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The Failure Behavior of an Epoxy Resin Subject to Multiaxial Loading

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Abstract

The failure behavior of an epoxy resin (EPON 826) was investigated by a series of tests on thin-walled tubular specimens and the results are presented in this paper. The tests were designed such that a constant octahedral shear strain rate was applied along different loading paths. The rate effect was also studied by changing the octahedral shear strain rate. The experimental investigation showed that a change in stress state influences the failure strengths and failure modes. The different failure strengths and failure modes are attributed to the influence of the hydrostatic component of stress. Changing the strain rate influenced the failure stress, but not the failure characteristics.

Introduction

One of the biggest challenges facing our cities today is the deterioration of underground piping systems (e.g., water and sewer systems). In the past, excavation was used exclusively to replace deteriorated water and sewer pipes. However, as cities became more congested, the disruption and expense associated with excavation has become less acceptable. Therefore, polymer-based linings were developed permitting pipe rehabilitation with little or no excavation. Of these, epoxy-based cured-in-place pipe (CIPP) linings are becoming popular because of their high strength and toughness, good corrosion resistance and low shrinkage during curing. Epoxy polymers are also widely used as adhesives or matrices in other applications in a variety of industries, e.g., automotive, aerospace, oil and gas, and marine industries. With the increasing use of such epoxy resins in critical-load-bearing structures and with the increased application of limit states design methods in the design of these structures, it is imperative to understand the failure behavior of the polymeric materials.

The stress state in many applications is complex and multiaxial because of the constraints imposed by other components and reinforcement, in combination with the loading conditions (Asp et al. 1996). For metals and alloys (elasto-plastic materials), yielding is governed by the shear stress component and the effect of the hydrostatic stress component is negligible. For polymers, however, earlier studies (Ward

* This research was part of the researches toward a Ph.D. degree and conducted at the University of Alberta.

1971a, Anderson 1988, Asp et al. 1995, 1996, Kody and Lesser 1997, among others) have shown that the effect of a multiaxial stress state on the failure behavior of polymers includes two aspects, failure mode and failure stress. Ductile yield and brittle fracture are two failure modes common to most polymers and a change in stress state may affect the failure behavior from ductile yield to brittle fracture or vice versa. The influence of a multiaxial stress state on yield strength may be described by a modified von Mises criterion or by a modified Tresca criterion (Ward 1971a, Raghava et al. 1973, among others). Both modified failure criteria recognize that an appropriate failure criterion for many polymers must consider the hydrostatic stress effects on failure behavior.

Although a large number of experiments have been done to verify these criteria and/or to determine their constants, the design of the experiments has often been inadequate. In most experiments, multiple sample geometries were used to arrive at the different stress states (see e.g., Ward 1971a, Asp et al. 1996). As pointed out by Kody and Lesser (1997), this approach severely limits the number of different stress states that can be investigated and convolutes the results with effects of fabricating different specimen geometries. In studies where single geometries were used (Broutman, et al. 1970, Sultan and McGarry 1973, among others), the time effect and/or strain rate effect of the viscoelastic materials was not fully considered. Kody and Lesser (1997) overcame these problems by maintaining a constant octahedral shear strain rate, $\dot{\epsilon}_{oct}$, along the octahedral shear planes for all stress states and investigated different stress states using one specimen geometry and test configuration.

This paper presents the results of an experimental investigation whose aim was to elucidate the yield and fracture response of polymers and relate this response to the state of stress and strain rate. EPON 826/EPI-CURE 9551 was chosen for this purpose because it has excellent mechanical and thermal properties and, therefore, is suitable for CIPP and other high performance applications. An attempt was made to determine the multiaxial failure behavior of the EPON 826 epoxy system and the relative importance of deviatoric and hydrostatic stress components in the failure behavior of the epoxy. Rate effect was also studied by changing the octahedral shear strain rates.

Specimen Preparation and Test Facility

Specimen fabrication

EPON 826 and EPI-CURE Curing Agent 9551 are a bisphenol-A epoxy resin and a non-MDA (methylene dianiline) polyamine system, respectively. EPON 826 and hardener were mixed with 2.3:1 (volume) or 100:36 (weight) ratio, stirred thoroughly and poured into a tubular mould. The samples were then cured for 2 hours at 50°C with subsequent post cure for 2.5 hours at 120°C and cooled to room temperature in the oven prior to machining.

Specimens were manufactured from the samples on a computer numerical controlled (CNC) lathe that provides for precise machining of any transition profile geometry. The machined geometry is shown in Fig.1. The specimen had a uniform gauge length of 20 mm. The outside and inside diameters in the gauge length were 35.56 mm and 32.56 mm, respectively. The ratio of radius over wall thickness was about 11.4 and, therefore, the specimen could be treated as a thin-walled tubular specimen. Aluminum end tabs were glued to the tube ends so that the specimen could be inserted into the gripping system of the test machine without damaging the specimen extremities during gripping process.

Test Facility

All experiments were conducted in a servo-hydraulic, computer-controlled, multiaxial testing machine (see Ellyin and Wolodko (1997) for detailed description). This test facility could apply a combination of axial load, differential pressure (inside and outside pressures) and torsion on tubular specimens, and was capable of generating principal stress and strain ratios in all stress/strain quadrants, as well as change in the direction of the applied principal stresses and strains. Stress/strain controlled, monotonic/cyclic, and in-phase/out-of-phase (non-proportional) tests under ambient temperature conditions, could be performed with this system. The associated computer controlled hardware and software allows for a number of complex user-defined loading and acquisition schemes.

Figure 1. Thin-walled tubular specimen geometry and end tabs

Loading Scheme and Stress State

The loading scheme and stress state for tubular specimens are shown in Fig.2(a). Axial load, pressure differential between internal and external pressures, and torsion could be applied to the specimen simultaneously or in stages, or individually. This then induced axial, hoop and shear stresses within the tube wall, Fig.2(b). (The radial stress component, σ_r , was smaller by an order of magnitude and could, therefore, be neglected in comparison to the other two principal stress components). The axial, hoop, and shear stresses imposed on a thin-walled tube, subject to a combined axial load F , internal pressure P_i , external pressure P_e , and torque T , could be calculated by

$$\sigma_a = \frac{F}{\pi D t} + \frac{(P_i - P_e) D}{4 t} \quad (1)$$

$$\sigma_h = \frac{(P_i - P_e) D}{2 t} \quad (2)$$

$$\tau = \frac{2 T}{D t} \quad (3)$$

where D is the mean diameter and t is the thickness of the tube, σ_a , σ_h and τ are the axial, hoop and shear stresses, respectively.

Figure 2. Loading scheme and strain gauge layout (a) and stress state (b)

In order to compare the mechanical behavior of epoxy resins under different stress states, an equivalent stress is often used. Here the octahedral shear stress, τ_{oct} , was chosen which is defined as:

$$\tau_{oct} = \frac{\sqrt{2}}{3} \sqrt{\sigma_a^2 - \sigma_a \sigma_h + \sigma_h^2 + 3\tau^2} \quad (4)$$

Another important parameter for polymers is the hydrostatic stress, σ_m , which is given by:

$$\sigma_m = \frac{1}{3}(\sigma_a + \sigma_h) \quad (5)$$

Strain Gauge Layout

A pair of strain gauges, one in the axial direction and another in the circumferential direction, served as an axial and hoop strain transducers (Fig.2a). Two additional pairs of strain gauges mounted at $\pm 45^\circ$ to the axial direction were used for shear strain measurement.

CEA-13-062UW-350 strain gauges from Micro-Measurements Co., were used for measuring the strains. These gauges were attached to the tubular specimens with the M Bond, AE-10/15 adhesive system. The strain ranges for the axial and shear strains were all calibrated to $\pm 5\%$ strain with a resolution of 0.0005%.

Test Procedure

The failure behavior of this epoxy resin was studied by a loading scheme shown in Fig.3. Four different loading paths, labeled O1, O2, O3 and O4, were chosen in the principal strain space. These 4 paths correspond to uniaxial tensile and compressive ($\varepsilon_a / \varepsilon_h = -\nu$), equi-biaxial tensile ($\varepsilon_a / \varepsilon_h = 1$) and pure shear stress ($\varepsilon_a / \varepsilon_h = -1$) states, respectively. Due to material isotropy, the stress values at three other points, 1', 3' and 4' were assumed to be the same but with different signs (material symmetry). No data were obtained in the third quadrant because of the occurrence of buckling in the range of applied strains. A constant octahedral shear strain rate, $\dot{\varepsilon}_{oct}$, was imposed along all loading paths of Fig. 3. The octahedral shear strain rate, $\dot{\varepsilon}_{oct}$, is defined as:

$$\dot{\varepsilon}_{oct} = \frac{\sqrt{2}}{3} \sqrt{\dot{\varepsilon}_a^2 - \dot{\varepsilon}_a \dot{\varepsilon}_h + \dot{\varepsilon}_h^2 + \frac{\nu}{(1-\nu)^2} (\dot{\varepsilon}_a + \dot{\varepsilon}_h)^2 + \frac{3}{4} \dot{\gamma}^2} \quad (6)$$

where $\dot{\varepsilon}_a$, $\dot{\varepsilon}_h$ and $\dot{\gamma}$ are the axial, hoop and shear strain rates, respectively and ν is Poisson's ratio.

One specimen was utilized for each stress path at a given octahedral shear strain rate. The rate effect was investigated by loading specimens up to failure at three different octahedral shear strain rates of $10^{-3} s^{-1}$, $10^{-4} s^{-1}$, and $10^{-5} s^{-1}$.

Figure 3. Loading paths in principal strain space

All tests were performed at ambient environments (25°C and 50% humidity).

Test Result

Uniaxial tensile

Figure 4 shows the tensile stress – strain curves up to failure at three different octahedral shear strain rates of $10^{-3} s^{-1}$, $10^{-4} s^{-1}$ and $10^{-5} s^{-1}$. All these three stress – strain curves have similar patterns to failure with a highly nonlinear response prior to failure. The failure mode is a brittle fracture (Ward 1971b). An increase in the strain rate results in an increase of the failure stress, from 72.3 MPa to 81.0 MPa, however, the failure strains decrease (c.f. Fig.4).

Uniaxial compressive

Figure 5 depicts the uniaxial compressive stress-strain behavior of this epoxy at three different strain rates. These tests were conducted at a constant displacement rate control using a solid cylinder, as shown in the insert of the figure, due to the buckling of the tubular specimens. The diameter and height of the solid cylinders were 12.7 mm and 25.4 mm, respectively (in conformity with ASTM D 695-96). Compared with the tensile failure curves depicted in Fig. 4, the compressive tests have higher failure stresses and strains. Another difference is the failure mode: for the compressive tests, the material manifested a ductile failure (Ward 1971b), with peak stresses at approximately 6.25% strain.

Figure 4. Tensile stress-strain curves to failure at three different octahedral shear strain rates: $10^{-3} s^{-1}$, $10^{-4} s^{-1}$ and $10^{-5} s^{-1}$

Figure 5. Compressive stress-strain curves to failure at three different octahedral shear strain rates: $10^{-3} s^{-1}$, $10^{-4} s^{-1}$ and $10^{-5} s^{-1}$

Pure shear

The pure shear stress-strain curves to failure at three different octahedral shear strain rates are shown in Fig.6. These curves have maximum stresses prior to their final failures, thus indicating ductile yield behavior. It is noted that the failure stress increases with the increasing strain rate.

Equibiaxial tensile

The equibiaxial stress-strain curves to failure at three different octahedral shear strain rates are shown in Fig.7. It is observed that these typical biaxial stress-strain curves have some common features as the uniaxial curves shown in Fig.4. For example, linear behavior can be observed at low stress levels in both axial and hoop stress-strain curves. With the increased strain, the rate of increase in stress

decreases in both loading directions. The axial and hoop stress-strain curves were slightly different possibly due to the asymmetry of the specimen's geometry. The equibiaxial tests also failed in a brittle manner and the failure stresses increased with the increase of the in applied strain rate.

Figure 6. Shear stress-shear strain curves to failure at three different octahedral shear strain rates: 10^{-3} s^{-1} , 10^{-4} s^{-1} and 10^{-5} s^{-1}

Figure 7. Equibiaxial stress-strain curves to failure at three different octahedral shear strain rates: 10^{-3} s^{-1} , 10^{-4} s^{-1} and 10^{-5} s^{-1}

Hydrostatic stress effect

The octahedral shear stress versus octahedral shear strain curve is used to compare different loading paths (Fig.8). For metals and alloys (elastic-plastic materials), these curves for different proportional loading paths tend to collapse to one curve (Ellyin 1997). Figure 8 shows four octahedral shear stress – octahedral shear strain curves for the uniaxial tensile ($\sigma_a > 0$ and $\sigma_h = 0$), uniaxial compressive ($\sigma_a < 0$ and $\sigma_h = 0$), equibiaxial tensile ($\sigma_a = \sigma_h > 0$), and pure shear ($\sigma_a = -\sigma_h > 0$) loading paths, respectively. It is obvious that, for the epoxy resin, the curves are generally different from one loading path to another, with the uniaxial compressive curve the highest and the equibiaxial tensile curve being the lowest one. In between are the uniaxial tensile and pure shear curves with the uniaxial tensile curve slightly higher than that of the pure shear. The difference can be attributed to the influence of the hydrostatic stress.

For the uniaxial tensile test, $\sigma_a > 0$, consequently $\sigma_m > 0$, while for the uniaxial compressive test, $\sigma_a < 0$ and hence $\sigma_m < 0$; as for the pure shear test, $\sigma_a = -\sigma_h$, therefore, $\sigma_m = 0$. Since both $\sigma_a > 0$ and $\sigma_h > 0$ for equibiaxial tensile test, the corresponding σ_m value should be the highest among the four stress states. Therefore, a higher hydrostatic component of stress corresponds to the lowest stress response and a lower hydrostatic component of stress corresponds to a higher stress response. The relationship between the failure stress and the hydrostatic stress was described by a modified von Mises or modified Tresca equation (Kody and Lesser 1997, Asp et al., 1996):

$$\tau_y^{oct} = \tau_{y0}^{oct} - \mu \sigma_m \quad (7)$$

where τ_{y0}^{oct} is the failure shear stress in the absence of any overall hydrostatic stress and μ is commonly referred to as the coefficient of internal friction. If σ_m has no effect on τ_f^{oct} , then μ is equal to zero, the failure is said to follow a typical von Mises or Tresca behavior.

The quantitative relationship between the failure stress and the hydrostatic stress is shown in Fig.9. In this figure, the experimental failure data are compared with the modified Tresca criterion (eq. (7)) (only the Tresca failure envelope for 10^{-4} s^{-1} is depicted in this figure), here,

$$\tau_y^{oct} = \frac{1}{2}(\sigma_1 - \sigma_3) \quad (\sigma_1 > \sigma_2 > \sigma_3) \quad (8)$$

It is observed that the modified Tresca criterion fits the experimental data fairly well. For comparison, a Tresca envelope is also included in the figure with dotted lines. No experimental data was obtained for biaxial compressive failure stress in the third quadrant due to buckling of the tubular specimens. Those data, if available, will further check the aforementioned criterion.

Figure 8. Octahedral shear stress versus octahedral shear strain curve for different loading paths at a fixed strain-rate

Figure 9. Comparison of experimental data with the modified Tresca criterion

Comparison of Figs 5-8 shows that the failure modes are different: the failure mode for uniaxial tensile and equibiaxial tensile tests is brittle fracture while pure shear and uniaxial compressive tests show ductile yielding behavior. Since the uniaxial tensile and equibiaxial tensile tests have positive hydrostatic stress and the pure shear and uniaxial compressive tests have zero or negative hydrostatic stress, a high positive hydrostatic component of stress tends to produce a brittle fracture failure while ductile yielding prevails when the hydrostatic stress is zero or negative.

Conclusions

Specimens were loaded to failure under specified octahedral shear strain rates to investigate the failure behavior of the EPON 826/EPI-CURE 9551 epoxy system subject to multiaxial stress state. From the results presented in this experimental investigation, the failure behavior was found to be dependent on the stress state as manifested by different octahedral shear stress -- octahedral shear strain curves. The failure modes were also different depending on the stress state. The different failure curves and failure modes are attributed to the influence of the hydrostatic component of stress. A high positive hydrostatic component of stress tends to produce a brittle fracture failure while ductile yielding prevails when the hydrostatic stress is zero or negative. A modified Tresca criterion can describe the failure stress envelope quite well when the hydrostatic component of stress is included in the modification criterion. Changing strain rate only influences the failure stress, but not the failure characteristics.

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