Rate-dependent Deformation and Fracture of a Thermoplastic Elastomer Tissue Surrogate

Yao Chen[1] and Jow Ding*†[1]

[1]Washington State University – United States

Abstract

Characterizing and modeling the mechanical behavior of tissue-like materials are essential for various biomedical applications. In addition to deformation-related properties such as strength and ductility, fracture toughness is a critical material property as it reflects a tissue's ability to resist defects and fractures. Experimental techniques commonly used to measure the fracture toughness of soft materials include the trouser tear test, the pure shear test, and similar methods. Fracture toughness, or the critical energy release rate, is typically calculated using rate-independent nonlinear elasticity analyses.
For the trouser test, the critical energy release rate is given by:

J = 2(L)(F)/(B) - 2W(strain)(H), (1)

where L is the stretch ratio, F is the critical force at the initiation of the crack growth, W is a hyperelastic strain energy function of strain, B and H represent the sample width and height, respectively. In practice, the strain energy stored in the branched sections of the sample, where tensile force is applied, is often ignored, yielding a simplified expression:

J = 2(F)/(B). (2)

For the pure shear test, J is given by

J=2W(strain)(H). (3)

Although these equations are grounded in rate-independent strain energy functions, they are often applied to materials exhibiting rate-dependent fracture behavior, where fracture toughness varies with crack velocity or loading rate. This rate dependence arises from the rate-sensitive critical values of F, L, or strain at the initiation of crack growth, which serve as inputs to evaluate the rate-independent strain energy functions. However, for rate-dependent materials, the strain energy function is expected to depend not only on strain but also on strain rate. This raises important questions about the role of rate-dependent strain energy functions in fracture toughness measurements, motivating the present study.

A recent investigation (1) explored the deformation behavior of a synthetic SEBS gel (styrene-ethylene-butylene-styrene), a widely used tissue surrogate, under uniaxial compression across a broad range of strain rates. The material exhibited highly nonlinear and rate-dependent

*Speaker

†Corresponding author: jowlian_ding@wsu.edu

mechanical behavior. Based on these observations, a visco-hyperelastic model was developed, extending Ogden's hyperelastic framework to incorporate rate sensitivity. This model, using a rate-dependent strain energy function, W(strain, strain rate), effectively captured the material's essential characteristics.

Building on this model, the current study investigates the influence of rate-dependent strain energy functions on fracture toughness measurements. Both trouser tear and pure shear tests were performed to assess the impact of rate dependence across test configurations and to cross-validate results. The same SEBS gel from (1) was tested at strain rates ranging from 0.001/s to 0.1/s. Complementary tensile tests were conducted to validate the model's predictions for tension loading. Within this strain rate range, the material exhibited increased strength and toughness with increased strain rate.

Fracture test results were analyzed using both rate-independent and rate-dependent strain energy functions. For the pure shear configuration, rate-independent analysis, Equation (3), underestimated fracture toughness, while for the trouser tear configuration, Equation (1) overestimated toughness. Notably, the simplified analysis based solely on the critical force, Equation (2), reasonably approximated the rate-dependent analysis within the studied strain rate range. Incorporating rate-dependent strain energy functions proved essential for achieving consistent fracture toughness measurements across different test configurations.

References
(1) Chen, Y., Ding, J.L., Babaiasl, M., Yang, F., and Swensen, J. P., 2022, "Characterization and modeling of a thermoplastic elastomer tissue simulant under uniaxial compression loading for a wide range of strain rates," J Mech Behav Biomed Mater, 131:105218.