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SILICONE REINFORCED BY NYLON FIBERS UNDER SIMPLE SHEAR FOR EMULATING BIOLOGICAL TISSUES

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Abstract. *The development of studies on mechanical behavior of biological tissues are motivated by prosthesis and artificial tissues improvements. It also has a great importance for understanding damage in tissues which may cause diseases. Nevertheless, biological materials bring difficulties such as ethical regulations, scarce availability and demand bureaucracy and specific care for their testing and maintenance. It would thus be of interest to mimic mechanical behavior of biological tissues by using synthetic materials. Several models based on composites with fibers embedded in an isotropic matrix have been proposed to mimic fibrous soft tissues. However, previous researches in the field of hyperelastic anisotropic materials have concentrated on theoretical models, which indicates that there is little experimental information about these materials. The aim of this work is to study the mechanical behavior of a transversely isotropic hyperelastic material under simple shear. Silicone specimens, reinforced with parallel nylon fibers, were tested under simple shear. Digital Image Correlation (DIC) was used to determine the amount of shear. This paper also presents some strain-energy density models and analyzes how well the models fit the experimental data. The experimental results indicate that the stiffness of the composite is influenced by the diameter of the fibers, the spacing between them and the effective distance between applied loads.*

Keywords: *artificial tissues, hyperelastic anisotropic, strain-energy density models, simple shear*

1. INTRODUCTION

Recently, there has been growing interest in the mechanical behavior of biological tissues. This knowledge has great importance for understanding tissue injury, which may cause diseases. For example, changes in the shear properties of plantar soft tissue may contribute to ulceration in diabetic patients (Pai and Ledoux, 2011). The development of study about the mechanical behavior of biological tissues has led to the hope for prosthesis and artificial tissues improvements. There have been several investigations into mechanical behavior of fibrous soft tissues (Destrade, 2015; Peña, 2011). However, working with real samples of soft tissue for experimental studies brings a number of difficulties such as ethical regulations, bureaucracy and scarce availability. Soft tissue specimens are also troublesome to fix and constrain, leading to complex experimental designs (Leibinger *et al.*, 2015). It would thus be of interest to emulate mechanical behavior of biological tissues by using synthetic materials.

Many biological soft tissues present fiber-reinforcement, which is the case of myocardial tissue (Humphrey, 2002), the annulus fibrosus (Hollingsworth and Wagner, 2011), porcine brain (Destrade et al, 2015) and rat-tail tendon and porcine flexor tendon (Kondratko-Mittnacht et al, 2015), for example. Several models based on composites with fibers embedded in an isotropic matrix have been proposed to mimic fibrous soft tissues (Ehret and Itskov, 2009; Horgan and Murphy, 2011). The study of hyperelastic anisotropic materials has become an important aspect for the characterization of mechanical behavior of fibrous soft tissues. Spencer (1982) proposed a formulation for anisotropic solids. This formulation has been widely used by researchers to develop theoretical models based on the strain-energy density (Merodio and Ogden, 2005; Lopez-Pamies, 2010; Holzapfel and Ogden, 2015).

Previous researches in the field of anisotropic hyperelastic materials have concentrated on theoretical models, which indicates that there is little experimental information about these materials. Bugmann *et al.* (1998) and Austin *et al.* (2015) used silicone coated nylon dressing in burned patients. Based on these studies, a composite of silicone and parallel fibers of nylon can be used to mimic mechanical behavior of fibrous soft tissues. Furthermore, studies regarding simple shear in this field are relevant. For instance, modeling the shear response of the annulus fibrosus may be crucial to understand damage in the biological tissue (Hollingsworth and Wagner, 2011). Quantification of the effects of disease or treatment on shear properties can provide an insight into the relation between different tissue components (Gardiner and Weiss, 2001). The aim of this work is to study the mechanical behavior of a transversely isotropic hyperelastic material under simple shear. Silicone adhesive specimens with parallel fibers of nylon were manufactured and tested. This paper presents some strain-energy density models and analyzes how precisely the models fit the experimental data.

2. MATERIAL AND METHODS

The composite used in this investigation was composed of a polymeric matrix containing a single family of parallel fibers. The adhesive Pesilox from Adespec was used as the isotropic matrix and the fibers were polyamide 6 (nylon 6) monofilament fishing lines with diameters (d) of 0.25 mm and 0.45 mm. The test specimens were manufactured as described by Moreira and Nunes (2016) and its dimensions were 70 mm x 55 mm x 3.4 mm. The fibers were parallel to the shorter size of the specimen (55 mm), maintaining equal spacing (s), as shown in Fig. (1). The test samples are summarized in Tab. (1), where *e* denotes the effective distance between applied loads (see Fig. (2)).

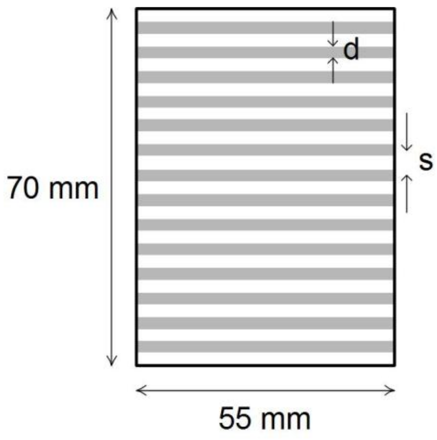

Figure 1. Schematic design of test specimens.

Table 1. Test specimens.

Samples identification	A	B	C	D	E
Fiber diameter, d (mm)	0.25	0.25	0.25	0.45	0.25
Spacing, s (mm)	2	4	6	2	2
Effective distance, e (mm)	3.5	3.5	3.5	3.5	6.5

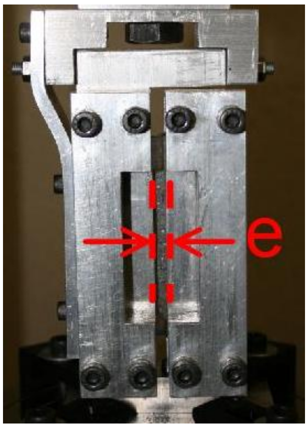

Figure 2. Effective distance between applied loads.

Figure (3) shows the experimental arrangement. It was composed of a tensile testing machine, a 100 kgf load cell and a special apparatus (see Fig. (2)) that was used in order to ensure that the samples would deform in simple shear.

Images of the specimen's surface were acquired using a high resolution camera before and during loading. Digital image correlation (DIC) was used to determine the displacement fields on the region of interest. A light source was used to homogenize the sample surface in a way that no external light would interfere in correlation.

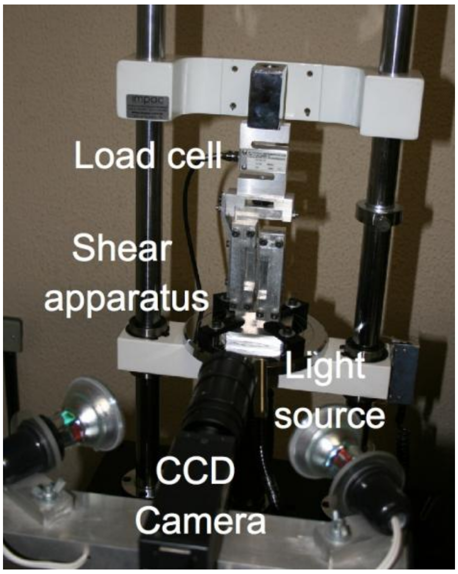

Figure 3. Simple shear apparatus.

3. THEORETICAL

The constitutive equation for incompressible transversely isotropic hyperelastic materials is given as

$$\boldsymbol{T} = -p\boldsymbol{I} + 2\frac{\partial W}{\partial I_1}\boldsymbol{B} - 2\frac{\partial W}{\partial I_2}\boldsymbol{B}^{-1} + 2I_4\frac{\partial W}{\partial I_4}\boldsymbol{a}\otimes\boldsymbol{a} + 2\frac{\partial W}{\partial I_5}(\boldsymbol{a}\otimes\boldsymbol{B}\boldsymbol{a} + \boldsymbol{B}\boldsymbol{a}\otimes\boldsymbol{a}), \quad (1)$$

where p is the arbitrary hydrostatic pressure arising owing to the incompressibility constraint, W is the strain-energy density function, $\boldsymbol{a}$ is the unit vector in the current configuration, I_i $(i = 1, 2, 4\ e\ 5)$ are the invariants. The two principal invariants for simple shear are defined as

$$I_1 = tr\boldsymbol{B} = 3 + k^2 \quad (2)$$

$$I_2 = \frac{1}{2}[(tr\boldsymbol{B})^2 - tr\boldsymbol{B}^2] = 3 + k^2, \quad (3)$$

where k is the amount of shear.

The usual anisotropic invariants are defined as

$$I_4 = \boldsymbol{a}.\boldsymbol{a} = k^2 + 1 \quad (4)$$

and

$$I_5 = \boldsymbol{F}^T\boldsymbol{a}.\boldsymbol{F}^T\boldsymbol{a} = 1 + 3k^2 + k^4. \quad (5)$$

For simple shear deformation, the left Cauchy-Green strain tensor ($\boldsymbol{B}$) is given by

$$\boldsymbol{B} = \boldsymbol{F}\boldsymbol{F}^T = \begin{bmatrix} 1+k^2 & k & 0 \\ k & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (6)$$

where **F** is the deformation gradient tensor.

The strain energy density may be written as an isotropic and an anisotropic portions.

$$W = W^{isotropic} + W^{anisotropic} \quad (7)$$

There are several strain-energy density functions that are used to describe the mechanical behavior of hyperelastic materials. In some of them, the authors separate the anisotropic portion as shown in Eq. (7). Then, this paper uses Lopez-Pamies (2010) model for the isotropic portion because it fits well the isotropic experimental data.

$$W^{isotropic} = \frac{3^{1-\alpha}}{2\alpha}\mu({I_1}^{\alpha} - 3^{\alpha}) \quad (8)$$

The initial shear modulus of isotropic matrix is μ and α is a material constant ($\alpha > 0.5$).

For comparison purpose, some models are described.

- Triantafyllidis and Abeyaratne (1983):

$$W^{anisotropic} = C_1(I_4 - 1)^2 \quad (9)$$

C_1 is a positive material parameter that is associated with the degree of anisotropy.

- Weiss *et al.* (1996):

$$W^{anisotropic} = C_2[exp(I_4 - 1)^2 - (I_4 - 1)^2 - 1] \quad (10)$$

C_2 is a material parameter.

- Bonet and Burton (1998):

$$W^{anisotropic} = [C_3 + C_4(I_1 - 3) + C_5(I_4 - 1)](I_4 - 1) - \frac{C_3}{2}(I_5 - 1) \quad (11)$$

C_3, C_4 and C_5 are material constants.

- Holzapfel *et al.* (2000):

$$W^{anisotropic} = \frac{C_6}{2C_7}\{exp[C_7(I_4 - 1)^2] - 1\} \quad (12)$$

C_6 e C_7 are positive material parameters.

- Holzapfel et al (2002):

$$W^{anisotropic} = C_8(I_4 - 1)\exp\,(C_9(I_4 - 1)^2) \quad (13)$$

C_8 e C_9 are positive material parameters.

- Merodio and Ogden (2005):

$$W^{anisotropic} = \frac{1}{2}\mu C_{10}(I_5 - 1)^2 \quad (14)$$

μ is the shear modulus of isotropic matrix andC_{10} is a material parameter that is associated with fibers reinforcement.

- Horgan and Saccomandi (2005):

$$W^{anisotropic} = -\frac{\mu_I}{C_{12}}C_{11}ln\left(\frac{(I_4-1)^{C_{12}}}{C_{11}}\right) \quad (15)$$

μ_I is the shear modulus of the composite that serves as a measure of the degree of anisotropy, C_{11} is a dimensionless parameter that is associated with the degree of rigidity of the fiber reinforcement (for elastomers C_{11} is near 100) and C_{12} may be used to reflect the fact that, as load is applied and gradually increased, more fibers become straightened and begin to carry load.

- Holzapfel *et al.* (2005):

$$W = C_{13}(I_1 - 3) + \frac{C_{14}}{C_{15}}(\exp\,(C_{15}[(1 - C_{16})(I_1 - 3)^2 + C_{16}(I_4 - 1)^2]) - 1) \quad (16)$$

C_{13}, C_{14}, C_{15} and C_{16} are positive material parameters and C_{16} is always smaller than 1.

- Balzani *et al.* (2006):

$$W = C_{17}(I_1 I_4 - I_5 - 2)^{C_{18}} \quad (17)$$

The material parameters are $C_{17} \geq 0$ and $C_{18} > 1$.

- Holzapfel and Ogden (2015):

$$W^{anisotropic} = \frac{1}{2} C_{19} C_{20} k^2 \tag{18}$$

C_{19} is a material parameter and C_{20} is a positive constant that shows the dispersion of the fibers.

4. RESULTS AND DISCUSSION

The shear stress as a function of the amount of shear for all the samples is shown in Fig. (4). The experimental results indicate that, as expected, the stiffness of the composite increases with the diameter of the nylon fiber when spacing is maintained constant. On the other hand, the growth of spacing between the fibers reduces its stiffness. This reduction is related to the decreased number of fibers in the sample. It can be seen that the effective distance between applied loads modify the resistance of the material. Although, for infinitesimal deformation, there is no modification. It is important to observe that variations in specimens area influences the results.

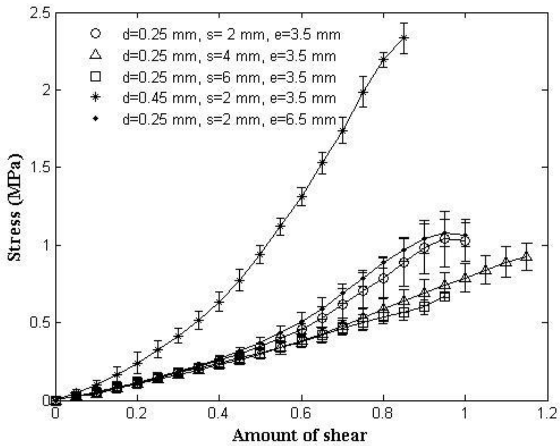

Figure 4. The shear stress versus the amount of shear.

In the sample group presented, special focus was given to those with different diameters. Using the described models (Section 2), the experimental data from samples A and D were curve-fitted and all parameters were estimated. Table (2) shows these models ranked in terms of the R-squared of the fit and error of the parameters. It can be also seen from Tab. (2) that Holzapfel et al (2002) model is the best between the analyzed ones and it is plotted in Fig. (5). The second model is from Holzapfel and Ogden (2015). Its parameter C_{20} increases with diameter of the fibers, demonstrating its relation to the reinforcement. The parameters of Triantafyllidis and Abeyaratne (1983) model also increases with the diameter of the fibers. It is consistent with the parameter definition that is related to the degree of anisotropy of the material. Similarly, Merodio and Ogden (2005) model (see Fig. (6)) presents a parameter that increases with the fibers diameters, demonstrating its significance for the measurement of fibers reinforcement. In addition to that, it can be seen that there are models with few citations that are as good as the ones with lots of citations. Besides that, it is shown that the last three models in the raking have larger errors than the values of the parameters, resulting in loss of its significance.

Table 2. Ranking of strain energy density function models.

Ranking	Model	Diameter (mm)	Parameters	Error	R-squared	Citations
1	Holzapfel et al (2002)	0.25	C_8=0.1749	0.0416	0.9905	376
			C_9=0.2933	0.1971		
		0.45	C_8=0.6179	0.1092	0.9894	
			C_9=0.1259	0.17647		
2	Holzapfel and Ogden (2015)	0.25	C_{20}=1.213	0.133	0,9955	34
			C_{19}=0.01658	0.015054		

		0.45	C_{20}=5.627	1.936	0,9699	
			C_{19}=0.04436	0.04706		
3	Balzani et al (2006)	0.25	C_{17}=0.1783	0.0158	0.9809	234
			C_{18}=1	**		
		0.45	C_{17}=0.4305	0.0505	0.968	
			C_{18}=1	**		
4	Triantafyllidis and Abeyaratne (1983)	0,25	C_1=0.3866	0.126	0.9655	53
		0,45	C_1=1.413	0.0527	0.8931	
5	Holzapfel et al (2000)	0.25	C_6=0.3936	0.0671	0.9665	2192
			C_7=0	**		
		0.45	C_6=1.228	0.356	0.8644	
			C_7=0	**		
6	Weiss et al (1996)	0.25	C_2=-1.902	0.495	0.9248	675
		0.45	C_2=-5.599	2.571	0.6941	
7	Merodio and Ogden (2005)	0,25	C_{10}=0.6142	0.4704	0,8451	175
		0,45	C_{10}=2.235	1.801	0,5982	
8	Holzapfel et al (2005)	0.25	C_{13}=0.302	0.1477	0.9963	575
			C_{14}=0.1421	0.5972		
			C_{15}=0.0006824	*		
			C_{16}=0.8012	*		
		0.45	C_{13}=0.7495	0.5209	0.9912	
			C_{14}=0.3168	2.3625		
			C_{15}=0.03154	*		
			C_{16}=0.7423	*		
9	Bonet and Burton (1997)	0.25	C_3=-0.2534	0.1038	0.9959	113
			C_4=-426.4	*		
			C_5=213.3	*		
		0.45	C_3=-1.159	0.412	0.9906	
			C_4=-62.57	*		
			C_5=31.58	*		
10	Horgan and Saccomandi (2005)	0.25	μ_I=0.3915	0.2184	0.9659	94
			C_{11}=100	*		
			C_{12}=2	*		
		0.45	μ_I=2.824	**	0.893	
			C_{11}=100	*		
			C_{12}=2	*		

* Error values larger than 10 times parameter values.

** Parameter values fixed at bound.

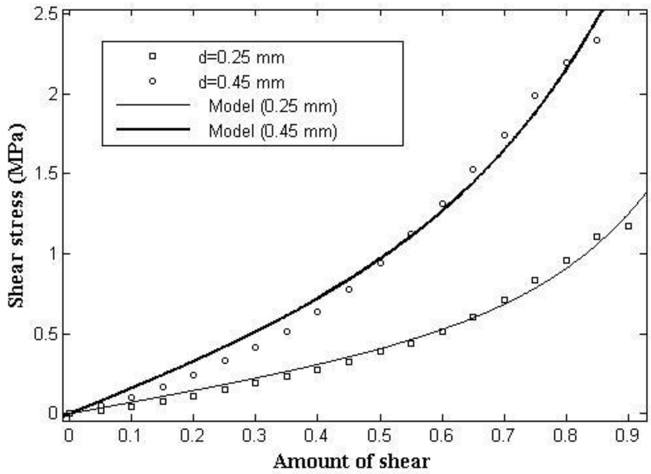

Figure 5. Plot of the adjustment of Holzapfel et al (2002) model to the experimental data.

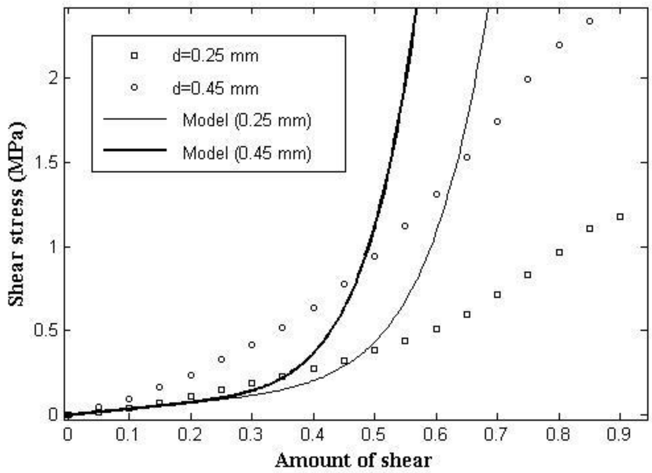

Figure 6. Plot of the adjustment of Merodio and Ogden (2005) model to the experimental data.

5. CONCLUSIONS

In this work, the mechanical behavior of fiber-reinforced rubberlike materials was investigated. The experimental results demonstrate that the resistance of the composite is influenced by the diameter of the fibers and by the spacing between them. As expected, the stiffness increases with the diameter of the nylon fibers and decreases with the spacing between them. Some strain-energy density models were adjusted to these data and the values of their parameters were determined. Holzapfel et al (2002) was the best model of the analyzed ones in terms of the R-squared of the fit and error of the parameters. The results contribute to the improvement of the models that have already been proposed and to the development of a more accurate one. As a closing remark, the obtained results can be useful in understanding the mechanical behavior of fiber-reinforce rubberlike solids and fibrous soft tissues.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Austin, R. E., Merchant, N., Shahrokhi, S. and Jescheke, M. G., 2015. A comparison of biobrane and cadaveric allograft for temporizing the acute burn wound: Cost and procedure time. Burns. 41, 749-753.

Balzani, D., Neff, P., Schröder, J. and Holzapfel, G. A., 2006. A polyconvex framework for soft biological tissues. Adjustment to experimental data. International Journal of Solids and Structures. 43, 6052-6070.

Bonet, J. and Burton, A. J., 1998. A simple orthotropic, transversely isotropic hyperelastic constitutive equation for large strain computations. Computer Methods in Applied Mechanics and Engineering. 162, 151-164.

Bugmann, Ph., Taylor, S., Gyger, D., Lironi, A., Genin, B., Vunda, A., La Scala, G., Birraux, J. and Le Coultre, C., 1998. A silicone coated nylon dressing reduced healing time in burned paediatric patients in comparison with standard sulfadiazine treatment: a prospective randomized trial. Burns. 24, 609-612.

Destrade, M., 2015. Incremental equations for soft fibrous materials. Non linear mechanics of soft fibrous materials. 233-266.

Destrade, M., Gilchrist, M. D., Murphy, J. G., Rashid, B. and Saccomandi, G., 2015. Extreme softness of brain matter in simple shear. International journal of non-linear mechanics. 75, 54-58.

Ehret, A. E. and Itskov, M., 2009. Modeling of anisotropic softening phenomena: Application to soft biological tissues. International journal of plasticity. 25, 901-919.

Gardiner, J. C. and Weiss, J. A., 2001. Simple shear testing of parallel-fiber planar soft tissues. Journal of Biomechanical Engineering. 123, 170-175.

Hollingsworth, N. T. and Wagner, D. R., 2011. Modeling shear behavior of the annulus fibrosus. Journal of mechanical behavior of biomedical materials. 4, 1103-1114.

Holzapfel, G. A., Gasser, T. C. and Ogden, R. W., 2000. A new constitutive framework for arterial wall mechanics and a comparative study of material models. Journal of Elasticity. 61, 1-48.

Holzapfel, G. A., Gasser, T. C. and Stadler, M., 2002. A structural model for the viscoelastic behavior of arterial walls: Continuum formulation and finite element analysis. Europe Journal of Mechanics A/Solids. 21, 441-463.

Holzapfel, G. A. and Ogden, R. W., 2015. On the tension-compression switch in soft fibrous solids. European journal of mechanics A/Solids. 49, 561-569.

Holzapfel, G. A., Sommer, G., Gasser, T. C. and Regitnig, P., 2005. Determination of layer-specific mechanical properties of human coronary arteries with nonatherosclerotic intimal thickening and relate constitutive modeling. American Physionlogical Society. 289, H2048-H2058.

Horgan, C. O. and Murphy, J. G., 2011. Simple shearing of soft biological tissues. Proceedings of the royal society A. 467, 760-777.

Horgan, C. O. and Saccomandi, G., 2005. A new constitutive theory for fiber reinforced incompressible nonlinearly elastic solids. Journal of the Mechanics and Physics of Solids. 53, 1985-2015.

Humphrey, J. D., 2002. Cardiovascular Solid Mechanics. Springer, New York.

Kondratko-Mittnacht, J., Duenwald-Kuehl, S., Lakes, R. and Vanderby Jr., R., 2015. Shear load transfer in high and low stress tendons. Journal of mechanical behavior of biomedical materials. 45, 109-120.

Leibinger, A., Forte. A. E., Tan, Z., Oldfield, M. J., Beyrau, F., Dini, D. and Baena, F. R., 2015. Soft tissue phantoms for realistic needle insertion: a comparative study. Annals of Biomedical Engineering. 0, 1-11.

Lopez-Pamies, O., 2010. A new I_1-based hyperelastic model for rubber elastic materials. Comptes rendus mecanique. 338, 3-11.

Merodio, J. and Ogden, R. W., 2005. Mechanical response of fiber-reinforced incompressible non-linearly elastic solids. International journal of non-linear mechanics. 40, 213-227.

Moreira, C. S. and Nunes, L. C. S., 2016. Simple shearing of rubberlike materials filled with parallel fibers at large strain. Journal of composite materials. 0, 1-9.

Pai, S. and Ledoux, W. R., 2011. The shear mechanical properties of diabetic and non-diabetic plantar soft tissue. Journal of biomechanics. 45, 364-370.

Peña, E., 2011. Prediction of the softening and damage effects with permanent set in fibrous biological materials. Journal of the mechanics and physics of solids. 59, 1808-1822.

Spencer, A. J. M., 1982. The formulation of constitutive equation for anisotropic solids. Comportement mecanique des solides anisotropes. 295, 3-26.

Triantafillidis, N. and Abeyaratne, R., 1983. Instabilities of a finitely deformed fiber-reinforced elastic material. Journal of Applied Mechanics. 50, 149-156.

Weiss, J. A., Maker, B. N. and Govindjee, S., 1996. Finite element implementation of incompressible, transversely, isotropic hyperelasticity. Computer Methods in Applied Mechanics and Engineering. 135, 107-128.

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