DETERMINATION OF MATERIAL PROPERTIES FOR THE CRASH CALCULATION OF ELASTOMERS, TAKING INTO ACCOUNT LARGE TENSILE AND COMPRESSIVE STRAINS

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THEME

Structural analysis (material characterisation)
Confidence in Results (Verification & Validation)
Optimisation (Algorithms)

SUMMARY

For FEM users, a major challenge remains for very many materials in the automotive industry. It is to examine which material model best fits the simulated material and the specified load, whilst at the same time deciding what is possible and is justified in terms of cost, in order to determine the required material parameters. In this lecture, the determination of a material data set to simulate the viscoelastic behaviour of a compact elastomer is presented, coupling optical metrology and nonlinear multi-parameter optimisation. Here an experimentation and evaluation methodology is used in which it is possible to take account of multi-axial stress conditions right through to large deformations, both tensile and compressive, together with crash-relevant strain rates of up to 200 / s within an optimization routine. First, the experimental studies on selected test specimens are presented. On the one hand, perforated rectangular specimens are used, which, under tension, result in inhomogeneous strain fields on the surface.

On the other hand, additional cylindrical compressive test specimens can be measured under local strains of up to 50%, in order to be able to calibrate the material parameters for pronounced compressive loads. Later in the lecture, there is an explanation of the main evaluation steps in reverse engineering. After the optically measured displacement fields are interpolated by means of triangulation onto a corresponding FEM mesh, using the least squares method the distances of all the node offsets determined experimentally and by simulation, are minimised within an optimisation routine. It should be noted that for filtering superimposed translations and rotations, due, for example, to slippage in the clamp, all displacements are based on a relative node on the specimen surface.

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Finally, detailed verifications are discussed, based on the comparison of measured and simulated local deformation parameters for relevant load combinations and strain rates.

KEYWORDS

Material Data Identification, Crash-Simulation, Elastomers, Verification

1: Introduction

One of the most important modeling tasks for users of finite element (FE) simulation tools is representing material behavior under mechanical stress as realistically as possible and determining which material laws are most suitable for the given simulation. Furthermore it is necessary to determine the accompanying material parameters by means of suitable test and analysis concepts, so that the load conditions, which are to be simulated later on the material component, are already taken into consideration as completely as possible within the material test program. Because it is the goal of this study to calculate a single material dataset for simultaneous simulations of the behavior of elastomer components at high strains and high strain rates, this study's testing program considers both the multi-axial stress conditions that occur on components at up to high deformation ranges as well as a large spectrum of strain rates.

The evaluation of the experimental data was conducted with the help of an optimization procedure from the field of reverse engineering, which offers algorithmic tools that are also applicable for high-grade non-linear material models, the application of inhomogeneous strain fields [1], and consideration of scattering in material behavior [2,4,5,6]. As an optimization algorithm the method of least squares is applied along with the Levenberg-Marquardt algorithm, whereby the goal is to minimize the differences between the inhomogeneous displacement fields measured on the test specimen surface and those that are simulated. The test simulations are force-controlled, whereby the temporal force progressions measured during the respective tests are utilized as a boundary condition. On the basis of the simultaneous setting of parameters for multiple experiments, unambiguous parameter estimations can be far better guaranteed as compared to serial evaluation procedures, which moreover are often based on multiple varying methods. Furthermore, the procedure of generalized parameter identification, as presented here, guarantees a better consideration of the scatterings that occur during repeated test trials.

2: Material Examination

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Experimental Setup / Specimens

All tests were conducted in a climatized test room at 21.5 ± 0.2 °C. The tests utilized a universal testing machine made by the company Zwick (model 1474) for tension and compressive tests as well as a hydraulic high-speed testing machine made by the company Zwick/Roell (model HTM 5020) for high-speed tensile tests. The ARAMIS 4M system made by the company GoM and cameras with a corresponding frame rate were used as a measurement system for optical measurement of displacement fields on the test specimen surfaces.

Figure 1: Quasistatic compressive test, high-speed tensile test

The test specimens included rectangular tension test specimens and cylindrical compressive test specimens. While the tension test specimens were perforated with a circular hole in the middle of the specimen, the compressive test specimens were prepared as solid cylinders with aluminum plating vulcanized on top and bottom (Figure 2). When under stress, both test specimen shapes lead to an inhomogeneous stress condition as well as inhomogeneous distribution of local strain rates across the entire deformation range. The test specimens are coded with a randomly distributed pattern of gray values so that the displacement fields can be measured during the testing.

Figure 2: Perforated rectangular test specimens, solid cylinders, coded and uncoded

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In order to minimize any residual stress that might occur in the event of a conventional clamping of the tensile test specimens, protruding perforated plates were applied by means of full-surface adhesive. The transmission of force thereby occurs via a bolt in the plate and then fundamentally via the adhesive.

<u>Tensile and Compressive Tests</u>

The testing program for both materials consists of tensile testing at three varying tensile speeds as well as compressive testing at quasistatic strain speeds. The measured values recorded directly by the testing machines are the time, the force in the load direction, and the traverse path. Additionally the surface displacement is measured by means of optical, contact-free measurement technology. Distortion conditions of over 100% local technical strains were reached for the tensile testing, while a level of 50% was reached for the compressive testing. The following testing and camera configurations were used:

- Tensile load at 5 mm/min traverse speed, 1 photo frame per 6 seconds
- Tensile load at 0.3 m/s tensile speed, photo frame rate of 800 Hz
- Tensile load at 5 m/s tensile speed, photo frame rate of 9000 Hz
- Compressive load at 3 mm/min traverse speed, 1 photo frame per 6 seconds

For the later identification of parameters, the force-time functions are smoothed for the 0.3 and 5 m/s load speeds. The following figures depict the force-time functions of the four testing types, whereby the maximum traverse path was approximately 35 mm for the tensile testing and approximately 15 mm for the compressive testing.

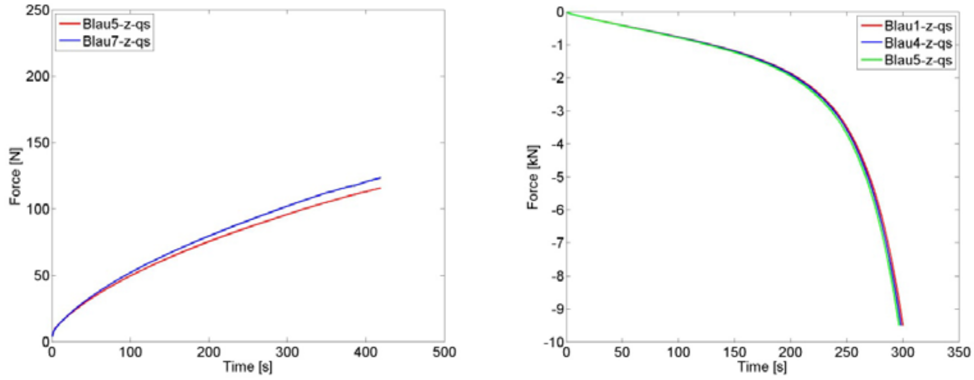

Figure 3: Quasistatic tensile testing (left) and compressive testing (right)

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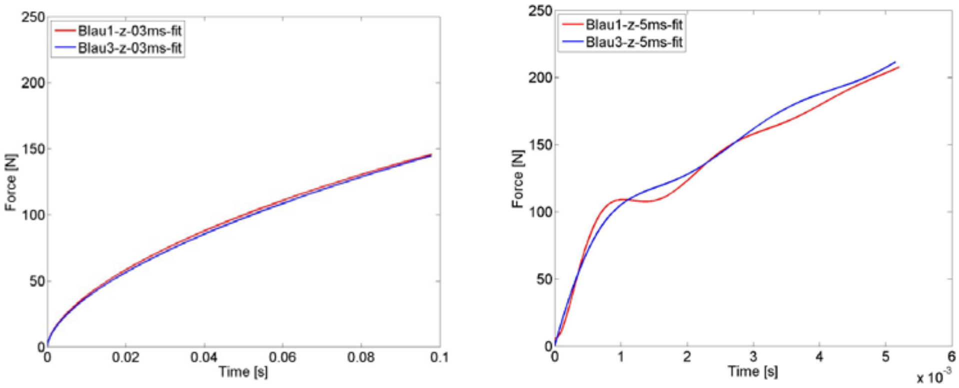

Figure 4: Tensile testing at 0.3 m/s (left) and 5.0 m/s (right)

To determine inhomogeneous displacement fields, a stochastically distributed pattern of gray values on the testing specimens was recorded with CCD cameras. Subsequently the analysis area was determined (Fig. 5) and analyzed by means of gray value correlation analysis. Figures 6 and 7 depict examples of the resulting displacement fields and strain fields of tensile and compressive testing.

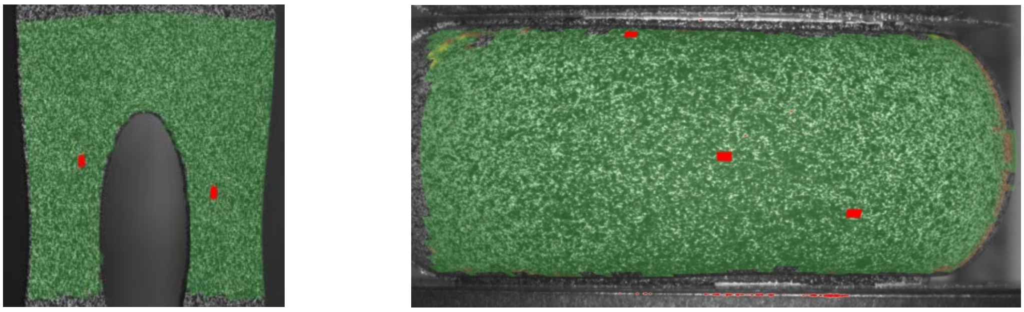

Figure 5: Original photos with overlaid evaluation mask

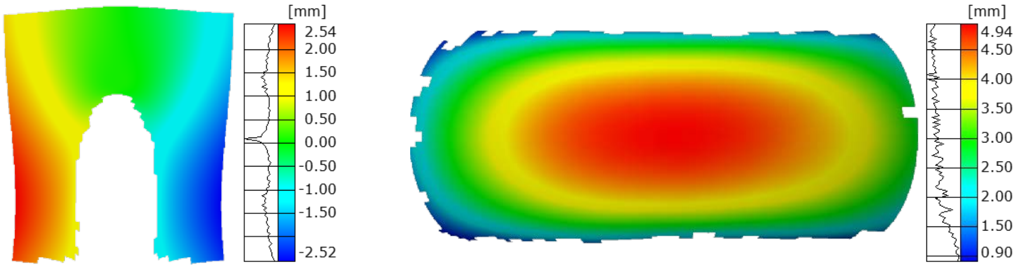

Figure 6: Displacement fields, tensile and compressive testing

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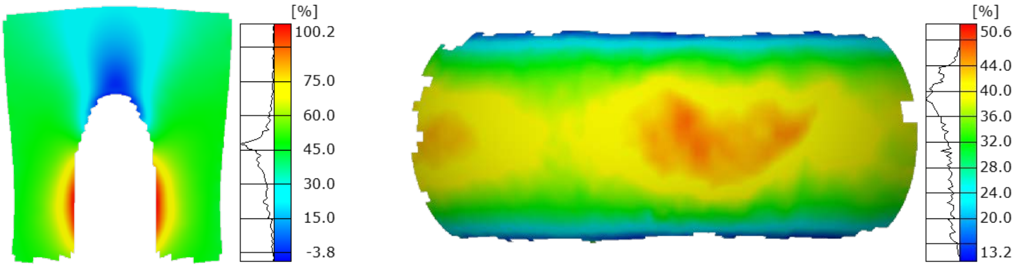

Figure 7: Course of the maximum local vertical strains

3: Determination of Material Properties

<u>Optimization Algorithm</u>

The simulated and the experimentally determined displacements $\bar{\boldsymbol{u}}_{ij}^{exp}$ and $\bar{\boldsymbol{u}}_{ik}^{exp}$ have respectively two and three varying displacement directions, depending on whether tensile or compressive testing was conducted. To calculate the material properties, the experimentally measured displacement fields must first be made comparable to such field values in the corresponding FEM model. To this end the displacements measured on the testing specimens are interpolated onto the identification nodes of the FE model by means of triangulation. For this purpose, the coordinate system of the measuring field is moreover transformed exactly in the middle of the perforation (Figure 8).

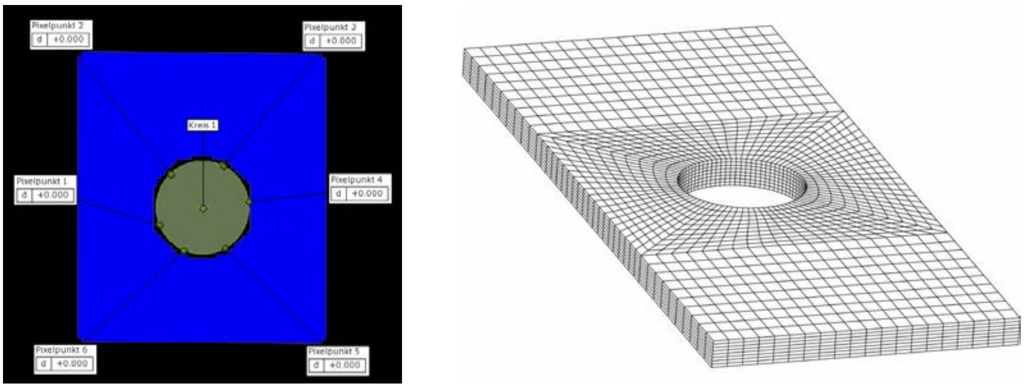

Figure 8: Transformed coordinate system and FE model (examples)

In order to be able to simultaneously calculate the material properties using multiple testing types, in this case tensile testing on perforated testing specimens and compressive testing on solid cylinders, the following formulation of the sum of the square of errors is utilized as the objective function $f(\kappa)$:

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$$f^{AB...Z}(\kappa)=\frac{1}{2}\left[\underbrace{\sum_{i=1}^{N_A}\sum_{j=1}^{T_A}\left[\boldsymbol{W}_{ij}\cdot\left[\bar{\boldsymbol{u}}_{ij}(\kappa)-\bar{\boldsymbol{u}}_{ij}^{exp}\right]\right]^2}_{\text{Test A}}+...+\underbrace{\sum_{m=1}^{N_Z}\sum_{n=1}^{T_Z}\left[\boldsymbol{W}_{mn}\cdot\left[\bar{\boldsymbol{u}}_{mn}(\kappa)-\bar{\boldsymbol{u}}_{mn}^{exp}\right]\right]^2}_{\text{Test Z}}\right] \quad (1)$$

$T_A, T_B, ..., T_Z$ represent the number of load steps observed in the respective testing type and $\boldsymbol{W}_{ij}, ..., \boldsymbol{W}_{mn}$ represent the weighting matrices for the corresponding displacement in longitudinal and transverse directions. $N_A, ..., N_Z$ describe the number of identification nodes. Due to the fact that undesired effects may occur during the testing, e.g., slippage in the clamping or the influence of machine stiffness, the absolute values of the displacements are not normally considered for the identification, but rather the displacements as related to a relative node. This in turn has the result that translation and rotation movements decoupled from the material behavior can be filtered ahead of time. This hereby changes the general depiction of the sum of the square of errors as follows:

$$f(\kappa)=\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{T}\left[\left[\bar{\boldsymbol{u}}_{i_r j}(\kappa)-\bar{\boldsymbol{u}}_{ij}(\kappa)\right]-\left[\bar{\boldsymbol{u}}_{i_r j}^{exp}-\bar{\boldsymbol{u}}_{ij}^{exp}\right]\right]^2 \rightarrow min \quad (2)$$

$\bar{\boldsymbol{u}}_{i_r j}(\kappa)$ represents the simulated displacements at relative nodes , $\bar{\boldsymbol{u}}_{i_r j}^{exp}$ represents the measured displacements according to the interpolation to the coordinates of the relative node RN. The following figure depicts the position of the respective relative node and of the five verification nodes selected for subsequent verification on the tensile and compressive test specimens.

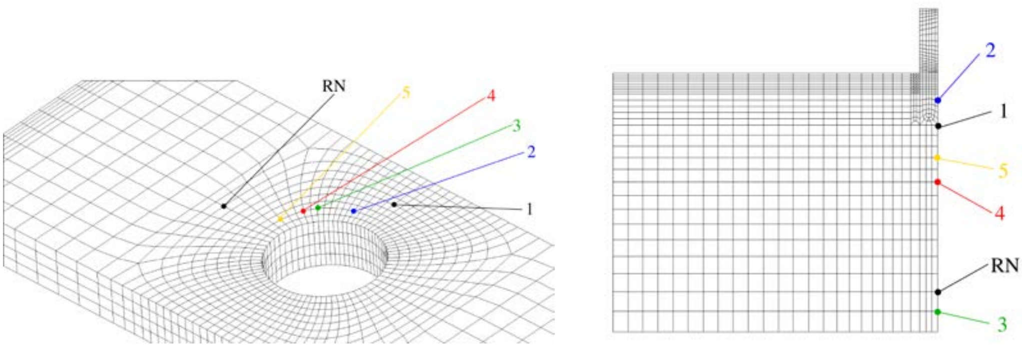

Figure 9: Position of the relative node and the verification nodes on the FE model of the tensile and compressive test specimens.

The final material dataset will be determined by means of an iterative strategy, in which an approximation is conducted initially with a broad mesh, 'faster' elements, and corresponding numerical settings. The resulting parameters are then used as an initial parameter set in the subsequent more exact model, until the settings, which are most exact in accordance with each previously named aspect, are implemented for the concluding identification. A hyper-viscoelastic material model [3] is used as a material model. The basic elasticity is thereby depicted using an Ogden model. Three to four relaxation terms are also utilized.

Verification and Validation

The results of the parameter identification are verified by means of a comparison between the measured and simulated time-displacement curves of selected verification nodes (Fig. 9). Depending on the testing type, vertical, horizontal, and radial displacements are taken into consideration. The following figures show the verifications for two different displacement directions for all four testing types. It is to be noted again here that all simulations conducted for verification were conducted with a single material dataset.

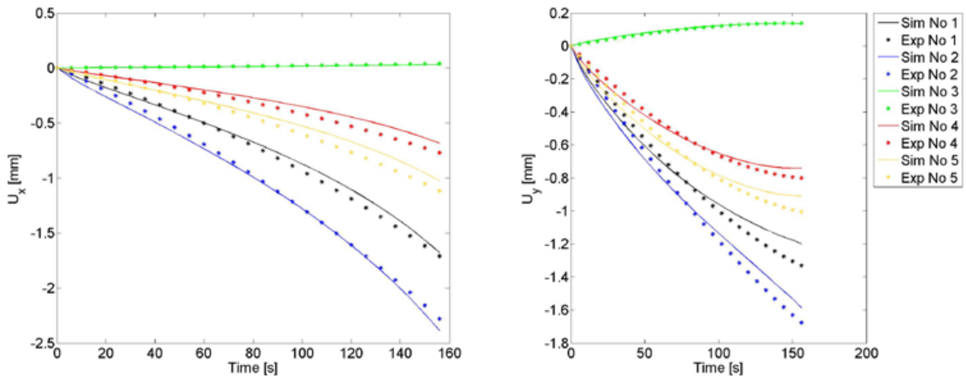

Figure 10: Relative measured and simulated radial and longitudinal displacements for selected identification nodes, quasistatic compressive testing

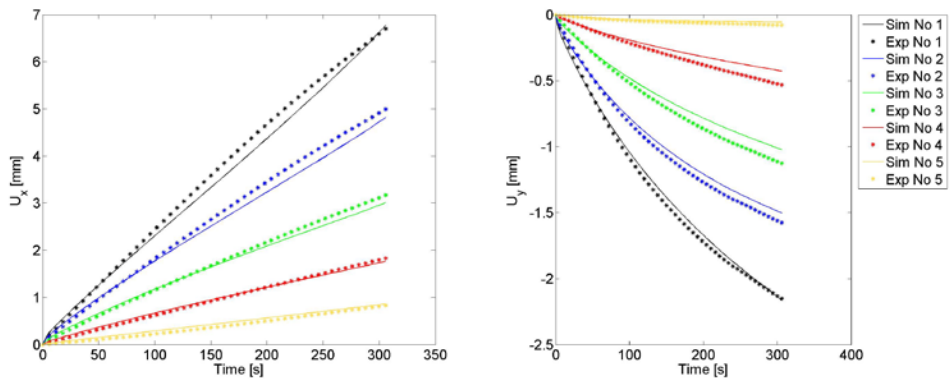

Figure 11: Relative measured and simulated longitudinal and transverse displacements for selected identification nodes, quasistatic tensile testing

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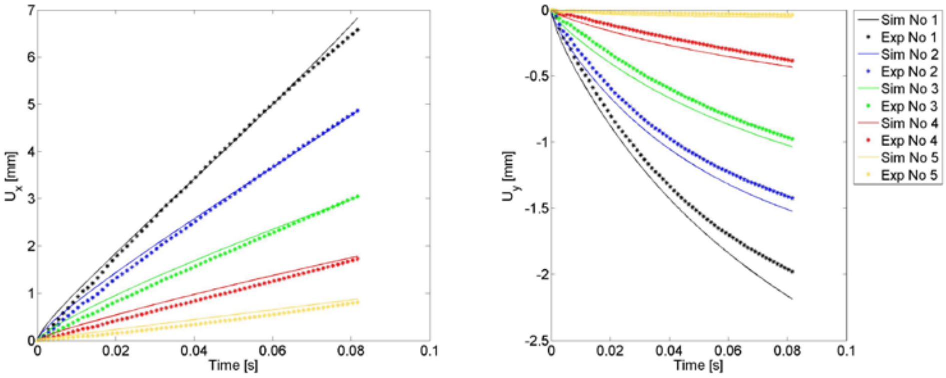

Figure 12: Relative measured and simulated longitudinal and transverse displacements for selected identification nodes, tensile testing at 0.3 m/s

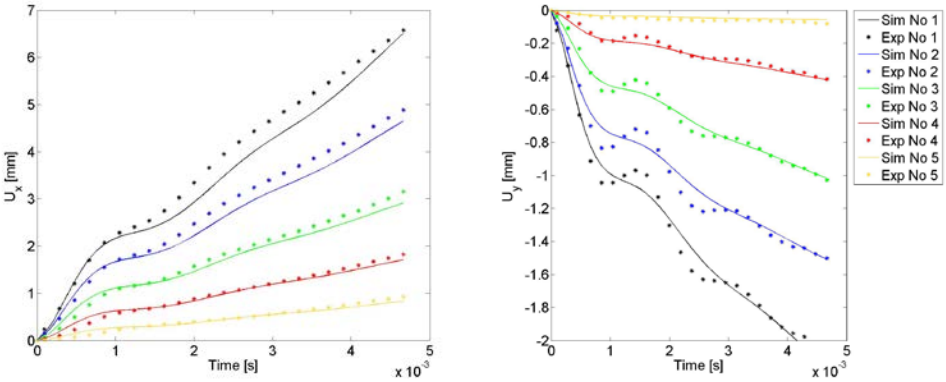

Figure 13: Relative measured and simulated longitudinal and transverse displacements for selected identification nodes, tensile testing at 5.0 m/s

The verifications show that the hyper-viscoelastic material law that was utilized is highly suitable for simulating the mechanical behavior of the studied elastomer both qualitatively and quantitatively up to a local technical strain of approximately 50% under compressive strain and approximately 100% under tensile strain. The simulated inhomogeneous displacements in the area of the perforation on the tensile test specimen as well as in the area of the bulge of the compressive test specimen, which resulted from the multi-axial stress states, correspond very well with the corresponding experimentally measured displacements.

This holds for the entire strain rate spectrum, both measured and simulated. In order to be able to safely prove that the calculated material dataset can be used to conduct realistic simulation calculations for other component shapes, which were not used for the identification, as well as possibly for higher local strains and/or strain rates, it is recommended to conduct a validation procedure in addition to the verification. To illustrate the qualitative influence of the strain

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rate on stress distribution, the following figure depicts FEM plots of the tensile testing specimens at uniform deformation, but with three different load speeds.

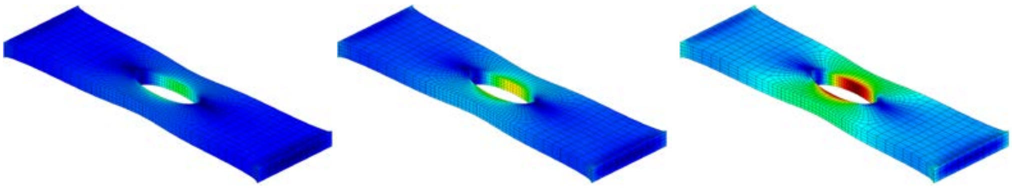

Figure 14: Stress distribution at a quasistatic load (left), at 0.3 m/s (middle), and at 5.0 m/s (right)

In addition to the presented verifications, validations were conducted by means of component testing of engine mounts at drop towers. With the variation of fall heights and fall weights, a wide spectrum of dynamic loads can be applied to the elastomer component of the engine mounts. When applying the identified material parameters, the FEM simulations are in a very good correlation with the corresponding experimental results.

4: Conclusions

It turns out that using the method presented here, all important aspects of the material modelling of a 3D component simulation of elastomers can be taken account of in a suitable manner. The verifications, both for three different extension speeds in the perforated tensile test (quasi-static up to 5 m / s) and for pronounced compressive loads at a slow loading rate, each provided a very good agreement between the measured and simulated local displacement values. In comparison to the previously utilized material parameters, these results show a considerable improved depiction of elastomer behavior. This holds in particular in regards to consideration of the strain rate dependence of the elastomer. Because the verifications and the validations led to positive results, the new material parameters are being applied in crash calculations at Volkswagen.

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