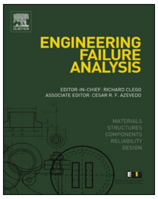
Engineering Failure Analysis 90 (2018) 404–424

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal



Predicting failure in rubber membranes: An experimental-numerical approach

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ARTICLE INFO

Keywords:
Damage
Hyper-viscoelastic
Cohesive traction law
Rubber

ABSTRACT

A material model to predict tearing of a rubber membrane in finite element analysis was developed. Using experimental data from uniaxial tension test and tearing of rubber sheets, we combined a cohesive traction law with a hyper-viscoelastic constitutive equation to create this material model. The resulting material model described hyper-viscoelastic behavior before damage, damage initiation, and damage evolution and consequent crack growth through a finite element mesh. The numerical simulations of tearing rubber sheets were found to be in good agreement with test data in terms of force-displacement response, onset of fracture and crack growth path. A key advantage of using this proposed material model is that there was no need to pre-define crack paths in the finite element analysis. Crack paths were controlled by the damage initiation and evolution laws as well as the tearing energy of the rubber.

1. Introduction

Rubbers find any applications in numerous industries owing to their unique properties, such as flexibility, high extensibility, resilience and durability under complex loading conditions. A few examples of this include the tires, belts, hoses, bushings, mounts and seals used in the automotive industry, and the diaphragms, gaskets, seats and ligature bands used in the medical industry. The conveyer belts found in most factories are made of reinforced rubber and much of today's machinery would not function without rubber belts, seals, hoses and gaskets. Rubber is indeed an indispensable industrial material. However, rubbers are one of the most difficult materials to model because its long-chain molecular structure results in nonlinear, hyperelastic and time-dependent, viscoelastic properties. Such behavior becomes even more complicated when fillers, primarily carbon black and silica, are introduced in rubber formulations in order to improve its stiffness, wear and durability. This paper is concerned with predicting failure of a rubber membrane. All rubbers contain microscopic defects, and damage can potentially initiate from such defects. Microscopic defects eventually grow and coalesce into micro-cracks or micro-cavities under the life of a part. Micro-cracks, in turn, may grow to a critical crack size and result in a sudden or unstable rupture thereby causing catastrophic failure of a rubber component.

The objective of this paper is to develop a material model that can be used to numerically predict tearing of a rubber membrane when it is subjected to dynamic tensile loading. Specifically, we examine Styrene Butadiene Rubber (SBR) sheets under dynamic loading. Styrene Butadiene Rubber is a widely-used rubber in industry due to its excellent abrasion resistance, aging stability and affordability. Experiments have been performed on SBR dumbbell and sheet specimens under a various loading rates by [1]. These results are used in this study to develop a material model that can be incorporated in an ABAQUS Explicit user-material subroutine (VUMAT) and used to predict damage initiation and growth of cracks in a rubber membrane. The material model is developed based on the concept of cohesive traction law, which has been used widely in computational work to determine crack propagation in

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https://doi.org/10.1016/j.engfailanal.2018.04.003
Received 16 January 2018; Received in revised form 24 March 2018; Accepted 2 April 2018

materials such as concrete, metals and composites [2–4]. Unlike conventional fracture mechanics, cohesive traction law describes crack propagation at the crack tip from a traction-separation law, and is not subject to singularity problems associated with stress intensity factors and J-integrals in finite element analysis (FEA). The choice of traction-separation law depends on micro-mechanisms of failure in the process zone of the crack tip, and therefore varies with the material type. Bazant and Oh [5] were the first to use this technique combining with fracture mechanics and continuum mechanics in simulating damage of concrete. However, it is now quite commonly-used for simulating damage in a wide variety of materials [6–8].

One of the key factors involved in the application of cohesive crack model is the fracture toughness or tearing energy. The measurement of tearing energy for non-crystallizing Styrene Butadiene Rubber was proposed in the work of Rivlin et al. [9] and Lake et al. [10]. Greensmith and Thomas [11] performed analysis for a relationship between tearing energy and tearing rate, which involved the viscoelastic behavior in high strain rate. Kadir and Thomas [12] investigated and compared the crack propagation in Natural Rubber (NR), SBR, Butadiene Rubber (BR) and Nitrile Rubber (NBR) for wide range of rates on a pure shear test piece. Sakulkaew et al. [13] developed a new technique to evaluate strain energy release rate ahead of the crack tip while the tearing initiates, and successfully predicted the tear strength for eight different types of rubbers.

Ebbott [14] and Wei et al. [15] used finite element analysis (FEA) to evaluate the energy release rate changes by a crack at the edge of the cord-rubber tire components using various mesh densities. To analyze rubber tearing, Rahul Kumar et al. [16] developed a computational methodology to model crack propagation in viscoelastic materials based on cohesive elements, and analyzed peel test of a standard linear viscoelastic solid. Trapper and Volokh [17] computationally used the softening hyperelastic approach to find the critical tension corresponding to the onset of static instability in the thin sheets. Previati and Kaliske [18] investigated the fatigue life of rubber with particular focus on belt separation. A steady-state rolling finite element model of full truck tire was used to evaluate stress and strain fields in rubbers at edges of belts and compared to results from tests on real tire. Kroon and Elmukashfi [19] presented a dynamic crack propagation in rubber materials and investigated the parameters contributing to total fracture energy. A bilinear traction-separation law was used to model the fracture separation process and compared the crack propagation velocities with the crack speeds obtained from experiments. Li and Hoo Fatt [20] analyzed the tearing of pre-notched, strain-crystalizing NR tensile and pure shear specimens and reported good correlation between FEA and test data.

Although the above-mentioned approaches have proved to be effective to predict rubber damage, most of the above-mentioned research involve two-dimensional analysis and required a pre-defined crack path by introducing cohesive element or cohesive interface behavior in the FEA model. In this paper, a three-dimensional material model for SBR is developed and is used to analyze the crack initiation and propagation under dynamic loading. The material model is proposed for non-crystalizing SBR, and it is used to determine crack initiation and growth in SBR sheets without the presence of a notch or flaw. Thus the model is shown to provide more general usage in addressing the durability of rubber articles. The material model is incorporated in the form of ABAQUS Explicit user-defined material subroutine (VUMAT), and is specifically used to predict the crack initiation and propagation in SBR sheets subjected to in-plane tension loading. Crack growth is manifested through an element erosion criterion that is dependent on the tear energy of SBR. The following section describes experimental data from rate-dependent SBR tension tests and tearing of SBR sheets performed by Ouyang [1]. This data is used to develop hyper-viscoelastic constitutive equations for SBR before damage, a damage initiation criteria, and constitutive damage equations. Finite element analysis is then used to simulate crack initiation and growth in SBR sheets.

2. Prior SBR tensile test results

Experiments were performed by Ouyang [1] using a Charpy tensile impact apparatus, which was first introduced by Hoo Fatt and Bekar [21]. As shown in Fig. 1a, the Charpy pendulum was set to a certain drop height to control how much energy could be transmitted to the specimen. When the pendulum hit the slider bar, the potential energy of the hammer was converted to kinetic energy of the slider bar which, in turn, was used to apply tensile impact forces to the specimen. This was done by connecting the slider bar to copper cables that were fed around pulleys and attached to opposite ends of the specimen via the grips at A and B shown in Fig. 1b and c. The specimens were placed between the grips and the impact tensile load from the cables pulled both sides of the specimen evenly. Fig. 1b and c show two different types of specimens used in the test: (1) ASTM D412 and D638 tensile dumbbell specimens with gage lengths of 25.4 mm and 12.7 mm, respectively, and (2) SBR sheets with dimensions 25.4 mm × 50.8 mm × 2.54 mm. Tension tests were done until specimens broke.

During the test, the deformation of the specimen and grip displacement were recorded by a FASTCAM-Ultima high speed video camera at a rate of 20,000 frame/s. The tensile load was recorded by piezoelectric force sensors placed inside the grips holding the specimen. The experiment allowed the lens of the video camera to be focused in the center of the tensile specimens and sheets as opposite ends of them are pulled simultaneously. In conventional machines that are used for tensile tests, only one end the specimen is pulled. In these experiments, test pieces are extended at both ends so that crack initiation and propagation can be traced in the video images. Ouyang [1] used the above apparatus to obtain uniaxial stress-strain curves of SBR under varying strain rate as well as force-deformation and fracture response of SBR sheets under various drop heights of the Charpy hammer.

The composition of the SBR is listed in Table 1. The test data obtained from the uniaxial tests on SBR dumbbell specimens are used to determine the parameters of hyper-viscoelastic constitutive equations and damage initiation criterion or strength of SBR. The tearing energy or energy release rate of the SBR is found separately in Ref. [13]. The tension tests on SBR sheet up to break are used to validate the FEA prediction. The following sections describe the uniaxial tensile tests on SBR dumbbell specimens and tension tests on SBR sheets.