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Multiaxial deformation and failure of acrylic elastomer membranes

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ABSTRACT

Dielectric elastomers are increasingly used for so called electro-active polymer actuators, sensors and generators. The materials are typically shaped as thin membranes loaded with an electric field in thickness direction. To increase the electromechanical performance, the membranes are pre-stretched with an in-plane area stretch up to 36. These large deformations may lead to rupture and thus impair the mechanical integrity of the devices.

This work reports about a systematic investigation of the multiaxial deformation and mechanical failure characteristics of the acrylic elastomer membrane VHB 4910. Different tensile plane stress configurations were experimentally investigated using a large number of samples. Uniaxial and pure-shear tensile tests as well as membrane inflation tests were performed. Results of ultimate stretch, critical stress and stored deformation energy are reported along with stress–stretch relations for the three different kinematic configurations.

The critical value of the maximum principal stretch at failure is found to be in the range of 9 and to be relatively independent of the imposed state of deformation. This is attributed to local failure initiating at stress rising features at the edges of the membranes. Stress concentrations at notches or load introduction regions were observed to dominate the mechanical failure behavior of VHB 4910.

The present data are used to investigate the predictive capabilities of different nonlinear constitutive models previously proposed for VHB 4910. Limitations of the applicability of these models are shown for very large deformations and uniaxial stress states. A new set of parameters is determined for a simple Yeoh-model formulation to overcome these limitations.

1. Introduction

Dielectric elastomers (DE) are soft polymeric materials that recover very large deformations and insulate high electric fields. These materials are frequently used in so called electro-active material systems as actuators [1–4], sensors [5] and energy harvesting generators [6]. High electric fields and the corresponding electrostatic forces lead to large deformations of the very compliant elastomers. Applications are limited by the dielectric strength as well as mechanical integrity of the material. Further, some modes of operation may cause an unstable behavior of the device characterized by a sudden increase of deformation leading to electric breakdown see e.g. [7]. Data of dielectric strength [8] as well as constitutive relations needed to predict electromechanical instability can be found in literature [9]. Very little work however reports on the mechanical failure of homogeneous elastomer materials that are typically used in DE devices. Instead, for the description of failure modes, authors rely on assumptions about the maximum extensibility or maximum allowable mechanical stress [10,11]. The importance of a systematic investigation is further emphasized by the fact that a variety of applications uses large pre-stretches [4,12] such that avoidance of mechanical failure may determine the design of the devices.

This work presents results of an extensive experimental investigation of the mechanical failure of the acrylic elastomer membrane VHB 4910 (3 M). This commercially available material probably represents the most often used DE material. Superior actuation performance, availability and reproducibility of properties favor this material for investigations of fundamental aspects of DE technology [8,13] as well as for the development of new DE applications and designs [4,12,14]. Further, constitutive model equations suitable for finite element simulations have been proposed for this material [9,15].

With the aim to describe the ranges of allowable stress and deformation states of DE, experiments in different plane stress states were conducted. Specifically, a large number of uniaxial tensile and pure-shear tests as well as membrane inflation experiments were carried out. A low rate of deformation is applied in all experiments in order to assess the materials long-term behavior.

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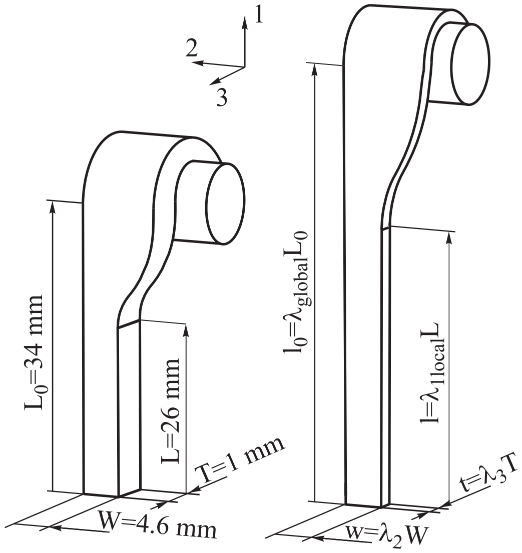

Fig. 1. Dog bone shape sample for uniaxial tensile tests (symmetry with respect to 1–3 plane, only right part represented).

Predictions of the stress–stretch curves from different constitutive models are compared with the experimental data. The edges of virgin and ruptured samples were investigated by optical microscopy. Thereby, the influence of notches on the sample surface, as introduced by the sample fabrication process, was characterized.

2. Experiments and results

All samples were extracted from the same batch of VHB 4910 and were stored in the laboratory before testing to equilibrate with the environmental conditions. All experiments were conducted at a temperature of 24 °C ± 1 K.

2.1. Uniaxial tension experiments

All uniaxial tension experiments were conducted on a tensile testing device (Zwick/ROELL Z005). A "dog bone" shape sample design was chosen in order to minimize the influence of stress concentrations. All samples tested in uniaxial tension were die cut to the shape shown in Fig. 1. The samples were wound around stainless steel cylinders of diameter 10 mm (Fig. 1). Due to the adhesive surface of the VHB samples, no slip occurred between sample and cylinders. The use of cylinders was favored over conventional clamping grips to reduce stress concentrations on the samples. A displacement ramp of 7.7 mm/min was applied and the resulting tensile force recorded with a 100 N force sensor (Zwick II 318950). Due to the varying cross-sectional area of the specific specimen design, an inhomogeneous deformation field arises, necessitating the measurement of local deformation. In preliminary experiments, we found that mechanical extensometers, typically used to locally measure stretch cannot be used for the characterization of VHB 4910. The very soft and fragile membranes consistently failed at the contact region with the extensometer. Optical measurements of stretch on the transparent VHB 4910 membrane rely on marks applied to the sample surface. The analysis of displacement of these marks however, is difficult in the case of large deformations. In general, deformable marks such as ink spots often do not provide enough contrast at very large deformations while stiff elements attached to the sample surface influence the failure behavior.

Up to this point, all samples were tested without a local measurement of deformation. Values of stretch were calculated with a calibration function (Fig. 2), that relates the local stretch, acting in the undisturbed region of the sample, to the displacement applied to the sample. This calibration function was determined from preliminary experiments on identical samples using an optical extensometer and two stiff circular markers. Their dimensions were small (diameter ~2 mm, distance ~20 mm) such that they had no significant influence on samples stiffness. The average rate of deformation resulting in the center of the specimen was found to be approximately 0.45%/s.

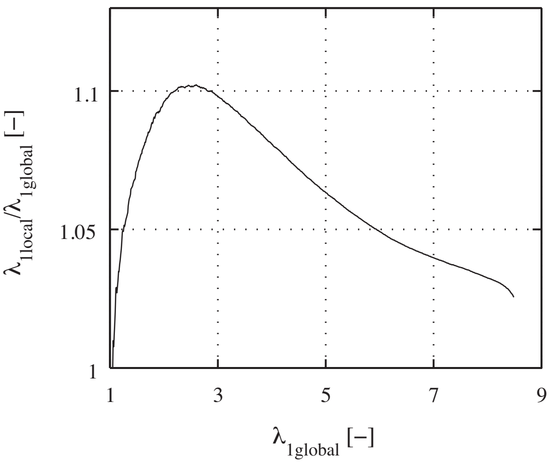

Fig. 2. Calibration function for local stretch determination.

The so derived values of stretch are used to calculate values of Cauchy-stress from the measured force signals. In this procedure we assume the material to preserve its volume at every material point. The principal stretches thus need to fulfill the following constraint:

$$\lambda_1\lambda_2\lambda_3 = 1 \tag{1}$$

From the calculated values of λ_1, λ_2 and λ_3 can be calculated assuming isotropic material behavior and therefore:

$$\lambda_2\lambda_3 = \frac{1}{\lambda_1} \tag{2}$$

Thus the component of Cauchy-stress in the direction of tension becomes:

$$\sigma_1 = \frac{F\lambda_1}{WT} \tag{3}$$

where F is the measured force, W and T are the width and thickness of the undeformed sample (Fig. 1). Results of Cauchy-stress and stretch in the uniform section of the specimen are reported along with the results of pure-shear and inflations tests in Section 2.3.

2.2. Pure-shear tests

Rectangular samples of width W = 300 mm and length L = 15 mm are stretched in their short direction (Fig. 3) using the same set-up of steel cylinders as described in Section 2.1. The applied displacement ramp of 1.925 mm/min on two actuators leads to almost the same rate of deformation as in the uniaxial experiments (0.0043 s^{-1}). Fig. 4 reports results of a finite element calculation of the sample used for the pure-shear tests. The model uses the Yeoh material model, with parameters as proposed in [9]. As can be seen in Fig. 4, the contraction perpendicular to the direction of applied displacement given as a function of the relative applied displacement changes by less than 2% even for very large deformations. Thus, the resulting state of stress is very close to a so called pure-shear state e.g. [16]. From the recorded force signal, values of Cauchy-stress are calculated using Eq. (3), with W = constant and