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MECHANICAL BEHAVIOR OF SILICONE RUBBER REINFORCED WITH PARALLEL FIBERS OF NYLON UNDER SIMPLES SHEAR: A STUDY ON ARTIFICIAL SOFT TISSUE

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Abstract. *The objective of this paper is to investigate the mechanical behavior of silicone rubber reinforced with parallel fibers of nylon under simple shear at large deformation. This study aims to reproduce the soft tissue behavior using synthetic material, overcoming the difficult to obtain experimental simple shear data. The obtained results allow us to understand and predict the mechanical response of fiber-reinforced incompressible non-linearly elastic materials. Simple shear tests were performed considering parallel fibers of nylon into silicone samples that were oriented at angles of 0, 45 and 90 degrees. Digital Image Correlation method was used to evaluate the amount of shear. As preliminary results, the stiffness of the hyperelastic composite material increases with increasing angle; however, a largest stiffness was observed for small values of amount of shear with values of angle near to 45 degree.*

Keywords: *digital image correlation, fibers of nylon, silicone rubber, artificial muscle*

1. INTRODUCTION

Hyperelastic materials are useful in a variety of applications. These materials have a high degree of deformability and are characterized by a nonlinear stress strain relation. That fact has been experimentally verified for many researchers, as Sasso *et al.* (2008) who characterized an elastomer using biaxial and uniaxial tests based in optic methods. Nunes (2011) studied the behavior of a silicone rubber under simple shear deformations. Nunes and Moreira (2013) analyzed the mechanical response of an incompressible hyperelastic solid under large deformation using a simple shear test.

Many investigators have recently turned to model the mechanical response of polymers. For instance, Lopez-Pamies (2010) proposed an alternative hyperelastic model based only on the first invariant for describing the behavior of rubber-like materials. Marckmann and Verron (2006) presented a comparison among twenty hyperelastic models for rubber-like materials and ranked them.

Nonlinear stress strain relation is also a characteristic of biologic soft tissues. Besides that, soft tissues have anisotropic properties because of collagen fibers. Melnik and Goriely (2013) studied a simple model of fiber reorientation in a rectangular elastic tissue reinforced by two symmetrically arranged families of fibers subjected to constant external loads. Destrade *et al.* (2008), in their work about surface instability of soft sheared tissues, verified that, under shear, elastomers surface keep plane while soft tissues surface shows instabilities. These surface instabilities can be related to pathologies, such as aneurysm formation, arterial kinking and brain trauma. This paper demonstrates that soft tissues study is extremely important for the development of heathy care.

Rashid *et al.* (2013) characterized a brain tissue under simple shear at dynamic impact conditions. It helps in the development of brain injury criteria and the better countermeasures against traumatic brain injury.

The response of fiber-reinforced elastomers has become a favorite topic for analysis and understanding of the mechanical behavior. Merodio and Ogden (2005) studied the mechanical response of some fiber reinforced elastic solids under homogeneous deformation. As expected, it was observed that the anisotropic nature of the material has a particular influence on its response.

Recently, Fereidoonnezhad *et al.* (2013) developed a constitutive model for hyperelastic materials reinforced with fibers. The problem was modeled using hyperelasticity theory taking into consideration non-linearity and incompressibility. Chagnon *et al.* (2014) proposed a review of the principal hyperelastic constitutive equations considering isotropy and anisotropy. Some published works using fibers of nylon as reinforcement to represent soft tissues. Haines *et al.* (2014) developed artificial muscles made of nylon and tested them to demonstrate that their performance is better than other artificial muscles made of expensive materials.

This work intends to improve soft tissues knowledge without needing to test real ones once it is difficult to get and keep tissue samples in adequate conditions. For this purpose, simple shear tests were done in silicone rubber reinforced with parallel nylon fibers organized in some different angles. In these tests, a noncontacting method, known as Digital Image Correlation (DIC), was employed to evaluate the full-field displacements.

2. MATERIAL AND METHODS

The materials used were the RTV-2 silicone rubber, model RT 402 M from Moldflex and nylon 6 monofilament fishing line, also known as “polyamide 6”. Specimens made of silicone rubber reinforced with parallel fibers of nylon were fabricated and tested under simple shear. The experiments were carried out in quasi-static condition and at room temperature, i.e., 25°C.

Simple shear deformations were measured using DIC method. DIC is a non-contact optical-numerical technic for full-field surface displacement measurement based on image comparison. A correlation program compares images of the specimen in the undeformed and in the deformed states. It needs a calibration, which means a correspondence between the size in millimeters and the quantity of pixels associated. The matching process is possible because of a random speckle pattern that covers sample surface.

2.1 Fabrication

For the specimen’s fabrication, first a glass plate was leveled, cleaned and a mold release (Wax O18) from Polinox was applied to the plate surface. A rectangular ring mold (281 mm x 225 mm x 3.4 mm) was manufactured from aluminum and, fibers of nylon were fixed to the mold keeping equal spacing of 2 mm, as illustrated in Fig. 1. In order to improve the adherence, the fibers received a treatment that consisted of abrading using a sandpaper of 150 and cleaning them with acetone before application of the silane.

The silicone resin was weighed, mixed with a catalyst and poured in the mold. Special care was given to guarantee that the resin was appropriately distributed in the mold. Its cure takes 24 hours before it can be handled, and 72 hours before it presents all its mechanical properties guaranteed. After cured, silicone rubber was unmolded and cut in specimen dimensions (77mm x 55mm x 3.4 mm), considering the angle nylon should have in specimen to position the right place to cut. The considered angles are related to the direction of shear force that will be applied. Four samples with parallel fibers of nylon angled 0°, two samples with nylon angled 45° and three ones with nylon angled 90° were made. The specimen’s surface, fixed in shear apparatus, was covered with painted speckles (random black pattern).

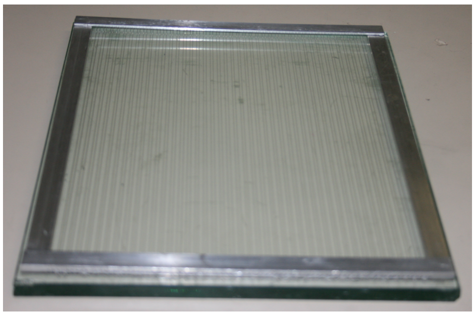

Figure 1. Mold developed to fabricate the specimens with some fibers of nylon.

2.2 Experimental set-up

The experimental arrangement was composed of an apparatus developed for applying shear load, a light source and a high resolution CCD (charged couple device) camera to capture images of the sample. This arrangement is illustrated in Fig. 2.

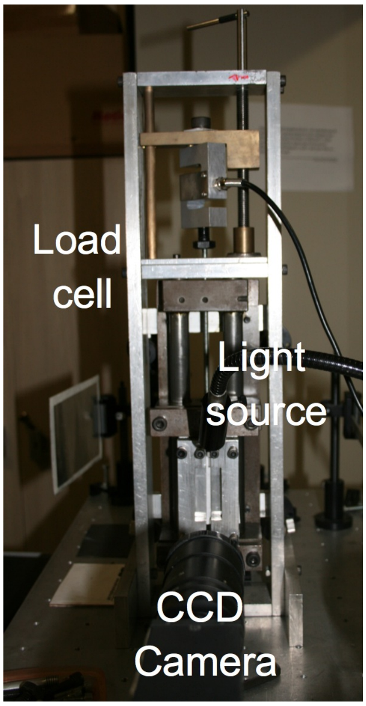

Figure 2. Experimental arrangement.

The basic idea of the experiment was to test the sample under simple shear while images of specimen in undeformed and deformed states were being acquired. These data were processed by a correlation program that determined the full-field displacements and consequently values of the amount of shear were estimated.

3. RESULTS AND DISCUSSION

Figure 3 shows the results of full-field displacements obtained from a sample of silicone reinforced with fibers of nylon with angles of orientation close to 45 degree under an applied load of 28.1 MPa. These maps were obtained on surface area at central region of the specimen. The v and u displacement fields of the selected region are related to vertical and horizontal directions respectively. In v displacement, the largest displacement happens in the sample part that receives shear load directly from experimental apparatus. U displacement is very small when compared with vertical one.

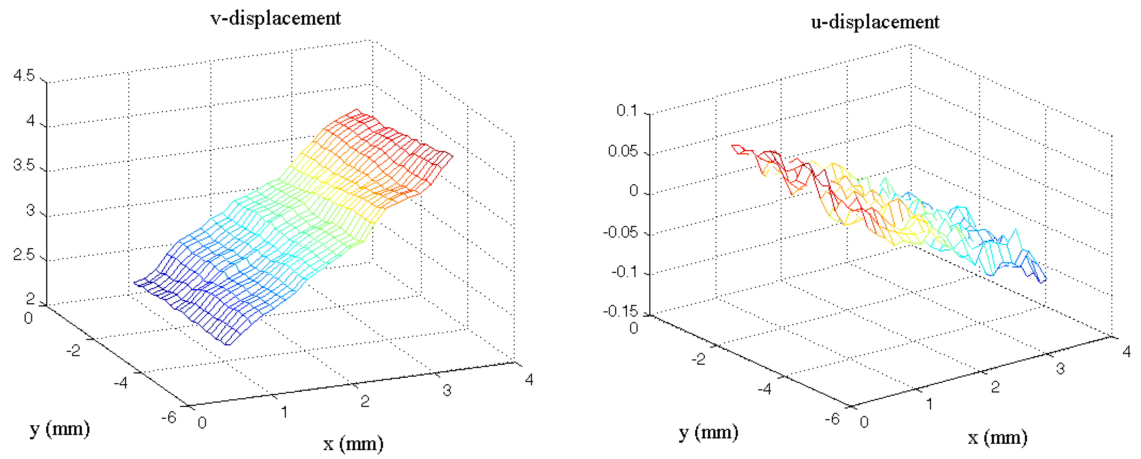

Figure 3. Full-field displacements obtained from a sample of silicone reinforced with fibers of nylon with angles of orientation close to 45 degree under an applied load of 28.1MPa.

The values of amount of shear were determined using full-field displacements at a small central zone of gage section. Figure 4 shows the mean values of shear stress as a function of amount of shear for silicone reinforced with parallel fibers of nylon aligned at angles of 0, 45 and 90 degrees. The mean values and standard deviations were evaluated from three tests.

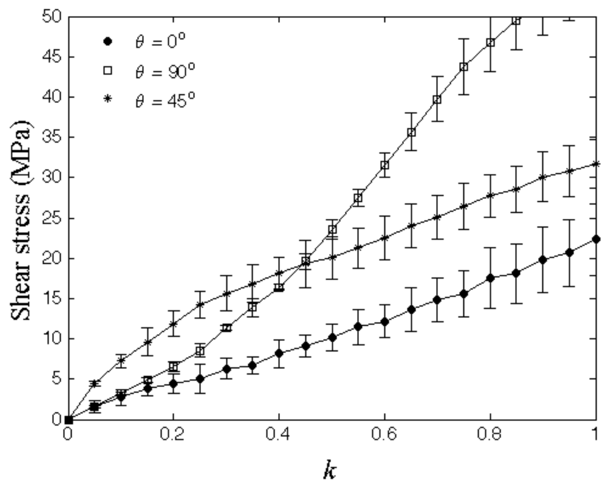

Figure 4. Curves that related shear stress with amount of shear for parallel fibers of nylon angled 0°, 45° and 90°.

To better understand the results presented in Fig. 4, it could be considered a square structure with their ends articulated and some inextensible parallel fibers positioned in different angles, as shown in Fig. 5. Now, consider that a force is applied in this structure, producing a shear deformation. The results are illustrated in Fig 6.

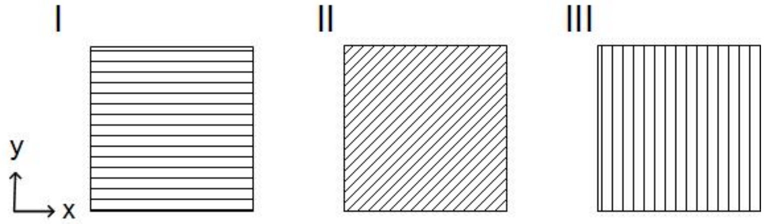

Figure 5. Scheme of the structure and its fibers with 0°, 45° and 90° angles, respectively.

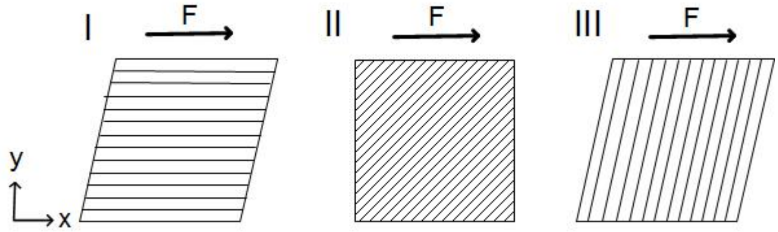

Figure 6. Scheme of the structure represented in Fig. 3 after a force F being applied.

In the case I, the structure moves as if there were no fibers. That happens because fibers are angled 0° in relation to the applied force, i.e., positioned parallel with the force, offering no resistance. This phenomenon is represented in the curve that corresponds to nylon angle 0°. It has the lowest shear stress when compared with the others. In this case, the result indicates that fibers cause no effect to reinforce the material resistance.

Case II shows the structure with parallel fibers positioned diagonally, with about 45°. This is the position that the only way of moving the structure is to stretch the fibers. As fibers are supposed to be inextensible, structure movement is blocked when force is applied. The last case presents the structure with fibers angled 90°, i.e., perpendicular to the applied force. In this case, fibers do not inhibit the movement.

The curve that represents samples with angles of 45 starts as the one which has bigger shear stress, as in the case II. The angle of the fibers rises during the test because of shear, becoming closer to the case III and, as consequence, reducing the resistance. Specimens with nylon angled 90° has very low resistance in its first points, as in case III. However, as fibers angles are decreased by shear process, resistance is getting bigger, especially when it gets near 45°, that is the case II. The curve of nylon angled 45° cross the one angled 90° in a distortion of about 50%.

4. CONCLUSION

In this work, a synthetic material was used as an alternative for better understanding of soft tissues. Experimental tests were performed under simple shear deformation. Full-field displacements were measured using Digital Image Correlation method. Based on these data, values of amount of shear were estimated and plotted against applied stresses for fiber of nylon with angles of 0, 45 and 90 degrees.

It was shown that, for samples with nylon angle of 0 degree, there is no difference in silicone resistance. It is the lowest one. The specimen with fibers angle 45 degrees presents the biggest shear stress until a distortion of about 50%. After that distortion, sample with nylon angle 90 degree become the most resistant. The main contribution of this work is to present a new way to study soft tissue, overcoming some difficulties for performing tests in biological materials.

5. ACKNOWLEDGEMENTS

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