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Creep in carbon/epoxy composites manufactured by filament winding

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Investigation of carbon-fiber-reinforced epoxy laminates shows that their viscoelastic behavior depends on both fiber orientation and creep performance.

Carbon-fiber-reinforced polymer composites (also known as laminates for their fibrous layer structure) are valued for their high stiffness and strength-to-weight ratios, as well as their corrosion resistance. For this reason, the marine, aerospace, and aeronautic industries are increasingly replacing metallic structural components with their composite counterparts in order to increase payload.[1] But the mechanical performance of advanced composites also has certain limitations. One reason is that the mechanical properties of the composites, including interfacial and interlaminar properties, depend significantly on time, temperature, and fiber orientation. For instance, although laminae (i.e., individual layers) are generally not prone to 'creep' when loaded in the fiber direction, mismatches between them can lead to excessive strain and premature failure.

Creep refers to time-dependent deformation under a constant load at a specified temperature. It is considered a crucial material property from a long-term point of view[2] as it is directly associated with viscoelastic strain. Because temperature, stress, and time are crucial parameters in describing viscoelastic behavior, several models have been proposed to predict the long-term creep behavior of composites. However, previous attempts to predict creep at different temperature and stress levels have fallen short due to the amount of time and the costs involved.

Our approach proposes a fast and cheap methodology that also offers a high degree of precision for both temperature and stress applications. We applied the Findley empirical power equation[3]—which describes the creep behavior of several polymers with good accuracy over a wide timescale—and the Burger four-parameter creep model[4]—which includes the essential Maxwell and Kelvin-Voight elements and can satisfactorily model the practical behavior of viscoelastic materials—to predict the creep behavior of carbon-fiber-reinforced epoxy filament-wound flat laminates and to validate the analytical results with experimental ones.

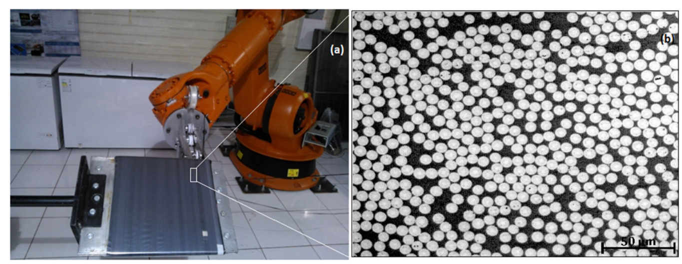

Figure 1. *Manufacture of a flat laminate (a) and view of the final unidirectional fiber distribution (b).*

We used carbon-fiber-reinforced epoxy prepreg tow (or towpreg), which is composed of Toray T700–12K-50C carbon fibers and UF3369 epoxy as the resin system. We produced flat laminates (see Figure 1) using a filament winding system,[5] in which the towpregs were wound onto a flat stainless steel mandrel. A shrink tape was used to help consolidate the laminate through the curing process that followed. The final fiber volume fraction was ∼72%, and the overall mean thickness of the 12-layer laminate was 4.2mm. Unidirectional laminates were produced and cut at off-axis angles to provide the following specimens: $[0]_{12}$, $[30]_{12}$, $[45]_{12}$, $[60]_{12}$, and $[90]_{12}$ (the subscripted '12' represents the number of layers).

We carried out creep tests using dynamic mechanical analysis (DMA Q-800 from TA Instruments) with a three-point bending setup. A static stress of 2MPa was applied at the center point along the specimen length for 10min after conditioning at 30°C, and creep strain was measured as a function of time (30min) at 30 and 60°C.[5]

We applied the Findley and Burger models to predict the creep behavior of the laminates. Findley's power law is given by:

$$\varepsilon(t) = \varepsilon_0 + At^n \tag{1}$$

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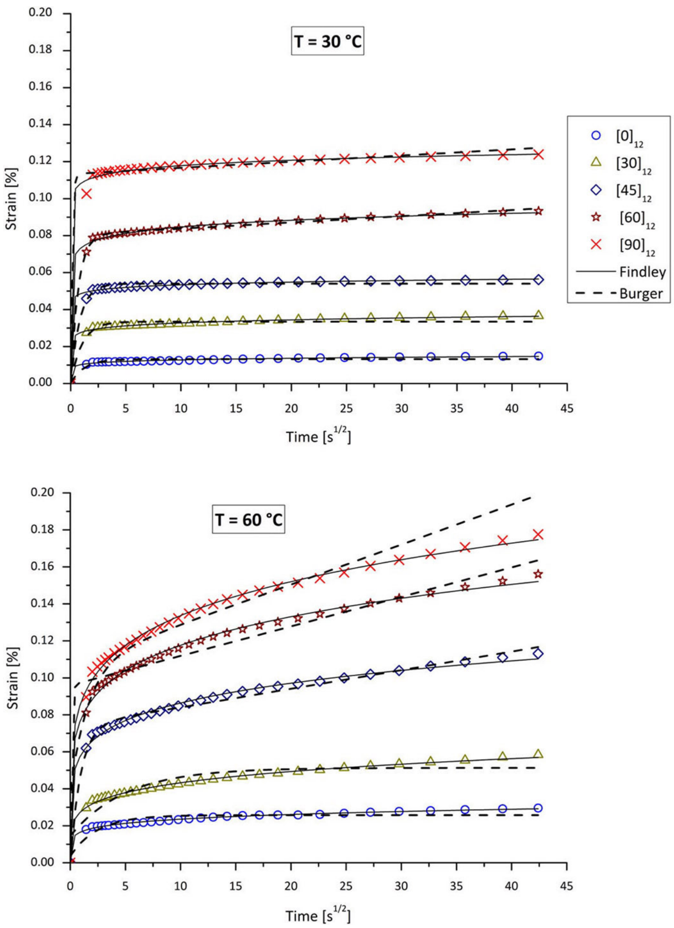

Figure 2. Creep curves obtained at 30 and 60°C (stress level: 2MPa) and fit to the Findley and Burger models.[5]

where $\varepsilon(t)$ is the creep strain at time t, ε_0 is the instantaneous elastic strain or time-independent parameter, A is the amplitude of transient creep (time-dependent), and n is a constant.

Burger's model is shown in the following equation:

$$\varepsilon(t) = \frac{\sigma_0}{E_M} + \frac{\sigma_0}{E_K}\left(1 - e^{-E_K t/\eta_K}\right) + \frac{\sigma_0}{\eta_M}t \quad (2)$$

where σ_0 is the stress, E_M is the elastic modulus of the Maxwell model (spring, or restorative force component), E_K is the elastic modulus of the Kelvin model, and η_M and η_K are the viscosities of the Maxwell and Kelvin dashpots (damping components), respectively.

Creep curves for all laminates obtained at 30 and 60°C are shown in Figure 2, along with the fitting obtained using both the Findley and Burger models. Creep behavior varies with the orientation angle, especially instantaneous deformation. Off-axis specimens present higher deformation over time, since they are more dependent on matrix behavior than the $[0]_{12}$ specimen.

Instantaneous deformation is larger due to poorer stress transfer for transversely oriented specimens. Because fiber/matrix interactions are partly of the frictional type, and transverse load relies purely on the tensile decoupling of the fiber/matrix interface, this type of load is more prone to creep. A similar trend is observed in relation to fiber orientation at higher temperatures, but with greater deformation due to the higher molecular mobility induced by thermal effects.[5]

With respect to the fitting of Burger's model, a decrease in Maxwell viscosity is associated with restrained polymer chains because of more efficient stress transfer (for more longitudinally oriented specimens). Kelvin viscosity reduction is explained by a more even stress share between matrix and fibers as the orientation shifts from 0 to 90°. Thus, greater mobility is obtained for the composites in which the matrix carries more stress and the short-term viscosity of the amorphous polymer chains increases.[5]

In summary, the viscoelastic behavior of laminates depends on fiber orientation as well as creep performance. Both Burger's and Findley's models are suitable for predicting the creep behavior of unidirectional specimens, showing generally good fitting of the experimental data. However, Burger's model tends to deviate for higher temperatures and when fiber orientation shifts to higher angles. As next steps, we plan to develop a numerical viscoelastic model and an experimental setup for application of higher loads. We will also investigate curved, layered filament-wound coupons.

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