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Characterization and modeling of polymeric matrix under multi-axial static and dynamic loading

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ABSTRACT

A polymeric matrix (3501-6) used in composite materials was characterized under multi-axial loading at strain rates varying from quasi-static to dynamic. Tests were conducted under uniaxial compression, tension, pure shear and combinations of normal and shear stresses. Quasi-static and intermediate strain rate tests were conducted in a servo-hydraulic testing machine. High strain rate tests were conducted using a split Hopkinson pressure bar (Kolsky bar) system made of glass/epoxy composite bars having an impedance compatible to that of the test polymer. The typical stress–strain behavior of the polymeric matrix exhibits a linear elastic region up to a yield point, a nonlinear elastic–plastic region up to an initial peak or "critical stress," followed by strain softening up to a local minimum, plateau or saddle point stress, and finally, a strain hardening region up to ultimate failure. A general three-dimensional elastic–viscoplastic model, formulated in strain space, was developed. The model expresses the multi-axial state of stress in terms of an effective stress, incorporates strain rate effects and includes the large deformation region. Stress–strain curves obtained under multi-axial loading at different strain rates were used to develop and validate the new elastic–viscoplastic constitutive model. Excellent agreement was shown between model predictions and experimental results.

1. Introduction

Recent and ongoing research in fiber reinforced polymer composites has dealt with material characterization, constitutive behavior and failure prediction. The process of fabrication, testing and modeling of these composites is costly, time consuming, and impedes the introduction of new materials. To facilitate and accelerate the process of introducing, evaluating and adopting new composite materials, it is important to develop/establish comprehensive and effective methods and procedures of constitutive characterization and modeling of the constituent materials, e.g., fibers and polymeric matrix.

Lamina characterization and modeling under multi-axial states of stress has shown that there are significant nonlinear viscoelastic and rate effects on the matrix dominated constitutive and failure behavior of these materials [1–3]. In the case of carbon/epoxy composites, the matrix is a key element that controls the inelastic and nonlinear behavior of the composite.

The constitutive and strain rate behavior of epoxies under various loading conditions has been studied by many researchers [4–14]. Constitutive models have been proposed by Schapery [14], Hasan and Boyce [15], Zhang and Moore [16], Buckley et al. [17] and Goldberg et al. [18].

The objective of this study was to characterize the matrix resin under multi-axial loading at different strain rates and to develop a general three-dimensional elastic–viscoplastic model that incorporates rate effects, allows for coupling between dilatational and deviatoric deformation and differentiates between tension and compression. Emphasis was placed on development of a relatively simple model for evaluation of a given polymeric matrix [19].

2. Material characterization

2.1. Material and specimens

The polymer matrix investigated is a high stiffness, high strength epoxy (3501-6) commonly used in composites. It has a highly crosslinked structure that provides stiffness and strength but also reduces its ductility and leads to fairly brittle behavior. The resin (supplied by Applied Poleramic, Inc.) was cast into closed

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molds to produce thin (3 mm) plates for tensile coupons, thick blocks for prismatic compression coupons, and thin-wall cylinders for specimens to be tested under torsion and combinations of torsion and axial tension or compression. The geometry and dimensions of the specimens used are shown in Fig. 1.

An optimum aspect ratio for the compressive tests was determined by testing specimens of varying aspect ratios (from 0.125:1 to 2.7:1). It was found that the apparent stiffness reaches the plane strain value (C_{11}) , corresponding to a uniaxial stain test, when extrapolated to zero aspect ratio and reaches asymptotically the Young's modulus E of the material, corresponding to a uniaxial stress test, for larger aspect ratios (Fig. 2). As the aspect ratio of the specimen increases, it becomes more susceptible to buckling. The smallest aspect ratio was chosen that satisfies uniaxial stress conditions while minimizing the probability of buckling. Tests under pure shear (torsion) and combinations of shear and normal tensile or compressive stress were conducted on thin-wall cylindrical specimens.

2.2. Testing

The Young's modulus was obtained directly as the stiffness approaching the asymptotic value for uniaxial stress at large aspect ratios. The stiffness C_{11} corresponding to uniaxial strain, obtained by extrapolation to zero aspect ratio in Fig. 2, and the shear modulus are related to the Young's modulus and Poisson's ratio as shown below. Poissons ratio is calculated from the measured stiffnesses C_{11} and E.

$$C_{11} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \qquad G = \frac{E}{2(1+\nu)} \tag{1}$$

The following results were obtained:

$E = 4.60$ GPa
$\nu = 0.35$
$G = 1.70$ GPa

Experiments were conducted at various strain rates ranging from 10^{-5} to 1500 s^{-1}. Lower rate experiments at less than 1 s^{-1} were conducted in a servo-hydraulic testing machine while the higher rate tests were conducted in a Split Hopkinson Pressure Bar system using composite (G-10) bars. Tension and pure shear tests at lower rates, 10^{-4} to 1 s^{-1}, did not show much rate dependence in stress–strain behavior. The rate effect was much more pronounced under uniaxial compression.

Dynamic testing at high strain rates was conducted in a Split Hopkinson (Kolsky) Pressure Bar (SHPB) system. Conventional Hopkinson bar systems with metallic rods are not suitable for testing compliant materials such as polymers. The high impedance mismatch results in high noise-to-signal ratios and short duration pulses that do not reach high enough strain levels over a sufficiently long period of time. The resin tested was expected to reach ultimate strains higher than 20%. To overcome these problems, polymeric rods have been used by several investigators [20–23].

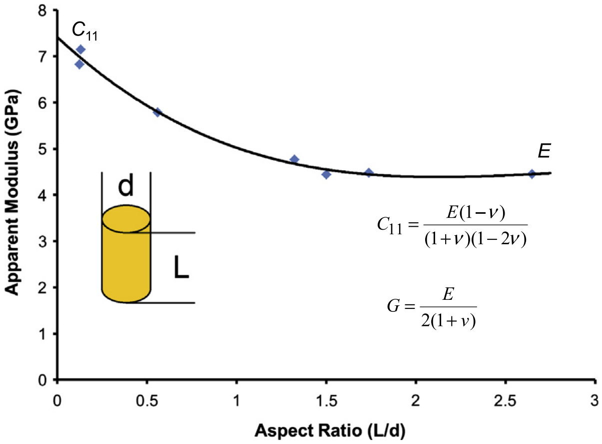

Fig. 2. Effect of aspect ratio on compressive response.

However, in the present case the specimen resin was stiffer and stronger than most polymers and it would damage the ends of typical polymeric bars. A compromise was reached with woven glass/epoxy composite (G-10) rods. The stress wave in the rods did not show much dispersion or attenuation and thus, there was no need for a more complex viscoelastic analysis of the signals.

A wave propagation analysis similar to that described by Daniel et al. [23,24] was conducted to establish the limits of validity of dynamic testing in the SHPB system. The stresses at the ends of the specimen are not equal initially, but approach each other as the wave pulse is reflected back and forth within the specimen. The ratio of stresses at the two specimen ends was calculated and plotted versus number of wave transits through the specimen for four Hopkinson (Kolsky) bar configurations, steel/epoxy/steel, aluminum/epoxy/aluminum, G-10/epoxy/G-10 and polycarbonate/epoxy/polycarbonate (Fig. 3). The analysis shows that, for the selected configuration, the difference between stresses at the two ends is less than 10% after four wave transits (one wave transit equals the time needed for the wave to propagate over one specimen length). This occurs at a time corresponding to less than 10% of the pulse duration.

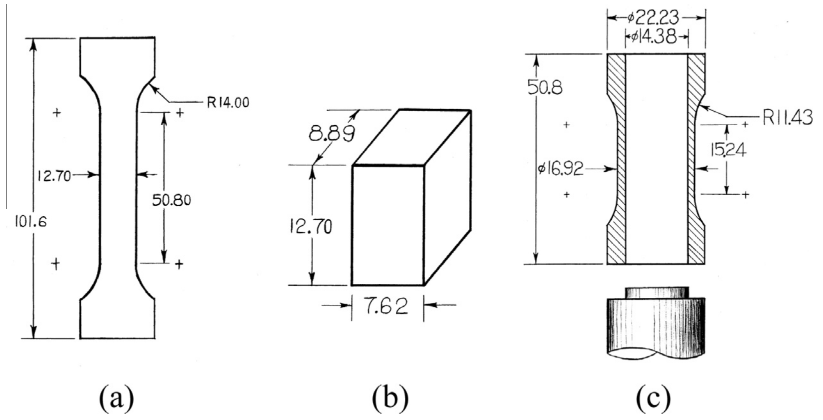

Fig. 1. Specimen geometries and dimensions. (a) Tensile specimen. (b) Compressive specimen. (c) Shear and combined stress specimen.