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Cohesive zone modeling of mode I tearing in thin soft materials

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ABSTRACT

The use of modeling and simulation is growing rapidly in applications such as surgery simulations, injury mechanics and tissue engineering. The aim of this study is to model and simulate tissue tearing and the resulting failure for use in such applications. In particular, our goal is to characterize the mechanics of mode I tearing in thin soft materials. We use the cohesive zone modeling approach to characterize the propagation of tears in a processed meat product (PMP). The bulk response of the PMP is modeled with a hyperelastic material model and the interface with a cohesive zone model. A multistep parameter estimation approach is developed to determine the bulk and the cohesive model parameters from uniaxial extension and tearing experiments. Results show that the proposed approach is able to capture both material and geometrical nonlinearities inherent to such problems, and accurately model the overall force–displacement response of thin soft materials during tearing at slow rates.

1. Introduction

The ability to accurately model and simulate the tearing of tissue is critical to applications like injury mechanics and surgery simulation, and requires a high level of realism. This is a challenging task because tissue tearing simulations involve both material and geometrical nonlinearities, as well as numerical issues such as instabilities associated with tracking the tip of the tear. On the other hand, conducting the experiments needed to develop the computational models is also challenging because of the difficulty in preparing, handling and testing soft tissue specimens, particularly in tension.

For surgery simulation-related applications, experiments measuring the forces in cutting tissue and soft materials have been carried out by many researchers including Valdastri et al. (2007, 2009), Lim et al. (2005), Chanthasopeephan et al. (2003, 2007), and Dowgiallo (2005). Chanthasopeephan et al. (2006) studied the fracture characteristics of liver tissue and found that its fracture resistance is not sensitive to crack length. The fracture resistance of biological materials has also been studied by Oyen-Tiesma and Cook (2001), Purslow (1989), Kendall and Fuller (1987), Pereira et al. (1997) among others.

Simulating the tearing and fracture of materials presents many challenges such as the resolution needed to capture

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such highly local damage phenomena, the representation of the topology of cracks in three-dimensional problems, and the associated computational complexities. Various approaches have been proposed for handling these difficulties. Wells and Sluys (2001) (and the references cited therein) developed a finite element method based on the partition of unity wherein the underlying basis is enriched with a discontinuous jump function. This allows the displacement discontinuity resulting from the crack to exist inside a standard finite element. In a related approach, Moës and Belytschko (2002) applied the extended finite element method to model the growth of arbitrary cohesive cracks. This approach allows arbitrary discontinuities (such as cracks) to exist in the finite element mesh and remeshing is not needed as the crack propagates. Another approach is the cracking particle method (Rabczuk and Belytschko, 2004, 2007), which can model arbitrarily oriented cracks as cylindrical planes centered at individual particles in the structure. As such, explicit representation of the crack's topology is not necessary in this approach. A related method motivated by the cracking particle method is discussed in Rabczuk et al. (2010). To address the computational cost of simulating localized failure, Kerfriden et al. (2011, 2012) developed reduced order modeling approaches in conjunction with Newton–Krylov solvers. In this global-local approach, a high resolution local problem (associated with the damage region) is coupled with a low resolution global problem, which is solved in a reduced space based on traditional proper orthogonal decomposition.

The overall goal of this work is to model normal (mode I) tearing in thin soft materials while fully taking into account the material and geometrical nonlinearities in the problem. Towards this end, we use the cohesive zone modeling approach, which treats the interface of the tear as a separate constituent with its own constitutive model. This constitutive model, called the traction-separation law, is distinct from the bulk material and describes the tractions required to achieve a given level of interface separation. It typically consists of an elastic response up to a maximum traction value, followed by an inelastic softening response before complete interfacial separation occurs. Consequently, the stress concentration at the tip of the tear and the resulting singularity predicted by linear elastic fracture mechanics are eliminated.

While the cohesive zone approach has been used extensively for engineering materials like metals, concrete, etc., its use in modeling biological materials and soft materials is more recent. For instance, it has been used to model tissue cleavage in needle-tissue interactions (Misra et al., 2008), probe insertion (Oldfield et al., 2010), and trabecular bone damage (Tomar, 2008). The ease of implementation of the cohesive zone approach makes it an attractive alternative to approaches based on fracture resistance.

In this work, we focus on the specific problem of modeling mode I tearing in thin soft materials using the cohesive zone approach. The modeling work is supported by experiments conducted on a processed meat product (PMP). Because of the challenges in procuring, preserving and preparing biological tissue samples, we use this PMP as the candidate soft material. The PMP has mechanical characteristics similar to soft cellular tissues like liver and can be easily cut into required shapes for specimen preparation. Uniaxial and tearing experiments are carried out to characterize the bulk and tearing characteristics of the PMP. The resulting data form the basis for the development of nonlinear constitutive models of the bulk and tearing responses, which lie at the heart of this work.

The bulk material is modeled in the continuum mechanics framework as a hyperelastic material. A four-term Ogden strain energy density function is used for this purpose. The Ogden model parameters for the PMP are found from the uniaxial tension experimental data using a nonlinear optimization procedure.

To model the tearing of the PMP we employ a modified version of the so-called PPR cohesive zone model proposed by Park et al. (2009). In the original model proposed by Park et al. (2009), the tractions in the interface are obtained by differentiating a potential function with respect to the normal and tangential interface separations. We modify the PPR model in the pre-damage region by opting for a linear elastic response, which makes it amenable to a straightforward implementation in the finite element code ABAQUS (Simulia, 2009). Once again, a nonlinear optimization procedure is used to determine the cohesive zone model parameters from the tearing response of the PMP.

2. Materials and methods

2.1. *Experimental methods*

PMP samples (smoked white turkey bologna) for the uniaxial extension and tearing experiments are freshly purchased from a local supermarket on multiple dates, and are covered with a damp towel to prevent drying during sample preparation. For the uniaxial extension experiments, samples are dimensioned 30 mm × 15 mm × 3 mm, as shown in Fig. 1(a). Samples are extended at a slow rate of 0.15 mm/s up to 50% nominal strain. The extension experiments are performed using a bench-top testing system, TestResources 100R (Shakopee, MN), with a 10 N load cell.

The same experimental set-up and parameters are used for the tearing experiments. However, a small cut of 2 mm is introduced perpendicular to the direction of the loading near

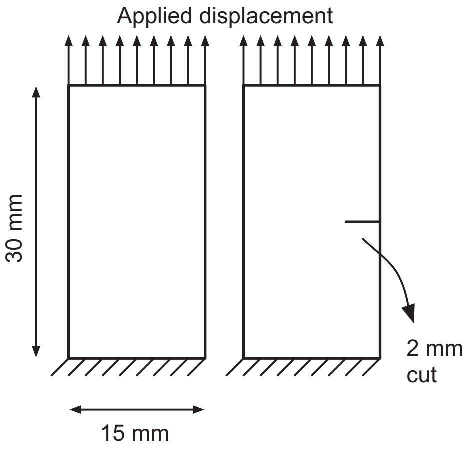

Fig. 1 – Schematic of the uniaxial extension and the tearing tests.