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Comparison of the material models in rubber finite element analysis

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Abstract. In rubber product design finite element analysis is widely used. The aim of this research is to choose the appropriate material models and to determine the related material parameters for finite element analysis of a rubber jounce. Rubber products can suffer from large deformation upon working conditions while behaving as a non-linearly elastic, isotropic and incompressible material. Hyperelastic material models accurately describe the observed material behaviour. Uniaxial compression test of rubber specimen has been performed to determine the stress-strain curve. Using test data and ANSYS for curve fitting process, the material constants for Mooney-Rivlin and Yeoh model have been established. Finite element analysis of the compression test has been made to validate the specified material constants. It can be stated that three term Yeoh model showed better agreement with the test data than the one term formula. Two term Mooney-Rivlin model showed good match with the measurement data, thereby it is also recommended for the future investigations of rubber jounce.

1. Introduction

The main object of the research is the determination of material models and constants for the finite element analysis of rubber jounce which serves as a secondary spring in the air spring of the lorries. In case of damage of air spring it is a requirement that the vehicle would be able to work with limited speed until the first service. For that reason the rubber product must fulfill predetermined special requirements. The operation circumstances need large deformations and under these conditions the rubber shows highly nonlinear material properties. Thanks to the continuum mechanics theory and hyperelastic material models the finite element software is a good way for design process [1-3].

The exact mixture of the rubber material is unknown by the investigated product, the manufacturing instruction prescribes 90±5 Sh° A hardness. According to the Shore hardness value the research [4] makes a proposal for the preliminary determination of the material constants in the range of 35-70 Sh° A, but the investigated product is beyond this range. Measurements on the base material are needed to determine the material constants used for finite element analysis. The main load of the rubber jounce is pressure so this research used simple compression and curve fitting method for determining the material properties which are fitted to more hyperelastic material models. The determined models were used for the finite element analysis of the specimen and the exactness of parameters was compared with experimental data.

2. Determination of material parameters

The test specimens were cut out from the rubber jounce according to ISO 23529 standards. The 'Figure 1' shows specimens used for measurements with the diameter of 29±0,5 mm diameter and height of 12,5±0,5 mm. The measurement was made according to 'A method' of ISO 7743 standards. The standard requires three pieces of specimens and lubricant during the measurement process to reduce friction between the rubber and metal surfaces.

The simple compression test was performed on a material test machine type INSTRON 5566. After three load cycles the necessary compressive load-extension curves were measured on each specimen according to the standards. The results can be seen on 'Figure 1'.
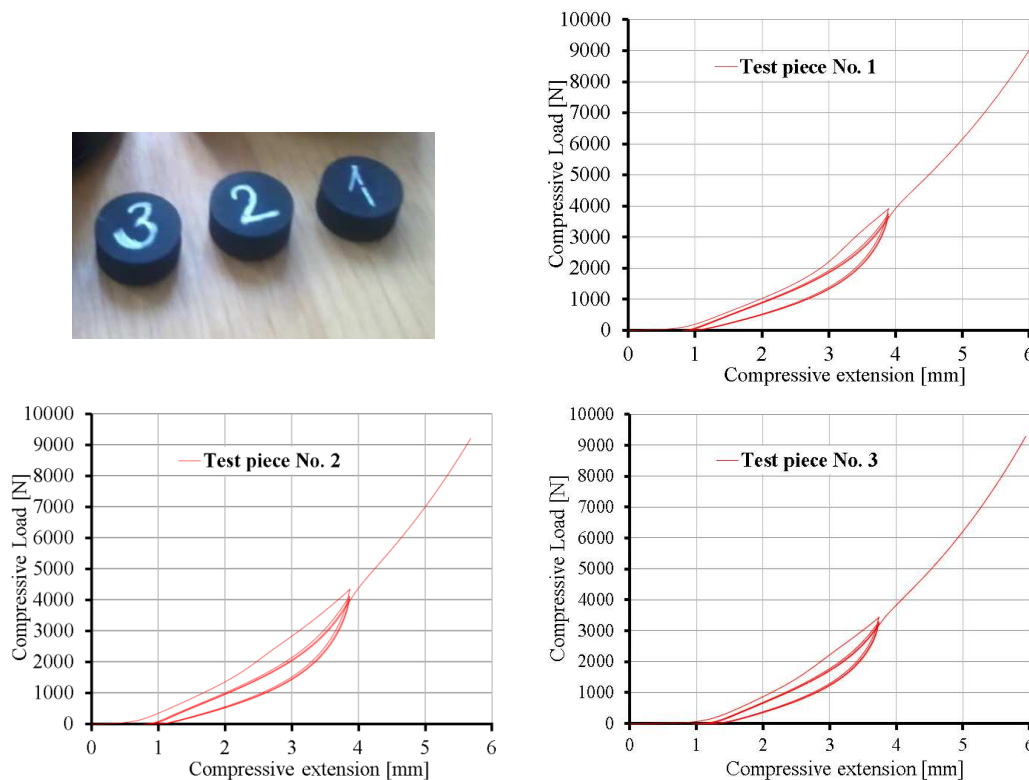

Figure 1. The test specimens with the simple compression measurement results.

The shape of the test specimens and circumstances of the measurement can be considered ideal and in this case linear relationship must be between the compressive extension and required load value under small deformation. But investigating the results this linear behavior is nearly right, furthermore until 1 mm extension the load value remained near zero because of the geometric differences therefore results must be corrected for further calculations. The friction cannot be eliminated from the measurement process despite of lubrication, thereby an abnormal behavior can be seen in the middle range of the measured curves. From the measured data the engineering strain along the longitudinal coordinate axis can be calculated with

$$\varepsilon = \frac{\Delta L_0}{L_0} = \frac{L - L_0}{L_0} \tag{1}$$

where L_0 is the original length of the specimen and L is the final length of the specimen. Furthermore, the stretch ratio is defined as

$$\lambda = \frac{L}{L_0} = \frac{L_0 + L - L_0}{L_0} = 1 + \frac{L - L_0}{L_0} = 1 + \varepsilon \tag{2}$$

Assuming complete slip between the rubber specimen and steel plate, the compression is homogeneous, and the stress-strain relationship predicted by Gaussian theory is applicable

$$\sigma = \frac{E}{3}(\lambda^{-2} - \lambda) \tag{3}$$

The 'Figure 2' shows the σ-ε curve which can be determined with the above-mentioned equation.
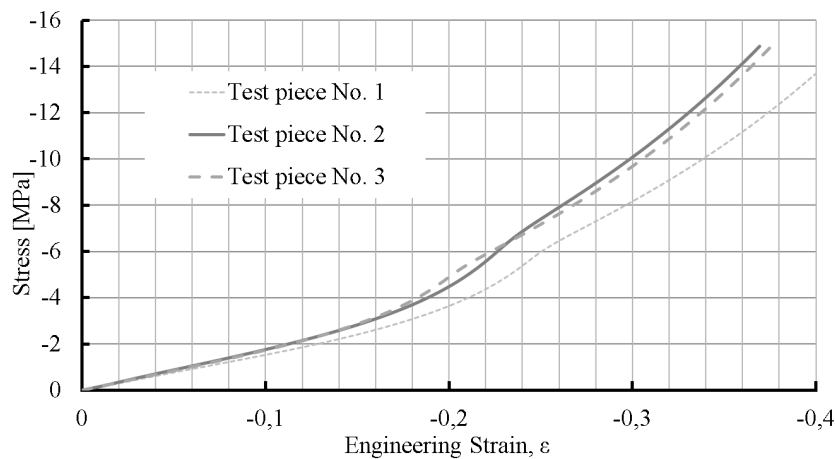

Figure 2. The calculated σ-ε curve for the rubber specimens.

Rubber behave as a nonlinear, elastic, isotropic and incompressible material, which can be described accurately with hyperelastic constitutive model. Within this several material models and material constants can be found. The material models for rubbers are generally given by the strain energy potential. A successful finite element simulation of rubber parts hinges on the selection of an appropriate strain energy function and on the accurate determination of material constants. Because of material incompressibility, the strain energy function can be divided [5]

$$W = W_D(\bar{I}_1, \bar{I}_2) + W_b(J) \tag{4}$$

where $W_b(J)$ denotes the volumetric terms of the strain energy function and J is for the Jacobian and $W_D(\bar{I}_1, \bar{I}_2)$ is for the deviatoric terms of the strain energy function. The polynomial form of the strain energy potential is based on the first $\bar{I}_1$ and second $\bar{I}_2$ strain invariants of the right Cauchy-Green tensor [6]

$$W = \sum_{i+j=1}^{N} c_{ij}(\bar{I}_1 - 3)^i(\bar{I}_2 - 3)^j + \sum_{k=1}^{N} \frac{1}{d_k}(J - 1)^{2k} \tag{5}$$

where determination of c_{ij} and d_k material constants are required in material model. The κ bulk modulus can be calculated as

$$\kappa = \frac{2}{d} \tag{6}$$

where d is the material compressibility parameter.

Mooney-Rivlin, Yeoh and Neo-Hookean material models are available within the polynomial form of the strain energy potential. If the measured engineering stress-strain curve contains one or more inflection points, more terms will be required within the polynomial form. Equation (5) with N=1 substitution is applied for single curvature, with N=2 or N=3 can be used if the measured stress-strain curve has one or two inflection points. This formula is commonly used as it has a very good curve fit ability. If limited test data exists, the use of Yeoh model need to be considered.

There are two-, three-, five- and nine-term Mooney Rivlin models available in ANSYS. As it can be seen on 'Figure 2' there is no inflection point in the measured data, hence N=1 substitution can be used. Thereby the expression of the polynomial form is equivalent with the two-term Mooney-Rivlin model.

$$W_{MR} = c_{10}(\bar{I}_1 - 3) + c_{01}(\bar{I}_2 - 3) + \frac{1}{d}(J - 1)^2 \tag{7}$$

The reduced polynomial form is based on first strain invariants of the right Cauchy-Green tensor only.

$$W = \sum_{i=1}^{N} c_{i0}(\bar{I}_1 - 3)^i + \sum_{k=1}^{N} \frac{1}{d_k}(J - 1)^{2k} \tag{8}$$

This formula is the well known Yeoh model, which is commonly considered with N=3.

ANSYS curve fitting tool was used to translate measured engineering stress-strain curve to strain energy potential function coefficients for the two-term Mooney-Rivlin, one- and three-term Yeoh model. Least squares fitting with normalized and absolute error calculation was used for curve fitting process. Generally normalized error can be used which gives equal weight to all data points

$$E_{normalized} = \sqrt{\sum_{i=1}^{N} \frac{\left(\sigma_i^{trial} - \sigma_i^{experiment}\right)^2}{\left(\sigma_i^{experiment}\right)^2}} \tag{9}$$

If large-strain behavior is sought, absolute error calculation must be use since larger values will be given more weight in this situation

$$E_{absolute} = \sqrt{\sum_{i=1}^{N} \left(\sigma_i^{trial} - \sigma_i^{experiment}\right)^2} \tag{10}$$

According to [7] $\kappa = 1000$ MPa value was selected and with the use of equation (6) $d_1 = 0,002 \; MPa^{-1}$ was determined. Table 1 contain the results of the curve fitting process.

Table 1. Material coefficients for the investigated rubber product and the calculated errors.

fitting method	$c_{10} \; [MPa]$	$c_{01}[MPa]$	$c_{20}[MPa]$	$c_{30}[MPa]$	SSE
MR2 normalized	0,58066	1,59492	-	-	486436
MR2 absolute	1,28801	1,13710	-	-	388628
Yeoh 1st normalized	2,67177	-	-	-	1466686
Yeoh 1st absolute	3,04777	-	-	-	332030
Yeoh 3rd normalized	2,2221	-	1,3787	-0,6666	345519
Yeoh 3rd absolute	2,1789	-	1,5879	-0,8499	293400

3. Finite element modelling of compression test

The aim is to determine that curve fitting method and hyperelastic material model from Table 1 that can be used for further analysis of rubber jounce. The geometry of the he investigated rubber specimen is axisymmetric, furthermore the boundary conditions are symmetric as well, thereby the deformation of the shape is independent from the φ axis. In such a case it is worth choosing axisymmetric element (isoparametric quadrilateral elements) for meshing. The size of the element was $2mm$, however the goodness of the finite element analysis was independent of the mesh density because of the ideal boundary conditions. At boundary conditions it is given 5 mm prescribed displacement for the top

edge, furthermore the bottom curve nodes were constrained along y axis, which is modelling frictionless conditions. The dependency of the loading speed was not analyzed in this research.
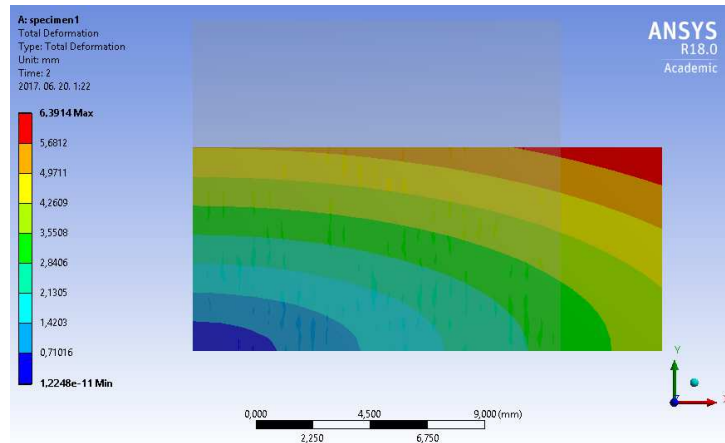

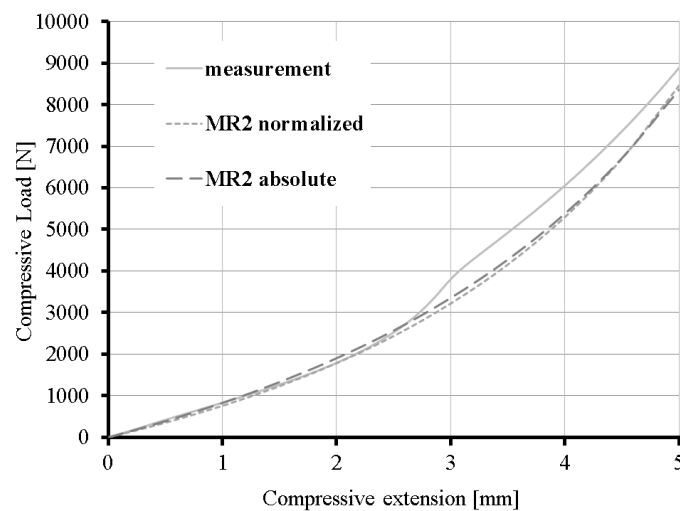**Figure 3.** Deformation state of the specimen.

Figure 4. Finite element results using two-term Mooney-Rivlin material models.
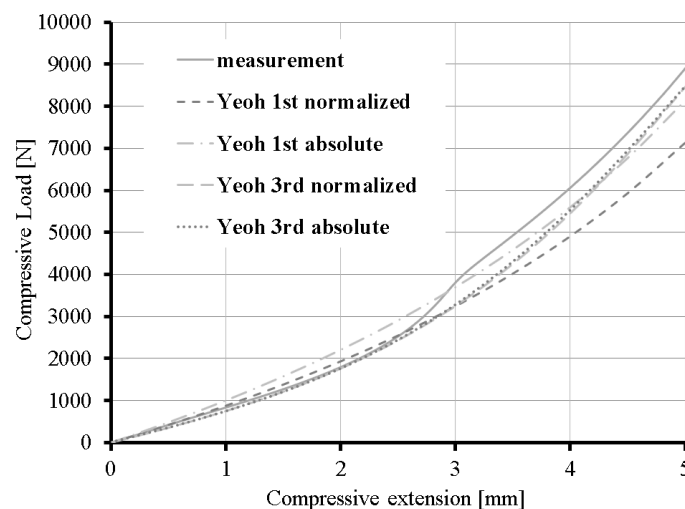

Figure 5. Finite element results using Yeoh material models.

Finite element analysis was run and the result was compared with the results of the simple compression tests. Material parameters and material models given in Table 1 was used for finite element analysis. First the two term Mooney-Rivlin material model was analyzed and its results can be seen in 'Figure 4'.

The results show proper matching with the measured data until the middle of the whole deformation, then difference can be found but it can be accepted for rubber products. The cause of the difference can be the abnormal behavior in the measured results.

Yeoh one- and three term material model was used for finite element analysis in 'Figure 5'. Sum of the squared differences (SSE) between each points of the run analysis results and the measured points was used to determine the material models goodness. The SSE error is listed in Table1.

4. Conclusion

The engineering stress-strain curve was determined with simple compression measurements. The Mooney-Rivlin and Yeoh material model constants were fitted using the above mentioned curve and ANSYS curve fitting tool. Finite element analysis of the compression test was created and it was stated that we got more exact results in case of Yeoh material model if three term form is used. Two term Mooney-Rivlin model showed good match with the measurement data, thereby both models can be recommended for the future investigations of rubber jounce. However, considering the evaluated SSE error quantities, the three term Yeoh material model with the use of absolute error calculation for curve fitting process shows the best fit. The friction cannot be eliminated from the measurement process despite of lubrication, thereby an abnormal behavior can be seen in the middle range of the measured curves. This behavior cannot be modelled by finite element analysis, as the finite element model represented a frictionless boundary conditions.

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