theory (CLT) and ANSYS to predict the rupture times which were found to be controlled by the glass transition temperature T_g of the matrix. A compression strength model was developed based on the Budiansky and Fleck model which included progressive thermal softening (material properties as functions of temperature) to predict compression failures in pultruded PMC's with a weave reinforcing phase.

The structural model presented here is similar to the work of Bausano et al. but includes thermoviscoelasticity. The compression strength model developed here is based on the Budiansky and Fleck model but is extended to include non-linear viscoelasticity (replacing the shear modulus G with the in-plane shear relaxation modulus G_{12}) and is applied to woven roving reinforced composite. An averaged laminate compression strength is calculated as a function to time and temperature and used to predict laminate compression failure due to local micro-buckling in unidirectional composites subject to both isothermal conditions and one sided heating.