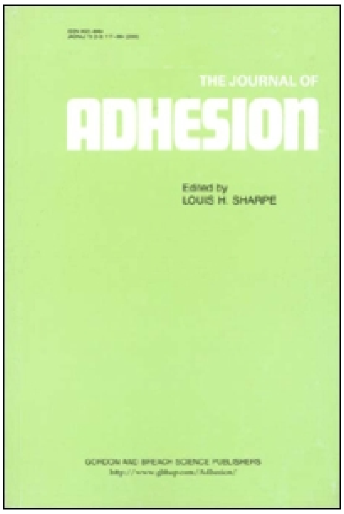

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Failure Criterion of a Typical Polyamide Cured Epoxy Adhesive

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INTRODUCTION

The use of adhesive joints as structural elements is increasing rapidly. A thorough understanding of failure behavior of bulk adhesive is essential in analyzing the failure mode of adhesive joints.[1] This article discusses existing failure criteria for continua under multiaxial stress fields in most general terms. From this general description, an attempt was made to formulate by simple experiments the specific failure criterion of a typical polyamide cured epoxy adhesive, which is to be an input for the failure analysis of a given adhesive joint system utilizing the same adhesive.

THEORETICAL CONSIDERATIONS

Failure criteria in complex stress state may be represented by the equation

$$f(\sigma_{ij}) = C \tag{1}$$

where

$$\sigma_{ij} = \text{stress components}$$
$$C = \text{material constant.}$$

Since one can always transform the general stress, σ_{ij}, into three orthogonal principal stresses, Eq. (1) is equivalent to

$$f(\sigma_1, \sigma_2, \sigma_3) = C_0 \tag{2}$$

where

$$\sigma_1, \sigma_2, \sigma_3 = \text{principal stresses}$$
$$C_0 = \text{constant.}$$

Eq. (2) may be expressed geometrically in the form of a failure surface in principal stress space. For an isotropic material, this surface is symmetrical with respect to the space diagonal.

Any combination of stresses is safe if the corresponding point in principal stress space falls within the failure surface. If the point lies on or outside this surface, the material in question will fail.

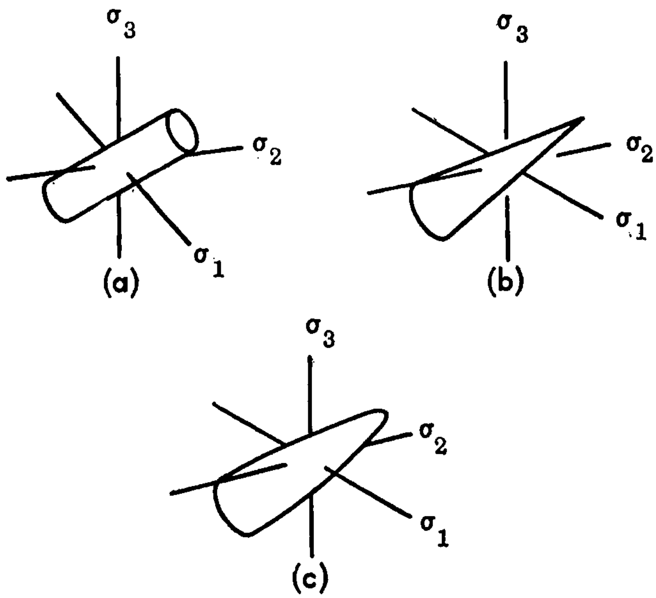

FIGURE 1 Failure surfaces in principal stress space. (a) Cylinder, (b) cone, (c) paraboloid.

Figure 1 shows representative failure surfaces;[2] their equations are as follows:

Cylinder

$$\sigma_{os} = \sqrt{\tfrac{2}{3}}\sigma_{Tb} \tag{3}$$

Cone

$$\frac{1}{\sqrt{2}}(\sigma_{cb} + \sigma_{Tb})\sigma_{os} + (\sigma_{cb} - \sigma_{Tb})\sigma_{on} = \tfrac{2}{3}\sigma_{cb}\sigma_{Tb} \tag{4}$$

Paraboloid

$$\sigma_{os}^2 + \tfrac{2}{3}(\sigma_{cb} - \sigma_{Tb})\sigma_{on} = \tfrac{2}{9}\sigma_{cb}\sigma_{Tb} \tag{5}$$

where

σ_{Tb} = failure stress in uniaxial tension

σ_{cb} = failure stress in uniaxial compression

σ_{os} = octahedral shear stress

$= \tfrac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}}$

σ_{on} = mean normal stress $= \tfrac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$

The significant points to observe in these equations are the dependence of octahedral shear stress on the mean normal stress. For example, for a cylindrical failure surface, the octahedral shear stress σ_{os} is independent of σ_{on} while, for a paraboloid $(\sigma_{os})^2$ is directly proportional to σ_{on}. Therefore, in the criterion expressed by Eq. (3), it is the critical value of the octahedral shear stress alone that determines the failure.

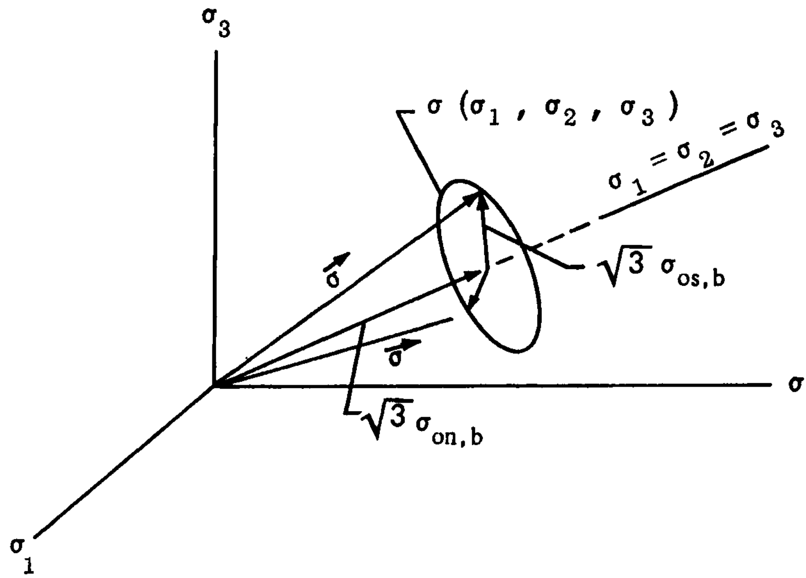

FIGURE 2 Deviatoric and isotropic components of the state of stress.

In principle, the failure surface may be determined experimentally by carrying out a sufficient number of tests under appropriate multiaxial loading conditions. An analytical representation of the surface can then be found, and this may serve as the failure criterion. However, it is time consuming, if not experimentally impossible to accomplish this task.

The failure criteria described by Eqs. (3), (4) and (5) can also be represented conveniently in a plane[3] by plotting $\sqrt{3}\,\sigma_{os,b}$ as a function of $\sqrt{3}\,\sigma_{on,b}$. $\sqrt{3}\,\sigma_{on,b}$ is the projection of the stress vector, $\bar{\sigma}$, on the space diagonal ($\sigma_1 = \sigma_2 = \sigma_3$ axis), and is called the isotropic component (see Figure 2). The former ($\sqrt{3}\,\sigma_{os,b}$) is the projection of the vector onto the plane perpendicular to the diagonal and is termed the deviatoric component. In a plane with the coordinates $\sqrt{3}\,\sigma_{on,b}$ and $\sqrt{3}_{os,b}$, the failure criteria appears as the intersection of the failure surface with any plane containing the space diagonal as the abscissa.

EXPERIMENTAL ASPECTS

The experimental approach chosen in this investigation was formulation of the failure criterion by determining the intersection of the failure surface with any plane containing the space diagonal as the abscissa from simple experiments. Specifically, the uniaxial tension, uniaxial compression, and shear (torsional) experiments were made to achieve this goal.

For strain rates below 1 in./in.-min the uniaxial tension (Microtensile specimen, ASTM–D 1708) and compression (solid cylindrical sample) tests were made on the Instron Universal Testing Instrument.† For higher rates, the closed-loop electrohydraulic MTS (Materials Testing System) low-cycle fatigue system‡ was used in conjunction with a Honeywell Visicorder§ with high-frequency galvanometers (1 kHz). The torsional actuator of the MTS system was used for the shear experiments (ASTM–D 1822, Type S sample, except cylindrical) in torsion.

The adhesive selected for this investigation is a two part epoxy system. The resin is the diglycidyl ether of bisphenol-A with an inert filler, kaolin. The hardener is a polyamide, likewise filled with kaolin. The popularity of this adhesive can be ascribed to its ease of preparation, its availability in kit form, its ability to be cured at room temperature as well as elevated temperatures, and its capability of bonding many dissimilar materials.

The cure cycle for the adhesive was three hours at 150°F, which included one hour to preheat the fixtures. After the cure cycle was complete, all specimens were allowed to equilibrate for a minimum of 24 hours at 72°F and 50% relative humidity before testing.

RESULTS AND DISCUSSION

Figures 3, 4 and 5 are the simple test results from which the bulk failure property of the adhesive in multiaxial stress fields was formulated. Namely, these are data from uniaxial tension, compression and shear (torsion) experiments at various strain rates. As apparent in the figures, dependence of bulk properties on strain rate is predominant at room temperature. This is not surprising, considering that the glass transition temperature, T_g (35 ~ 40°C)[4] is not much higher than room temperature. Consequently, the failure surface which appears to be paraboloidal is highly rate dependent as shown in Figure 6. The failure associated with the surfaces described in this figure is by yielding.

† Model TTD; Instron Corp., 2500 Washington St., Canton, Mass. 02021.

‡ Model 901.34; MTS Systems Corp., Box 24012, Minneapolis, Minn. 55424.

§ Model 1012; Honeywell, Inc., Industrial Division, 1100 Virginia Drive, Fort Washington, Pa. 19034.

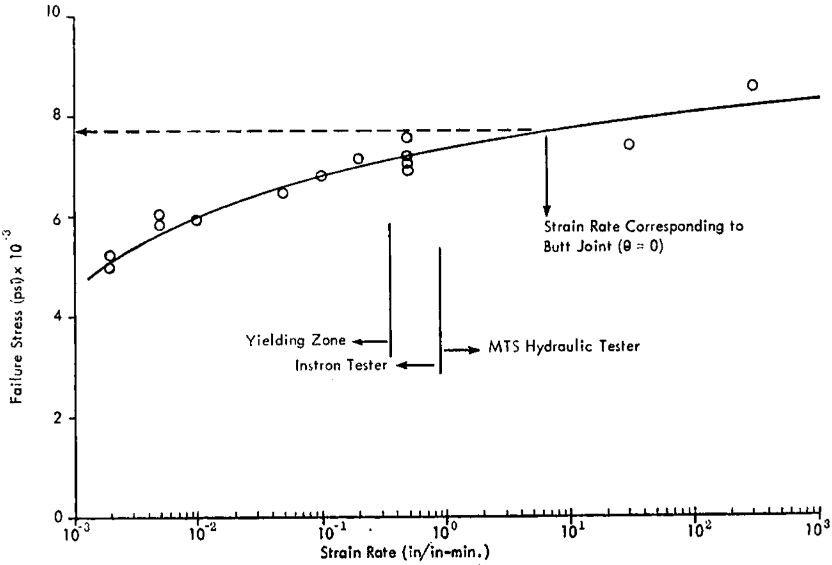

FIGURE 3 Rate dependence of Uniaxial tension failure stress.

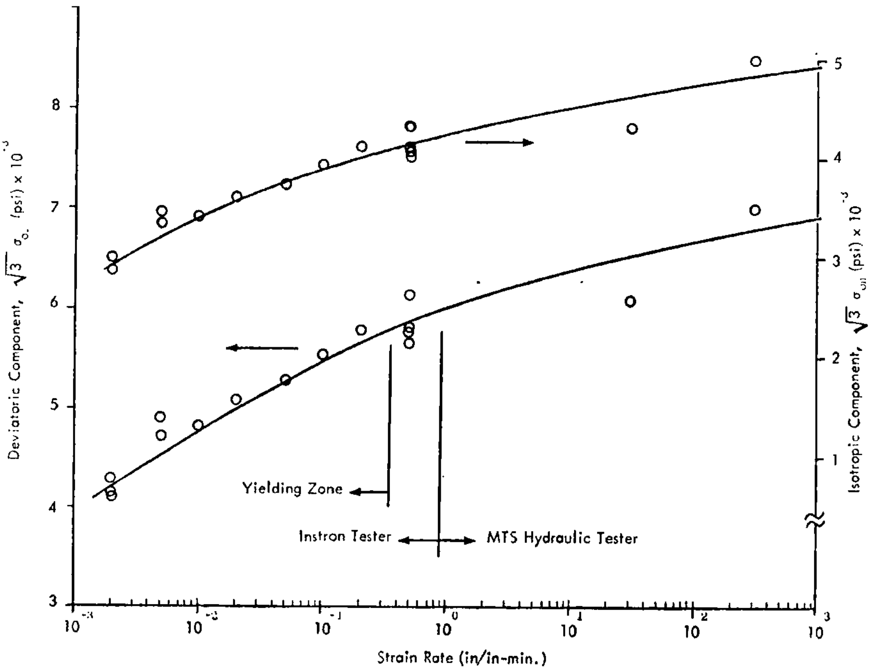

FIGURE 4 Dependence of deviatoric and isotropic failure stresses on strain rate (uniaxial tension)

In constructing the failure surface, the question, "What is the equivalent strain rate in shear?", was raised. Here, the numerical value of shear rate in torsion was treated as equivalent to the strain rate in tension and compression. Thus, the strain rate parameters in uniaxial and torsion modes are:

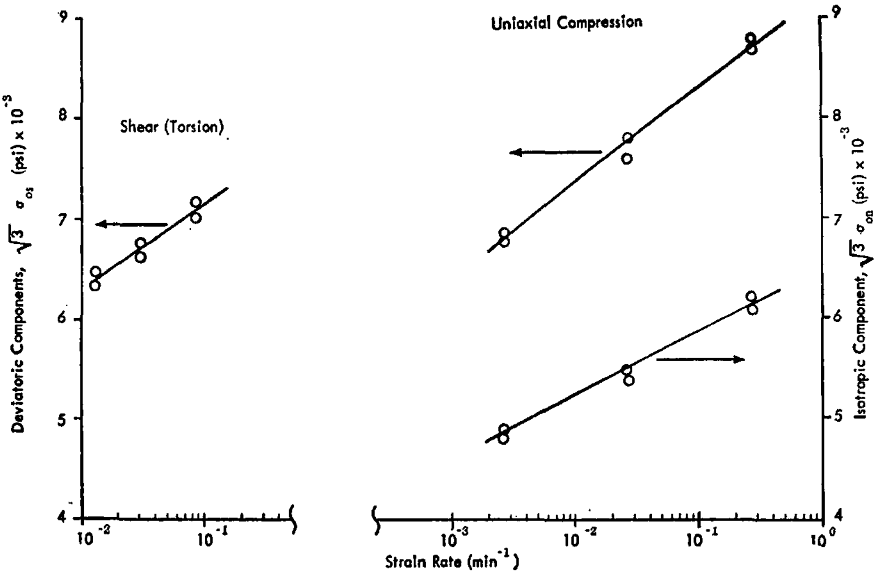

FIGURE 5 Dependence on Deviatoric and isotropic failure stresses on strain rate (compression and shear).

1. *Uniaxial*

$$\dot{\varepsilon} = XHS/Lo$$

where

$$\dot{\varepsilon} = \text{strain rate (in./in.-min)}$$
$$XHS = \text{crosshead speed (in./min)}$$
$$Lo = \text{gauge length (in.)}$$

2. *Torsion*

$$\dot{\gamma} = \dot{\theta}r/L$$

where

$$\dot{\gamma} = \text{shear rate (min}^{-1}\text{)}$$
$$\dot{\theta} = \text{rate of twist (rad/min)}$$
$$r = \text{radius (in)}$$
$$L = \textit{gauge length (in)}$$

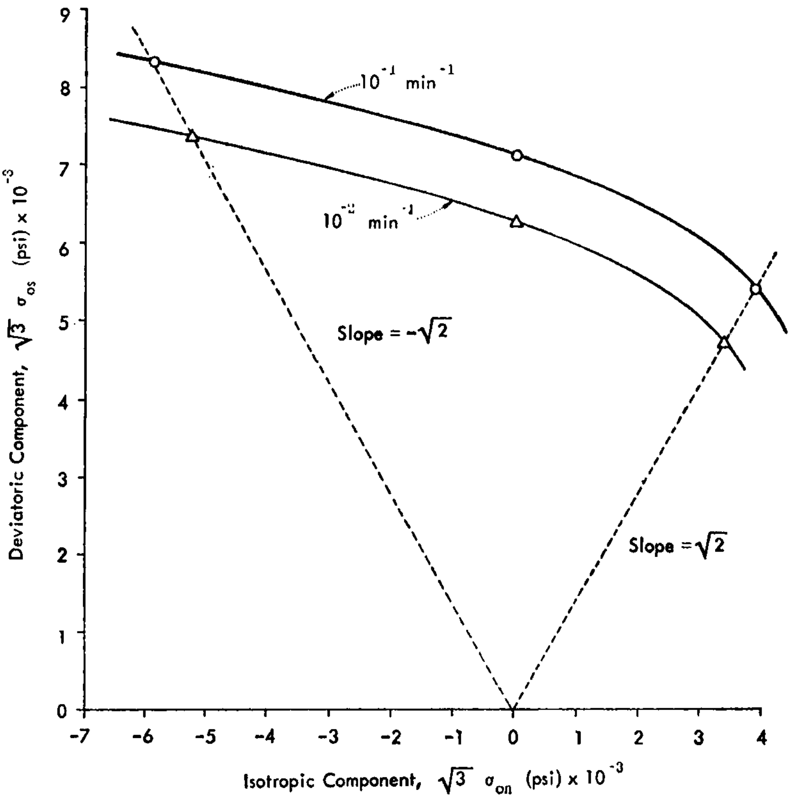

FIGURE 6 Failure surface for two different strain rates.

CONCLUSION

An attempt was made to formulate the multiaxial failure criterion of a typical polyamide cured structural epoxy adhesive from simple experiments. This is to be used as an input for the failure analysis of a given adhesive joint system utilizing the same adhesive.

The failure surface in principal stress space appears to be a paraboloid and, therefore, the failure criterion depends both on the octahedral-shear and mean-normal stresses. The failure surface is highly time (or rate) dependent even at room temperature as expected, due to the fact that the glass transition temperature of the adhesive is close to room temperature.

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