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FEM PREDICTIONS OF VISCOELASTIC BEHAVIOR OF NATURAL RUBBER FOR HIGHER SPEEDS

Elli Gkouti[1*], Burak Yenigun[1**], Aleksander Czekanski[1**]
[1]Department of Mechanical Engineering, Lassonde School of Engineering, York University, Toronto, ON, Canada
*gkoutiel@yorku.ca, **byenigun@yorku.ca, ***alex.czekanski@lassonde.yorku.ca

Abstract—The ability to simulate and predict elastomers' response to different causes for several condition is an important aim for mechanical engineering. Simulating real conditions means that the model must be able to mimic the viscoelastic behavior for several conditions, such as temperature, speed, strain value, etc. Ideally experimental investigation is able to provide all the necessary data for simulating any possible condition. However, the experimental tests are extremely costly and time-consuming in order to be the engineer's only choice. Consequently, creating models based on real experimental data can be used for predicting elastomers' behavior. In the present research, we managed to build a Finite Element Model (FEM) based on experimental data which is capable of predicting higher speeds. The accuracy of this model was tested by comparing the predictions with the experimental test data for 4 different speeds.

Keywords-Natural rubbers; viscoelastic behavior; finite element model; prediction; elastomers;

I. INTRODUCTION

Rubbers are commonly used elastomers in everyday life due to their light weight, their low production cost and their efficient viscoelastic behavior. They have been used in many highly sensitive applications, such as the production of automotive components (bumpers, interior panels, fuel tanks, etc.) and, since they are capable of sustaining large levels prior to failure, they lend themselves to many other applications. Due to the viscoelastic properties of rubbers, their stress-strain responses show considerable dependence to several conditions such as temperature, speed, strain level, strain rate, etc. The obvious way to simulate a rubber's response to deformation is by performing relative experimental tests for several conditions [1-4]. However, repeating experimental tests for every change in experimental conditions is extremely time-consuming and costly. Consequently, based on FE analyses accurate crashworthiness predictions with a view to improving the impact resistance of automobile parts can be created [5-6]. Hence, predicting higher speeds can be feasible by using accurate FE models based on input experimental test data.

Elastomers exhibit viscoelastic behavior that can be examined by performing several experimental tests where material samples are subjected to a desired strain level and then is held constant for some time. The stress response to those causes is the loading and relaxation for the corresponding time periods [7-8]. Simulating the experimental results amplifies the prediction of rubbers' behavior in different conditions and hence, the quicker and simpler the procedure becomes [5-7, 9].

In the last decades, several rubbers have been created and used in engineering applications. The consistency of these elastomers varies depending on the filler's material and the molecular chains with the matrix [10-12]. For our research we selected natural rubber which is a commonly used elastomer in several engineering applications. It is considered to be a mainly unfilled rubber, which means that its consistency is much simplest than filled elastomers. Filled rubbers develop strong molecular chains between particles and matrix, which make their viscoelastic behavior vary from the expected respond for higher temperatures, speeds or strain rates [13-15].

Large deformation (upper than 10-20% strain) are usually observed in engineering applications and so we chose to investigate the viscoelastic behavior of natural rubber for 100% strain. The material respond to so large strain subjection is merely complicated and several papers have been dealing with this field. For simulating the loading stage is similar to an elastic behavior, however, for large deformations the rubber behaves non-linearly and so more complicated theories than the Hooke's law must be used for describing the relationship between stress and strain. Hyperelastic models are mainly used which include the strain energy potential function for calculating the stress-strain equation [16]. The appropriate function can be selected by curve fitting with experimental data and calculating the appropriate parameters. For different conditions or rubber (filled or not) the models vary. In our case, the stress-strain equations for uniaxial, planar and equibiaxial tension was used for curve fitting the corresponding experimental tests and the most accurate model was selected for the hyperelastic behavior. Moreover, for simulating the stress relaxation stage, Prony series model was used with two terms. Similarly, the Prony series equation was used for curve fitting with the stress relaxation experimental results and the corresponding parameters were calculated. Several papers can be found in bibliography for a more detailed description of the curve fitting procedure [16-18].

In the current research, experimental tests were performed for four different speeds, where samples of natural rubber were subjected to 100% strain and then, held constant for a specific period of time in order to examine their viscoelastic response to those causes. For creating a Finite Element Model, uniaxial, planar, equibiaxial and stress relaxation experimental tests were performed for the lowest speed 0.1mm/s at room temperature. Using commercial software (ABAQUS) the model was built and used for predicting the response of natural rubber for higher speeds [19]. Finally, the experimental and FEM results were compared showing that the prediction of mechanical behavior of natural rubber for higher speeds is feasible for future use.

II. Different Speeds

A. Experimental Investigation

A dog-bone shape sample (115mm x 25mm x 3.175mm) of Natural Rubber has been subjected to uniaxial tension until it reached 100% strain and then was held constant for 900 sec. The crosshead's speed was 0.1mm/s at 23^{o}C temperature. We repeated this experimental test in the same conditions for three higher speeds, namely 1mm/s, 5mm/s and 16mm/s. The stress response of loading and relaxation has been recorded and showed with red line in Fig. 1. All experiments were performed in an MTS machine and an area of 5mm in the center of the sample was measured by a laser extensometer of 100mm capacity.

In order to simulate the viscoelastic response of natural rubber, planar, uniaxial and equibiaxial experimental tests were performed until the sample fractured for modeling the loading stage. The resulting data of the three tests were then analyzed and material parameters were evaluated in order to be used as the input for creating FEMs in a commercial software (ABAQUS). For simulating stress relaxation, we performed another test, where a sample was subjected to tension until it reached the 100% strain and then was held constant for 900 sec. The experiments concerning the input data were performed at 23^{o}C and for 0.1mm/s speed.

B. FEM Prediction

For many applications, which the material behavior is mandatory for checking the response or durability of am engineering structure, viscoelastic models can be used. Moreover, it is considered to be excessively time-consuming and costly to perform experiments every time the conditions change. As a result, creating FE models can reinforce the simulation and prediction of the viscoelastic behavior of rubbers with accuracy. These models can be built by using as an input the experimental test data for the loading and relaxation stage that was performed as described in the previous section for the lowest speed of 0.1mm/s. The data relative to the loading stage was used for choosing the appropriate hyperelastic model, which in our case was Ogden with one term. After appropriate curve fitting with the test data of loading, the relative parameters for Ogden model were calculated. Similarly, stress relaxation data were used for calculating the Prony series parameters. It must be mentioned that rubbers are considered to be nearly incompressible materials and so, the Poisson ratio is almost 0.5.

The FE model that simulated the behavior of natural rubber was built as described above and then was used for simulating loading and relaxation for four different speeds. Initially, we had to check the model for its accuracy and so, we applied the relative boundary conditions and steps for simulating the behavior of the rubber for 0.1mm/s speed. A static step followed by a visco step was used for simulating the loading and relaxation stage, respectively. The results, shown in the first graph of Fig. 1, prove that our model is very accurate as the experimental and FEM data almost coincide. Then, we used the same model for higher speeds, 1mm/s, 5mm/s and 16mm/s and the results are shown in the rest graphs of Fig. 1 compared to the corresponding experimental data.

III. Results and Discussion

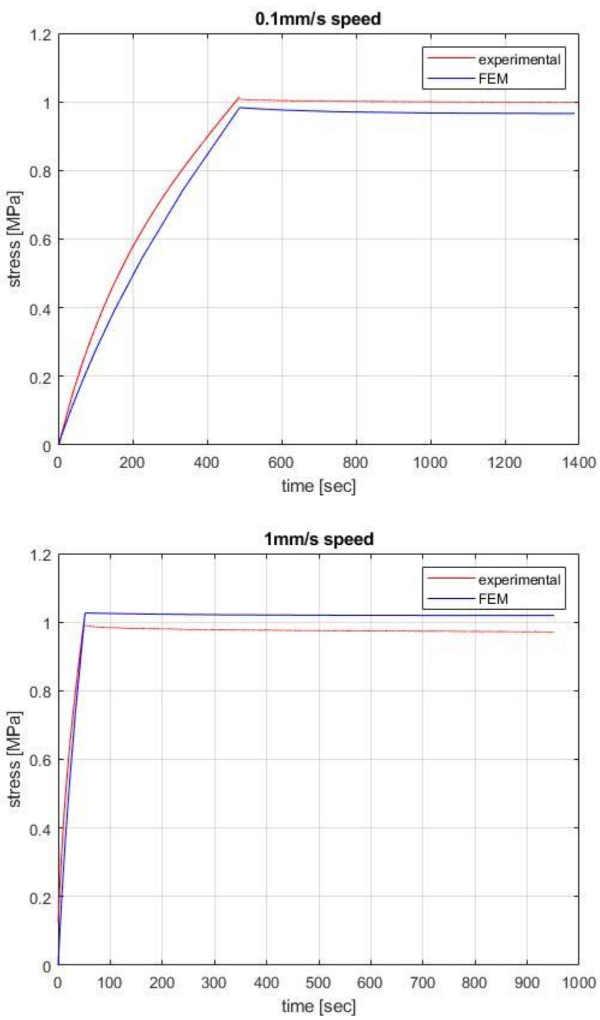
For the experimental data, there is a significant result that follows. The stress value needed to reach the desired strain value where the relaxation begins decreases with the increasing speed. Specifically, the required stress values for 0.1mm/s, 1mm/s, 5mm/s and 16mm/s are 1.01396MPa, 0.996767MPa, 0.969234MPa and 0.925189MPa, respectively. The above result constitutes an anticipated conclusion due to the quick and sudden subjection to a deformation which requires lower force for the material to reach the desired deformation.

Fig. 1 shows the differences between the experimental and FEM data. As it is obvious the differences increase with the higher speed as the model was based to the input data gained for the lowest speed of 0.1mm/s. We chose these data as they give a more accurate and detailed idea of the rubber's response due to their slow move. As higher as the move of the crosshead gets, the less accurate the model is. However, the simulations done by this model are acceptable as the error between the experimental and FEM data are 3%, 4%, 9% and 14% for the corresponding speeds 0.1mm/s, 1mm/s, 5mm/s and 16mm/s, respectively. As it is obvious, the results of loading stage coincide for experimental and FEM data due to the quick move of the crosshead. The differences are noticed to the relaxation stage where it is programmed to hold the strain constant for 900 sec. Consequently, the errors referring to higher speeds than 0.1mm/s concern the relaxation stage.

However, we must notice that the rubber that we used for the current research is natural rubber, which is mainly an unfilled rubber. Namely, the above results can not be used for any rubber as the consistency of every elastomer vary. Due to the molecular chains between the particles and the matrix, their behavior might be surprisingly different than expected.

IV. Conclusions

The stress value required for natural rubber to reach a desired large deformation is decreasing when the speed increases. This conclusion is obvious when observing the decreasing stress value in Fig.1. Furthermore, the costly and time-consuming procedure of experiment with different speeds can be avoided, as an FE model was created for predicting the viscoelastic response of natural rubber for higher speeds than 0.1mm/s. Although the error increases with the higher speeds, the results can be acceptable as they are lower than 14%. For future work, the prediction of higher speeds for higher temperatures can be tested, by using similar FE for each temperature. Finally, current work can be extended in several rubbers (filled or not) in order to compare the viscoelastic behavior in higher speeds.



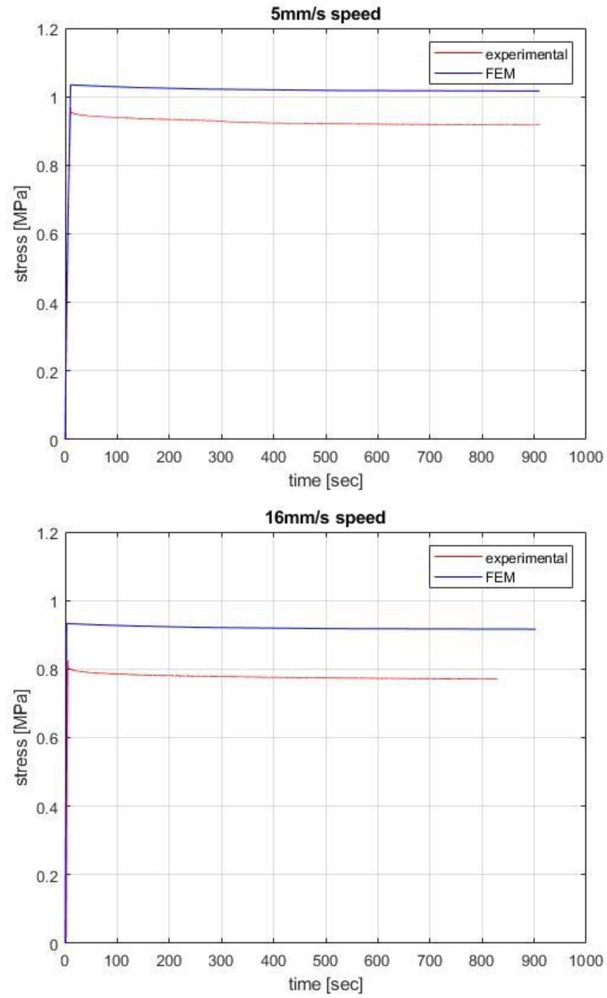


Figure 1. Comparison of experimental and FEM data of Nautral Rubber, subjected to 100% strain (loading-relaxation) at 23oC temperature for 0.1mm/s, 1mm/s, 5mm/s, 16mm/s speed, respectively.

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