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METHODOLOGY FOR STRUCTURAL ANALYSIS OF HYPERELASTIC MATERIALS WITH EMBEDDED MAGNETIC MICROWIRES

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Preliminary Note – Prethodno priopćenje

The article deals with the mechanical tensile tests of the hyperelastic materials and its mechanical properties estimation using embedded magnetic microwires. Hyperelastic materials are specific because of the elasticity, which means that they return to their original shape after the forces have been removed. The article processes the issue of the structural analysis of the hyperelastic materials, where the methodology for hyperelastic materials laws together with its implementation in the Creo-Simulate software is described. After the comparison of the simulation results with the experimental results a very good compliance was achieved. The created methodology together with the application of the tensile stress sensors based on the magnetic microwires embedded directly in the conveyor belts mean a significant improvement of the manufacturing and operation of the conveyor belts.

Key words: hyperelastic material, magnetic microwires, mechanical properties, numerical analysis, finite element method (FEM)

INTRODUCTION

In order to estimate mechanical stress inside the hyperelastic materials it is essential to create the methodology for describing the behavior of a magnetic microwire and hyper elastic materials, which is in this case rubber. An important part of the proposed methodology is to obtain the material properties which are necessary for the magnetic microwire application inside the hyperelastic materials. The methodology is based on the experimental data acquisition from the rubber samples and the second part is devoted to the finite element method analysis of the samples [1, 2].

EXPERIMENTAL

Application of magnetic microwire

For the purposes of the mechanical stress measuring inside the conveyor belt it is possible to build in a magnetic microwire. The magnetic microwire sensors will be applied inside the conveyor belt during its production [3].

The main purpose of the sensor inside the belt is to monitor the stress and any deflections during the belt operation. The belt conveyor segment can be seen in the Figure 1, from this belt the specimen was cut.

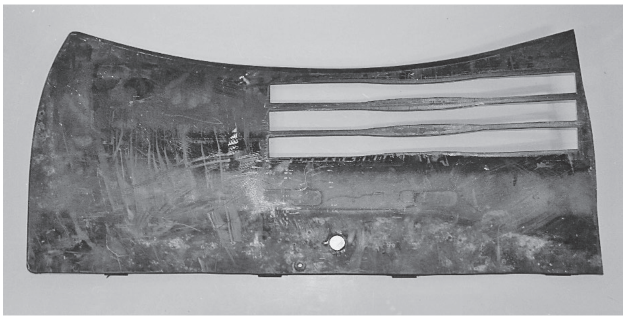

Figure 1 Conveyor belt segment

Analysis of hyperelastic specimens

Material samples are prepared to carry out the tensile tests in order to obtain mechanical properties. Mechanical properties are an essential part for the creation of the methodology for the hyperelastic materials with embedded magnetic microwires. The specimens are made of the same material like the airport conveyor belts. They are prepared using hydraulic press. The specimen's ends are gripped and fixed in the machine. The mechanical machine used in this case is the ZWIK ROELL Z030. The specimen in the machine can be clearly seen in the Figure 2.

It is important to ensure the symmetric attachment of the specimen during the testing. The output from the testing is the Stress-strain diagram (Figure 3) representing the characteristic curve for the hyperelastic material. According to this diagram it is possible to estimate material properties such as young modulus or poison ratio. Totally six specimens were tested.

K. Draganová, K. Semrád, L. Főző, M. Spodniak, R. Jurč, Faculty of Aeronautics, Technical University of Kosice, Slovakia, (e-mail: katarina.draganova@tuke.sk)

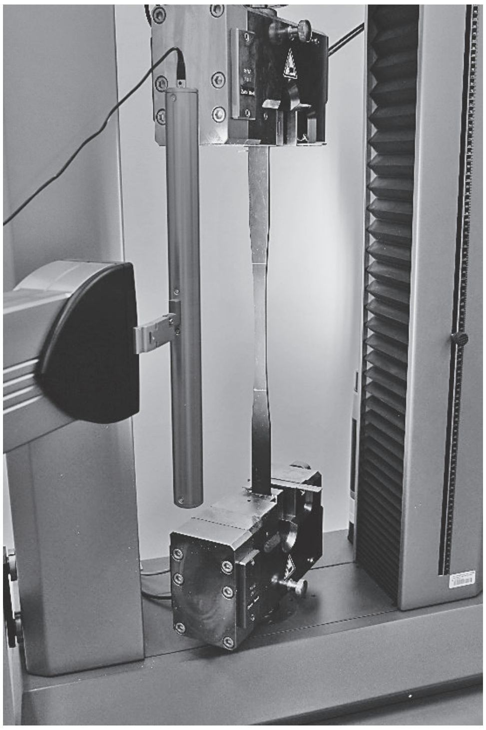

Figure 2 Mechanical tensile stress test

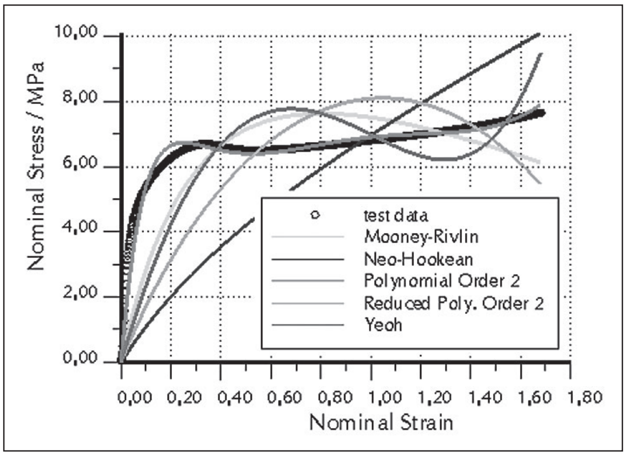

Figure 3 Hyperelastic material definition

Hyperelastic model in Creo

The Creo-Simulate is able to simulate the structural behavior of the model under the large deformation. Just ability to experience the large deformation under the small loads is a peculiar feature of the hyperelastic materials. The stress-strain behavior is highly non-linear; therefore the characterization of the elastic behavior of highly extensible, nonlinear materials is of a great importance. The calculations in the Creo-Simulate are based on the method of geometric elements, whose principle consists in the dividing of the analyzed volume into the elements exactly respecting the created 3D model. The 3D elements Tetra, Brick and Wedge were used for this SOLID volume model. The mesh is generated and optimized automatically to achieve a high quality computational model. If necessary, it is also possible to perform some manual interventions in this process, leading to the further improvement of the network.

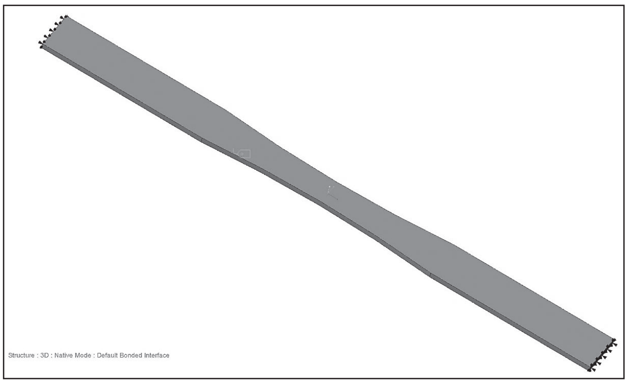

Figure 4 Belt conveyor specimen 3D model

In order to simulate behavior during the testing, the 3D model geometry of the specimen is created. Based on this model it is possible to perform the finite element model simulation. The 3D model of the specimen is shown in the Figure 4. The boundary conditions are applied on the model. The 3D model of the specimen is fixed in one end and on another one is applied force, which is equal to the force during the experiment [4].

When it comes to investigated specimen the material is isotropic with Stress-Strain Response Hyperelastic characteristics. The characteristics was obtained from the experimental tests. The results from the test were imported into the Creo-Simulate software in order to select the appropriate material model for the numeric analysis. From the various material models (Arruda-Boyce, Mooney-Rivlin, Neo-Hookean, Polynomial Order 2, Reduced Poly. Order 2, Yeoh) as the best fit Neo-Hookean model was selected. The material model is created according to the following ideas [5].

Implementation of hyperelastic laws in Creo-Simulate

Elastomers (like rubber) typically have large strains (often up to 100 %) at small loads (means a very low modulus of elasticity, for example just 10 MPa). The material is nearly incompressible, so the Poisson's ratio is very close to 0,5. Their loading and unloading stress-strain curves are not the same, depending on the different influencing factors (time, static or dynamic loading, frequency…). This viscous behavior is ignored if the hyperelastic material model is used for description. The nominal strain ε is defined as the change in the length Δl divided by the original length l_0:

$$\varepsilon = \frac{l_1 - l_0}{l_0} = \frac{\Delta l}{l_0}$$

where l_0 is the original length and l_1 is the current length after the deformation. The stretch ratio λ is other fundamental quantity describing the material deformation. It is defined as the current length l_1 divided by the original length l_0:

$$\lambda = \frac{l_1}{l_0} = \frac{l_1 - l_0 + l_0}{l_0} = \varepsilon + 1$$

Analogically considering the three principal strains, from the principal axis transformation we obtain three principal stretch ratios λ_1, λ_2, λ_3. The three stretch invariants I_1, I_2 and I_3 (dependent on the applied coordinate system) of the characteristic equation are analog:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$I_1 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_1^2\lambda_3^2$$

$$I_1 = \lambda_1^2\lambda_2^2\lambda_3^2 = 1 + \left(\frac{\Delta V}{V}\right)^2 = J^2$$

where J is the total volumetric ratio; considering incompressible material $J = 1$ and $\Delta V/V$ is the relative change of the volume [5]. The description of the strain energy density W is much more complex in compared to the linear elastic material, where the stress is just a linear function of the strain. For the hyperelastic material, the second Piola-Kirchoff stress is defined from the strain energy density function and Green-Lagrange strain (first derivative). In general, the strain energy density function in the hyperelastic material is a function of the stretch invariants $W = f(I_1, I_2, I_3)$ or the principal stretch ratios $W = f(\lambda_1, \lambda_2, \lambda_3)$. For the typical hyperelastic material models, often phenomenological models are used, where the strain energy function has the form:

$$W = \sum_{i+j=1}^{N} C_{ij}(I_1 - 3)^i (I_2 - 3)^j + \sum_{k=1}^{N} \frac{1}{D_k}(J-1)^{2k}$$

where the C_{ij} and D_k are material constants which have to be determined by the tests [5].

The Creo-Simulate now supports six hyperelastic material laws of such a type (Arruda-Boyce, Mooney-Rivlin, Neo-Hookean, Polynomial Order 2, Reduced Polynomial Order 2, Yeoh). Creo-Simulate automatically selected the "Neo-Hookean" model as the best fit to the data from the test, C_{10} = 1,98877 and D_1 = 0 (Figures 2, 3). The D_1 value is shown as zero (incompressible), since no volumetric test has been specified. However, internally the Creo-Simulate uses D_1=1/(500G_0), which corresponds to the Poisson ratio of 0,4995. The exclamation mark means that for a certain strain range, the model is unstable (Zero tangent stiffness). For the Arruda-Boyce model, the Least Square Fitting algorithm failed, so it cannot be used (and is not displayed). The Neo-Hookean is the simplest approach:

$$W = C_{10}\left(I_1 - 3\right) + \frac{1}{D_1}\left(J_e - 1\right)^2$$

where J_e is just the elastic volume ratio:

$$J_e = \frac{J}{J_{th}} = \frac{J}{\left(1+\varepsilon_{th}\right)^3}$$

where J is the total volumetric ratio and J_{th} the thermal volume ratio [5].

The initial shear modulus G_0=E_0/(2(1+μ)) and the initial bulk modulus K_0=E_0/(3(1–2μ)), can be described with help of the material constants, for example in the material model of Neo-Hookean:

$$G_0 = 2C_{10} \qquad K_0 = \frac{2}{D_1}$$

where E_0 is the Young´s modulus and μ is the Poisson ratio. The Poisson ratio used in the analysis can be determined from the used values for the initial shear and initial bulk modulus by the equation:

$$\mu = \frac{3K_0 - 2G_0}{6K_0 + 2G_0}$$

Finally, the only two necessary material constants C_{10}=G_0/2 and D_1=2/K_0 can be simply obtained from the initial shear and initial bulk modulus. If μ = 0,5, then we of course have $K_0 = \mu$ and so D_1 = 0. The Creo-Simulate uses the *p*-order finite element implementation to analyze the hyperelastic materials. One of the advantages is that no special procedure is needed when the Poisson's ratio approaches to 0,5. If the value specified for D_1=2/K_0 is less than 1/500G_0, the Creo-Simulate uses this value as limit for the D_1. So, for the maximum possible Poisson's ratio used to approximate the ideal incompressibility we obtain:

$$K_0 = \frac{2}{D_1} = 1\,000\,G_0 \Rightarrow \frac{E_0}{3(1-2\mu)} =$$

$$= \frac{1\,000\,E_0}{2(1+\mu)} \Rightarrow \mu = \frac{1\,499}{3\,001} \approx 0,4995$$

According to the previous ideology the material model is prepared in the Creo-Simulate in order to perform the simulation of the specimen.

Simulation results

Once the 3D model is meshed and the material models are prepared, the static simulation with the large deformation can be carried out. The nonlinear static analysis consists of ten steps from 0 to 200 mm deformation. The last step with the results is presented in the Figure 5, where the stress during the test and displacement of the specimen during the last step of the simulation and also during the experiment are shown. After this step the specimen is broken.

The results from the numerical analysis are in compliance with the mechanical test, where the tensile strength of the material is 7 MPa. Subsequently, this material model can be used to analyze the conveyor belts in operation.

CONCLUSION

The hyperplastic materials require individual approach in terms of the FEM analysis because of its hy-

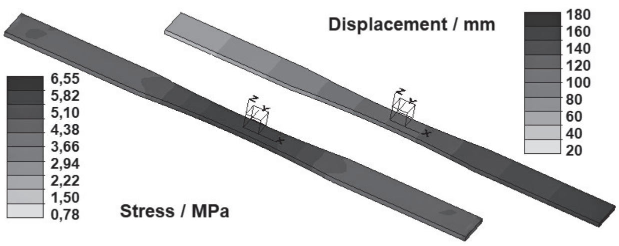

Figure 5 Belt conveyor static analysis results

per elasticity. In the article the issue of the large hyperplastic deformations is described and analyzed. The material properties that are essential for the magnetic microwire application were obtained from the specimen and results were described in the first chapter. It is possible to determine the Young's modulus and the Poisson ratio according to the experimental results. For the specimen the maximal deformation and the mechanical stress were calculated and the correctness of the theory was proved by the very good compliance of the simulation results with the experimental results. Based on this research it will be possible to apply magnetic microwires as the mechanical stress sensors inside the belt conveyor and to monitor the conveyor belts at the airports, which ensures reliable operation of the device.

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Note: The English Language translation was done by Katarína Draganová, PhD., ING-PAED IGIP, Technical University of Kosice, Slovakia