Determination of Relevant Material Behavior for Use in Stretchable Electronics

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Abstract

Stretchable electronics getting more and more in focus for medical applications (e.g. skin wearable body-monitoring systems or sensitive implants).Typically, electronic components and metal conductor paths are embedded in elastomeric substrates. These material combinations of highly elastic behavior of the substrate (strains up to ~ 150 %) and the relatively stiff metal components with a typical elastic stretchability (Cu < 1 %) cause a problem regarding the mechanical reliability. The important factor for reliability assessment by FEM is not only the material properties of individual components, but also the behavior of metal-polymer interfaces. Accurate prediction of component behavior requires both, suitable material models and accurate material properties data.

In this paper, we present our results of an adapted approach to assess material properties by mechanical test methods under plane stress conditions, under tensile loads and equi-biaxial tension experiments using an uniaxial testing machine. These results were used for the modelling of hyper-elastic material properties under multi-axial states of stress. This study is part of very important research to develop new simulation techniques and testing methods to be able to use hyper-elastic modelling approaches for industrial applications.

1. Introduction

More and more stretchable materials are applied in a wide variety of industrial, wearable or medical applications

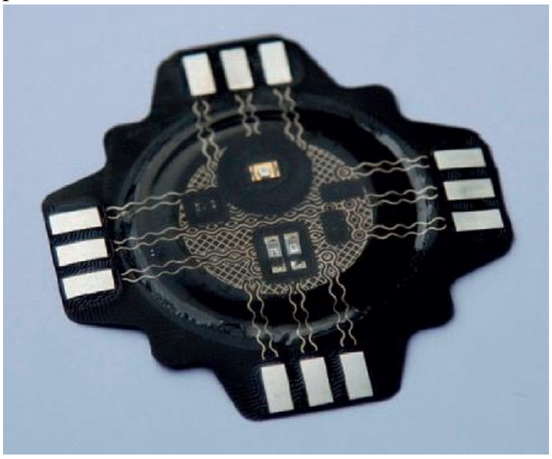

Fig. 1: Example of stretchable Circuit [1]

These materials exhibit a very large strain ability, with a strongly non-linear stress-strain relation under different states of stress. This material behavior is well known as hyper-elasticity. Many different material combinations of conformable polymers such as polyurethane and silicone were tested and examined [1].

The stress-strain behavior of typical flexible rubber-like materials is elastic (i.e. recoverable), but shows strongly non-linear stress-strain behavior, i.e polyurethane foil (Fig. 2).

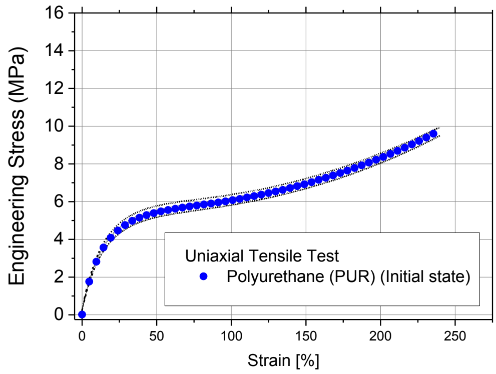

***Fig. 2:** Uniaxial stress-strain curve of polyurethane (own measurement)*

Accurate modelling of these hyper-elastic materials require the measurement of material properties in a large strain variety and different states of stress. Mechanical tests, performed on rubber-like material in tension type can be applied in uniaxial, planar or biaxial state (Fig. 3).

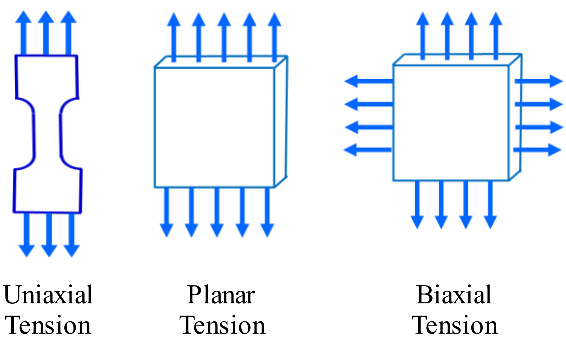

***Fig. 3:** Mechanical tests on hyper-elastic materials*

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The uniaxial tension test is commonly used for characterization of thin rubber-like materials. Unfortunately, this test methods are restricted to provide only uniaxial material information. The acquired data doesn't allow an accurate enough material characterization [2]. To be able to measure the material properties under multiaxial states of stress (and/or strain) several types of test techniques have been developed. The most commonly used test techniques are radial tension of a circular plate, bulge tests, planar tension test and biaxial tension tests. The biaxial tensile test induces a large variation of strain invariants as compared to the uniaxial tensile test for obtaining reliable input data for hyper-elastic modelling [2-4].

Modelling of deformation properties

The equi-biaxial tensile test induces a large variation of strain invariants as compared to the uniaxial tension test. These results were used for the modelling of hyper-elastic material properties under multi-axial states of stress.
According to Treloar are for the investigation of deformations in multiaxial materials the evaluation of plane invariants needed [8]. Fig. 4 shows, that possible deformation states are limited in the range between uniaxial tension and (equi-) biaxial tension. The uniaxial tensile test is represented by the lower limitation curve, an Equi-biaxial tension test by the upper curve. Every other state of deformation is located between these curves. For modelling all deformations the information from the uniaxial tensile test is not sufficient enough.

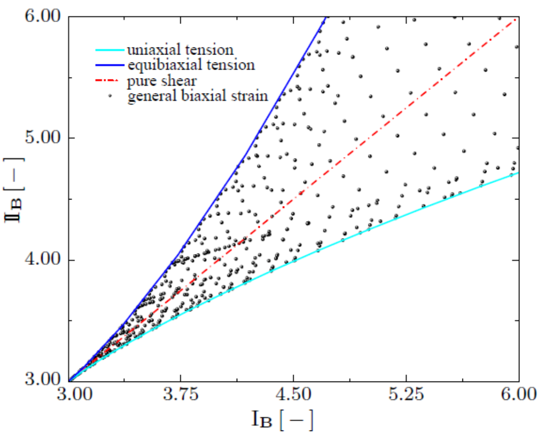

***Fig. 4:** All achievable deformation states between uniaxial tension and biaxial tension [8]*

To fit the experimental data a number of hyper-elastic models are available in literature [2,4]. Commonly used models are Mooney-Rivlin model, Ogden model and Neo Hookean model. After data fitting it is possible to implement models into commercial Finite-Elemente (FE) Simulation codes. Characteristic of these models: hyper-elastic models based on the definition of a strain energy function W.

For an isotropic and incompressible material W can be expressed as a function of principal stretches

$$W = W(\lambda_1, \lambda_2, \lambda_3) \qquad (1)$$

Stretches were calculated from technical strain (or Deformation).
For incompressible materials λ_3 can be eliminated, so that W becomes a function of λ_1 and λ_2.
The strain-energy function W can be defined depending only on the one remaining independent stretch:

$$W = W(\lambda) \qquad (2)$$

Stress can be defined as a function of strain energy function and stretches.

$$\sigma = \lambda \frac{\partial W}{\partial \lambda} \qquad (3)$$

All models below obtain explicit relation between stress and stretch.

The Mooney-Rivlin model is the first order in polynom form of hyper-elastic model and uses only the linear function of invariants. W can also be considered as a function of strain invariants I_i that are in function of principal stretches:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$
$$I_2 = (\lambda_1\lambda_2)^2 + (\lambda_2\lambda_3)^2 + (\lambda_1\lambda_3)^2 \qquad (4)$$
$$I_3 = (\lambda_1\lambda_2\lambda_3)^2$$

For incompressible materials $I_3 = 1$ and the strain-energy function will depend on the first two invariants

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \qquad (5)$$

Parameters C_{ij} are constants of the more elastic material.
The model of Ogden propose a form of strain energy and is given

$$W(\lambda_1\lambda_2) = \sum_{p=1}^{N} 2\mu_p \left(\lambda_1^{\alpha p} + \lambda_2^{\alpha p} + \lambda_1^{-\alpha p}\lambda_2^{-\alpha p} - 3\right)/\alpha_p^2 \qquad (6)$$

The constitutive model of Neo Hookean is given,

$$W = C_{10}(I_i - 3) \qquad (7)$$

which is a special case of the Mooney-Rivlin equation, with $(C_{01} = 0)$.

Further technical information of all used models will be described in detail in [2-7]. For the identification of real model parameters, respectively an accurate modelling of hyper-elastic materials behavior require material parameters under several stress states – uniaxial and biaxial tension.

In the following, for an isotropic material behavior the 3-dimensional Hook's law describes the relationship between the applied strain and stress. Especially for the 2-dimensional case (as a special case) the relationship between stress and strain can be described by the modulus and Poisson's ratio for relatively small strains [9].

$$\sigma_x = \sigma_y = \frac{E_s}{(1-\upsilon)}\varepsilon_{x,y} \tag{8}$$

Where E_s is the secant modulus from the tensile test and ν Poisson's ratio.

2. Experimental set up

Equi-Biaxial test equipment

The Biaxial Tension test technique is a useful method for evaluating strain energy density functions. A low cost biaxial test version is the equi-biaxial test equipment on in-plane deformed specimens. This test method can be adapted to any uniaxial tension test machine, which exist in almost all of the mechanical engineering laboratories. This methods produced also through deforming a specimen simultaneously in two directions. Assuming incompressibility, this deformation mode is characterized in terms of principle stretches: $\lambda_1 = \lambda_2 = \lambda_b$ and $\lambda_3 = 1/\ l_b^2$ where λ_b is the stretch in the perpendicular loading direction [5].

In [4-7] was a test fixture developed and shown to enable the performance of equi-biaxial tension measurements for using a uniaxial test machine. The test construction consists of moveable scissor-like arms that resolve the machine crosshead movement into extension of the test specimen at approx. 45° to the axis of the test machine. The base of the test equipment is shown in Figure 5.

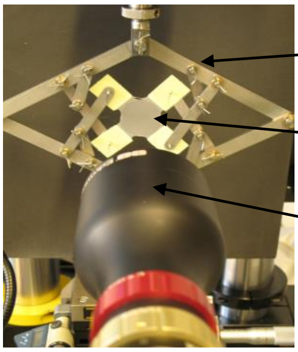

***Fig. 5**: Equi-biaxial test fixture on universal tension machine (INSTRON Microtester 5848)*

The total force measured on the pull rod of the test machine can be resolved into biaxial components through a geometrical correction factor.

Equi-Biaxial test specimen

Thin polyurethane foils (100 µm) with low stiffness were tested for all mechanical, uniaxial tension and equi-biaxial tension tests. For the uniaxial tension test dumbbell specimens with a length of 100 mm and a width of 10 mm were used. All samples were cut by laser technique. For equi-biaxial a square sheet sample will be deformed (Fig. 6). The samples were reinforced with a thin PCB material. The samples were mounted to the loading equipment as shown in Fig. 5.

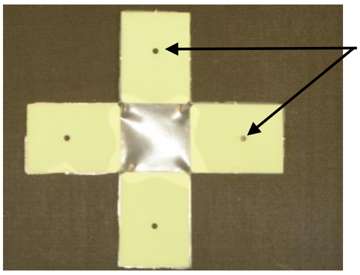

Fig. 6: Equi-biaxial tension - sample geometry

The deformation behavior of biaxial samples was measured in the center of the surface by using a CCD Camera. For analysis of this deformation field of samples the VEDDAC-Software was used. This Digital image Correlation (DIC) technique based on analyzing the recorded images under different loading conditions, made it possible to describe the complete two-dimensional (in-plane) displacement and strain fields with high accuracy.

3. Result and Discussion

All measurements were performed at room temperature with constant test speeds of 1 mm/min. Fig. 7 (left) shows that the displacements closer to the sample fixation (outside) are much more important than in the center of the specimen.

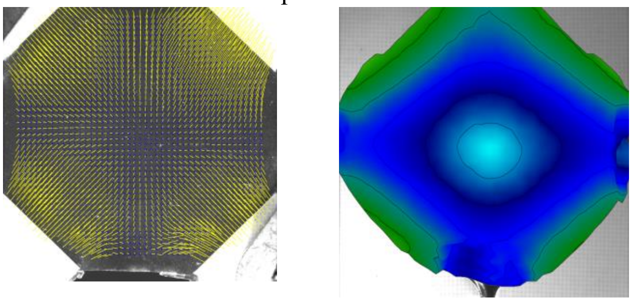

***Fig. 7:** Analyzed of Deformation in center field of loaded Biaxial sample*
Left: Illustration of vectors,
Right: Illustration of deformation field.

The results are showing the biaxial strain character in the center of the samples. The correlation software analyzed both strains simultaneously in vertical and horizontal directions and generated the values for each strain individually. The pictures in Fig.8 illustrate and compare the strain in both direction. The result reveals that the vertical and horizontal deformations show a nearly good agreement.

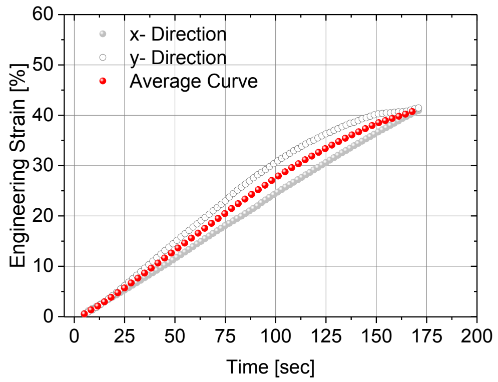

Fig. 8: *Comparison of the horizontal versus vertical deformations*

The graph in Fig. 9 presents both, biaxial tension and uniaxial tension test data and show respective upper and lower limits of possible deformation states of polyurethane.

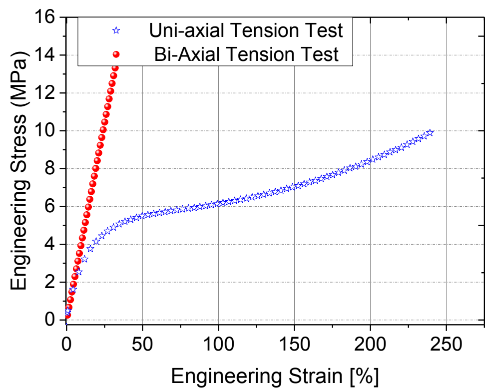

Fig. 9: *Uniaxial and biaxial tension test data of nominally stress vs. strain*

To fit hyper-elastic constitutive models the test results of experimental stress-strain curves from the uniaxial and biaxial tension were used. For these materials the best fit was obtain from the Mooney-Rivlin model in both uniaxial and biaxial way. The results of the fitted data are shown in fig. 10 and the evaluated parameter values are reported in table 1.

Table 1: *Material model parameters, Mooney Rivlin -Model*

C_{01}	C_{10}	C_{11}
19,525 MPa	-10,165 MPa	1,478 MPa

The Mooney-Rivlin fit has been implemented in simulations tools for life time modelling copper-polymer combination [10].

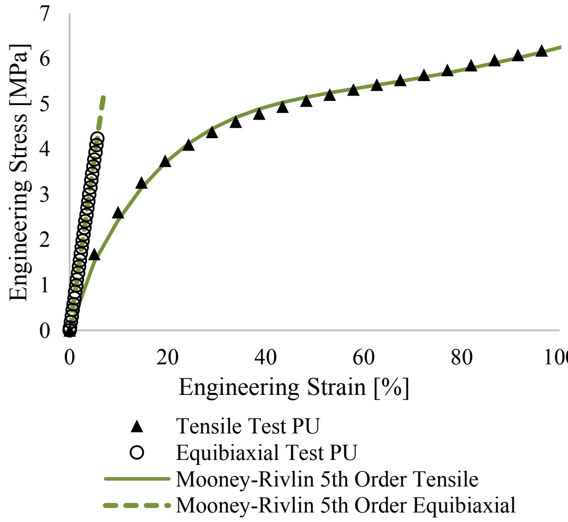

Fig. 10: *Mooney-Rivlin model fitting of uniaxial and biaxial experimental data (PUR) [10]*

4. Conclusions

In this work, the equi-biaxial tension equipment has been adapted to an existing uniaxial testing machine. An optical measurement system was used to determine large deformations. Both, uniaxial tension and equi-biaxial tension tests are well suited for the characterization of comprehensive material properties, just like the tested thin polymers films. The experimental data is needed to describe the hyper-elastic material properties of rubber-like materials. When comparing the available models in literature, it was found the Mooney-Rivlin model to be the most accurate. The measured data can be used for implementation of FE-Simulation codes.

In future studies the influence of strain rate and temperature will be conducted and the effect on the material properties examined. Furthermore, the investigation under cycling biaxial loading on the behavior is important.

Acknowledgments

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