

Establishing Failure Criterion for Elastomers Through Improved Biaxial Testing

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ABSTRACT

Testing elastomeric materials that undergo large strains pose challenges especially when establishing failure criteria. The failure criterion for composites and polymers based on finite elasticity published by Feng (1) requires testing under uniaxial and biaxial stretching modes. The classic inflation of a circular disk for biaxial stretch mode poses stability and safety challenges. The test can also be sensitive to end constraints resulting in failure of materials at the constraints. Biaxial stretching with a hemispherical punch is explored in this work. The biaxial stretching allows controlled and repeatable testing. It establishes a clear and reliable failure mechanism of the material at the poles. Through a combination of testing and numerical methods, the stretch ratios and its relation to failure have been established. The method greatly simplifies testing and provides reliable data for a failure criterion for elastomers in numerical modeling.

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INTRODUCTION

The failure criterion for composites based on finite elasticity developed by Feng et al. [1] and later extended for polymers and soft biological materials by Feng and Hallquist [2] depends on testing materials in two deformation modes, in tensile and biaxial condition.

The biaxial extension of elastomers has been accomplished by radial stretching of disks, balloon style extension of thin membranes, and by complex scissor grip systems all with reasonable success. However, observing failure in biaxial extension is problematic because the region where the elastomer is gripped or held will typically experience a higher strain than the biaxial region and fail first. This is certainly true for the radial stretching of disks and for the scissor grip system.

The balloon style biaxial failure has had some success when special molded sheets of elastomer are constructed wherein a thick clamping ring is molded into the elastomer membrane to allow a strain transition at the gripping region. However, this special molding of specimens is often not practical.

The approach described in this paper is to push a hemispherical probe into an elastomer sheet surface stretching it until failure. The data from the tests were used to establish failure criterion in a simplified rubber material model in the finite element code LS-DYNA.

MATERIAL MODEL WITH DAMAGE

Many hyperelastic material models use polynomial fits to derive their constants. The MAT_SIMPLIFIED_RUBBER material model implemented with LS-DYNA is designed to take direct engineering stress strain obtained using standard tensile and compression tests. Strain rate dependency can also be input as part of this material model. To model damage in the polymers unloading data can be provided; this unloading curve is not strain rate dependent. The basis of the MAT_SIMPLIFIED_RUBBER is the Ogden strain energy potential model.

The Ogden strain energy potential shown in [equation 1](#) is based on the principal stretch ratios shown in [equation 2](#). As observed from tests, rubber materials do not exhibit the same path dependent behavior during loading and unloading. This is due to damage in the material. The damage behavior is a function of the elastic deviatoric energy and the maximum deviatoric energy over the deformation path, [equation 3](#). The general implemented Ogden strain energy potential is limited to quasi-static state.

$$W = \sum_{i=1}^3 \sum_{j=1}^n \frac{\mu_j}{\alpha_j} (\lambda_i^{\alpha_j} - 1) + K(J - 1 - \ln J) \quad (1)$$

$$\lambda_i^* = \lambda_i J^{-1/3} = \frac{\lambda_i}{J^{1/3}} \quad J = \lambda_1 \lambda_2 \lambda_3 = \frac{V}{V_0}$$



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$$W = \left(1 - d \left(\frac{W_0}{W_{0,max}} \right) \right) \sum_{i=1}^3 \sum_{j=1}^n \frac{\mu_j}{\alpha_j} (\lambda_i^{\alpha_j} - 1) + K(J - 1 - \ln J) \quad (3)$$

Where, the damage functional is represented by

$$W_{0,max} = \max(W_0, W_{0,max}) \Rightarrow 0 \leq \frac{W_0}{W_{0,max}} \leq 1 \Rightarrow 0 \leq d \leq 1 \quad (4)$$

Material unloading due to stress relaxation in this material model is represented using Prony Series. Equation 5 below represents the series. Where the Shear Moduli are G_i and the decay constants are γ_i .

$$g(t) = \sum_{i=1}^n G_i e^{-\gamma_i t} \quad (5)$$

Failure in rubber is implemented in terms of strain invariants. The failure surface is defined by Equation 6. Since it is based on energy principle; failure occurs when the strain energy reaches a maximum.

$$I_1 - \Gamma_1(I_1 - 3)^2 + \Gamma_2(I_2 - 3) - K = 0 \quad (6)$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \text{ and } I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2 \quad (7)$$

Where, I_1 and I_2 are strain invariants and can be written in terms of principle stretches as shown in Equation 7. The Failure surface is defined using the principle stretch ratios as show in Figure 1.

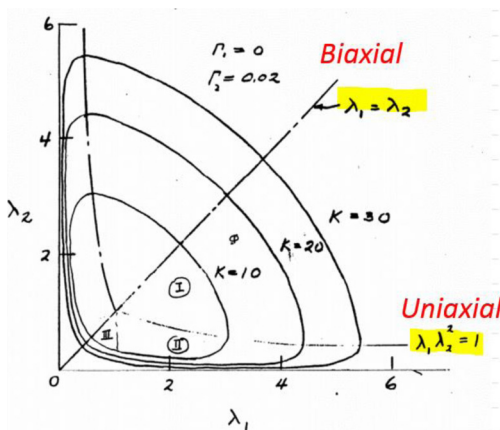


Figure 1. Failure surface for hyperelastic solids

The constants in Equation 6 were calculated using the following Formulae. We have three equations and three unknowns. Simultaneous equations are used to solve these. For most practical applications Γ_2 is Zero, leaving two unknowns.

From uniaxial test (compression or tension) principle stretch ratios in axis 2 and 3 are same

$$\lambda_2 = \lambda_3$$

For incompressible materials

$$\lambda_1 \lambda_2 \lambda_3 = 1 \quad (8)$$

Substituting these in equation 7 we get Strain invariants in terms of Principle Stretch Ratios for uniaxial test, Equation 9

$$I_1 = (\lambda_1^3 + 1)/\lambda_1 \text{ and } I_2 = \lambda_1 \quad (9)$$

From Biaxial test data

$$\lambda_1 = \lambda_2 \quad (10)$$

Substituting equations 8 and 10 into Equation 7 we get strain invariants in terms of principle stretch for biaxial data; see Equation 11

$$I_1 = 2\lambda_1^2 + 1/\lambda_1^4 \text{ and } I_2 = \lambda_1^4 + 2/\lambda_1^2 \quad (11)$$

Deriving Failure Constants - Uniaxial Mode

The uniaxial tension or compression test will provide one data point on the failure envelope. It is a simple and common test to perform. Three uniaxial tensile failure strains of 4.32, 4.4, and 4.53 were obtained from test shown in Figure 2.



Figure 2. Tensile test setup used to derive failure strains.