Constitutive model of filled elastomers capable of capturing Mullins effect, hysteresis, induced anisotropy and permanent set – Part II: Experiments & Validation

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1 Abstract

This contribution discusses experiments necessary to describe the behavior of filled elastomers under large strains. Filled elastomers show a variety of inelastic phenomena such as Mullins effect, hysteresis, induced anisotropy, and permanent set. While uniaxial tension tests to rupture provide virgin loading curves, other tests are necessary to gather information about the inelastic effects mentioned above. In order to capture these phenomena experimentally, cyclic uniaxial tension tests with stepwise increasing load amplitudes are carried out.

Since experimental stress-strain curves characterize some restricted set of defined loading conditions (such as uniaxial test, pure shear, or equi-biaxial tension), additional investigations of two-dimensional strain data from arbitrary deformations states are necessary. This strain data can be obtained for example by digital image correlation.

In particular, we demonstrate how the previously described constitutive model can be calibrated using a variety of experiments. We verify the calibration comparing the results of our subroutine implemented as UMAT in LS-DYNA with two-dimensional strain data obtained from digital image correlation of a plate with a hole subjected to tension. The described model shows good agreement with the obtained data.

2 Introduction

As mentioned before, the characterization of filled elastomers requires extensive experimental efforts, especially to calibrate a material model (e.g. [1]) with respect to a variety of inelastic phenomena such as Mullins effect, hysteresis, induced anisotropy, and permanent set. One can show that relying on one particular loading curve, like for example that one resulting from uniaxial tension, is not enough to describe material behavior in other load cases.

This is due to the fact that the first two principal invariants $\bar{\mathrm{I}}$ and $\bar{\mathrm{II}}$ of the isochoric right Cauchy-Green tensor $\bar{\boldsymbol{C}}$, given as

$$\bar{\mathrm{I}} = \mathrm{tr}\,\bar{\boldsymbol{C}}, \tag{1}$$

$$\bar{\mathrm{II}} = \frac{1}{2}((\mathrm{tr}(\bar{\boldsymbol{C}}))^2 + \mathrm{tr}(\bar{\boldsymbol{C}}^2)) \tag{2}$$

cannot be separately varied in the loading cases, such as uniaxial tension, pure shear, or equi-biaxial tension in the invariant plane, as depicted in Figure 1.

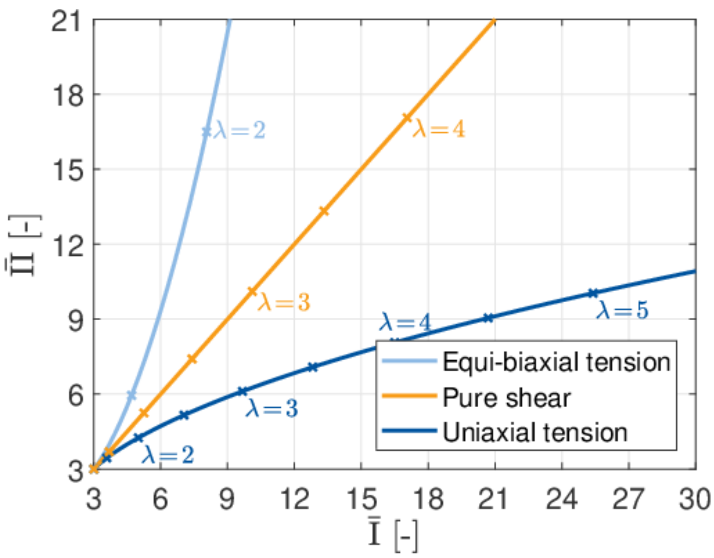

Fig.1: Dependencies of $\bar{I}$ and $\bar{II}$ in the cases of uniaxial tension, pure shear, equi-biaxial tension (cf. [3]).

These strictly defined loading conditions, represented as curves in the $\bar{I}$-$\bar{II}$-plane, are often considered to characterize elastomers. Thus, material model formulations in terms of $\bar{I}$ and $\bar{II}$ cannot be suitably calibrated on the basis of only one experiment. Especially uniaxial tension tests are commonly performed for the material law calibration, due to the relatively easy experimental setup and straightforward interpretation. In order to obtain a proper material characterization, a variety of deformation states needs to be considered [3]. To this end, we perform uniaxial tension tests of S3a [2] specimen, pure shear experiments, and additionally tension tests of a plate with a hole, as depicted in Figure 2. In the latter case, the clamping and the placement of the hole create an inhomogenous deformation field.

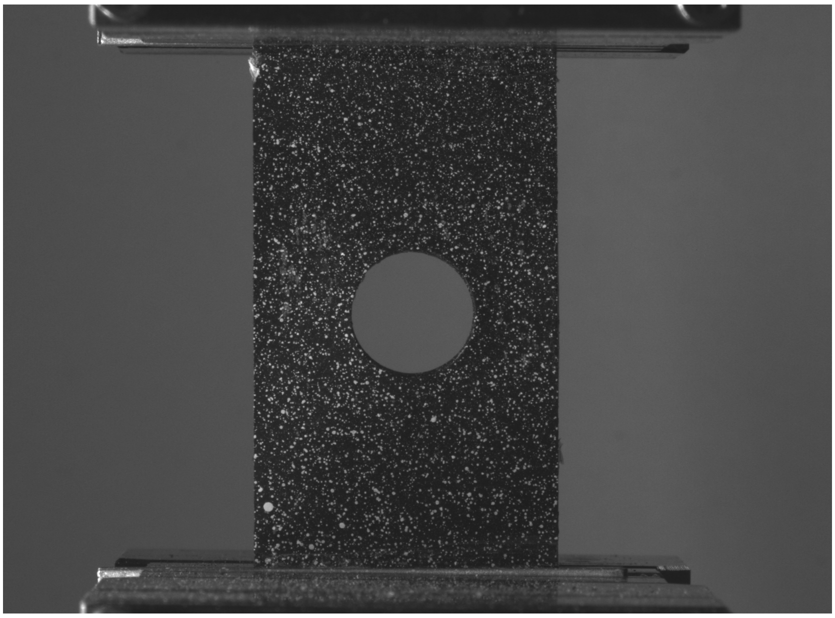

Fig.2: Clamped plate with a hole sprinkled with a contrast-rich color pattern.

Due to this inhomogeneity, an application of the finite element method (FEM) for calibration of the model is necessary. The FEM result is directly compared with the reaction force and the strain field measured in the experiment. To obtain the two-dimensional strain data, the specimen is sprinkled with a contrast-rich color pattern (see Figure 2) which is captured by a camera taking a picture every second. The image series is then further postprocessed using the digital image correlation (DIC) software GOM Correlate (Build 2018-11-29, GOM GmbH, Braunschweig, Germany).

3 Experiments

In the present study, we performed experiments under four different loading protocols, as follows

- Uniaxial tension tests:
  - To rupture
  - Cyclic with increasing amplitude
- Tension tests of a plate with a hole
- Pure shear tests.

While the tests to rupture deliver information regarding the limit state of the material, cyclic tests with stepwise increasing strain amplitude provide crucial information to characterize inelastic effects such as the Mullins effect, hysteresis, and permanent. Each amplitude was repeated three times. All experiments have been performed with the universal testing machine Z010 (Zwick/Roell, Ulm, Germany) using a strain rate of 33.33 %/min. The resulting stress-strain curves are shown in Figures 3 and 4.

All mentioned effects can be clearly identified in the experimental curves (Figure 3 and 4), which enables the user to calibrate the material model [1] precisely. To find suitable material parameters, the model was simultaneously fitted to all curves using the least-squares method. The so obtained parameter set results in the model prediction curves shown in Figures 3 and 4.

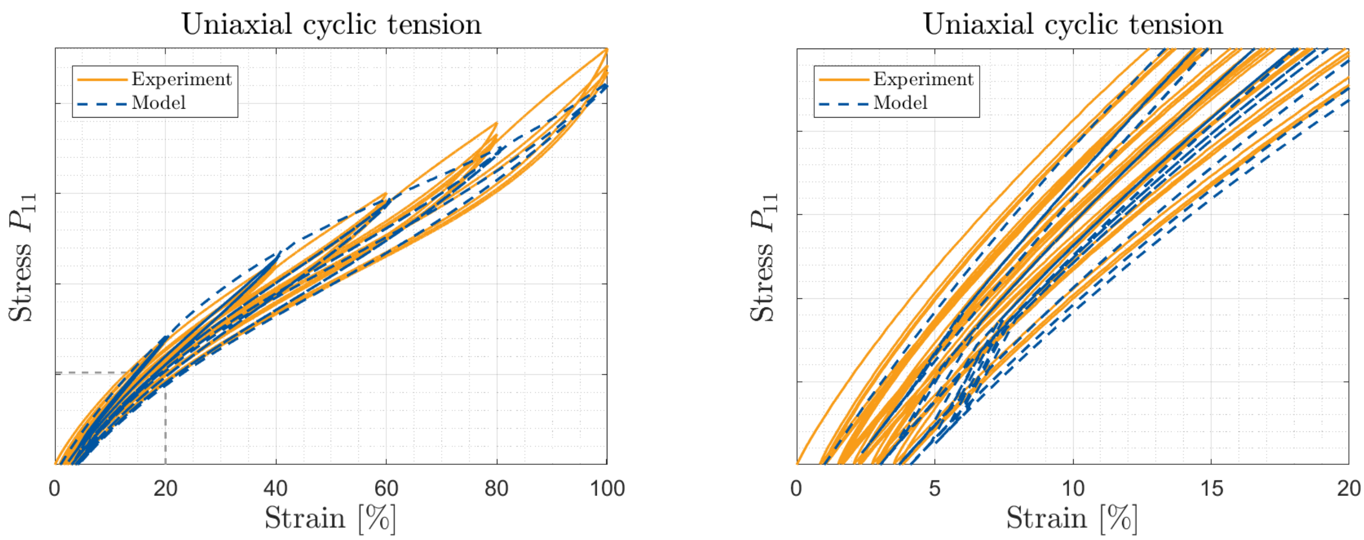

Fig.3: Comparison of the experimental data and the model predictions [1] in the case of cyclic uniaxial tension with stepwise increasing amplitude (five amplitudes, with three repetitions each). Left: complete curve. Right: cut-out of the small strain regime.

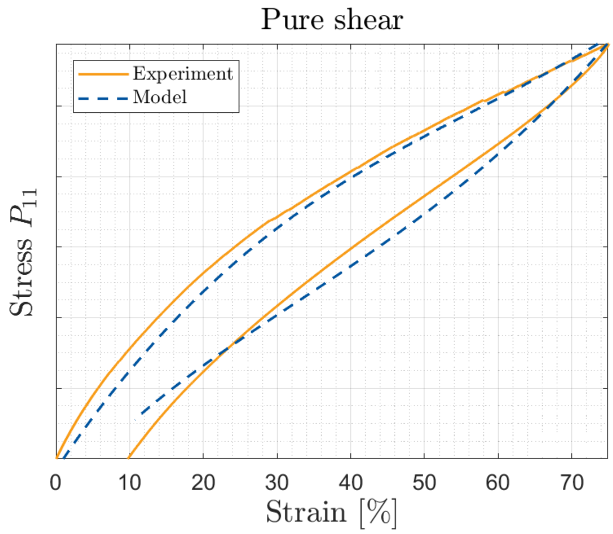

Fig.4: Comparison of the experimental data and the model predictions [1] in the case of pure shear.

4 Validation

The material parameters obtained from fitting the material model to the experimental data described in the previous section are further used in a FEM model of a plate with a hole as depicted in Figure 2. The model was implemented into a user-defined material subroutine (UMAT, see [1]). The simulations were carried out using LS-DYNA (Livermore Software Technology Corporation, Livermore, USA) using approximately 4'000 elements. In order to verify the material model under inhomogenous loading conditions, the two-dimensional strain field of the plate obtained by the digital image correlation was compared with the FEM simulations. Figure 5 shows a comparison of the two two-dimensional strain fields.

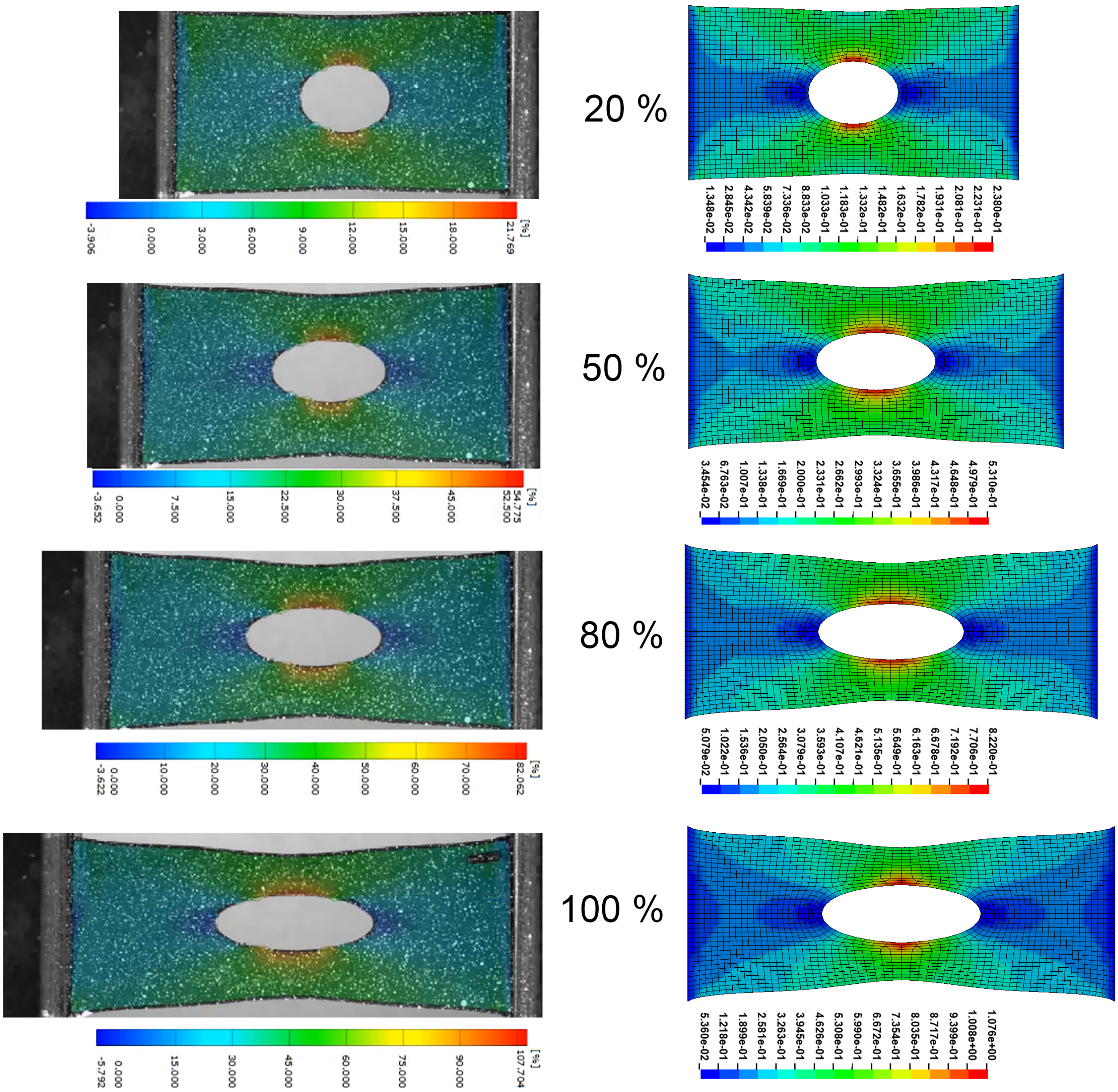

Fig.5: Two-dimensional strain data of a plate with a hole subjected to tension. The logarithmic (true) strains in loading direction obtained experimentally by the DIC (left) and numerically by the FEM using the material model described in [1] (right) are compared for strains of 20%, 50%, 80%, and 100%.

5 Conclusion

In this contribution, we calibrate the constitutive model described in [1] using uniaxial tension and pure shear tests. The resulting material parameter set was further validated by FEM on the basis of a UMAT subroutine in LS-DYNA. For this comparison, the force response and the two-dimensional strain field predicted by the model and obtained experimentally are considered. A good agreement with the experimental data is obtained.

6 Literature

[1] Chandrasekaran R., Hillgärtner M., Müller M., Burbulla F., and Itskov M.: "Constitutive model of filled elastomers capable of capturing Mullins effect, hysteresis, induced anisotropy and permanent set – Part I: Model theory & Implementation", Proceedings of the 12th European LS-DYNA Conference 2019, Koblenz, Germany, 2019

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