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EXPERIMENTAL CHARACTERIZATION AND FEM SIMULATION ON UNIAXIAL TENSILE AND COMPRESSION OF DIELECTRIC ELASTOMERS

BY

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Abstract. Dielectric elastomers (DEs) are being developed as artificial muscles for diverse applications, including soft machines, adaptive optics, haptic surfaces, micro air vehicles, strain sensors, fluidic micro-pumps and energy harvesting (Carpi *et al.*, 2008; Carpi *et al.*, 2010; Brochu & Pei, 2010; Kornbluh *et al.*, 2012). They are superior to piezoelectric, shape memory alloys and electrostrictive materials in terms of large voltage-induced deformation, high energy density, fast response, quiet operation, light weight, and low cost. To increase the electromechanical performance, the elastomers are pre-stretched with an in-plane area stretch up to 36. These large deformations may lead to rupture and thus impair the mechanical integrity of the devices. Further development of dielectric elastomer transducers demands accurate and efficient computational methods (Wissler, 2007; Lochmatter, 2007). The transducers involve nonlinear electromechanical coupling, and are often hybrid structures of soft membranes in tension and hard materials in compression.

This work reports about a systematic investigation of mechanical characteristics of elastomer films used as dielectric layer in actuation systems. Uniaxial tensile and compression tests were performed in order to investigate the elastic properties of some poly(dimethylsiloxane)-based elastomers. The results

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obtained in uniaxial tension and compression stress states were compared in terms of nonlinear elastic behavior and found to lead in similar values of elastic modulus. Various hyperelastic constitutive models were used to fit the experimental stress-strain data. Finite element method (FEM) was used to simulate the large strain deformation in tension and compression. The simulation results were compared with experimental data in terms of true stress-strain and showed good correspondence, especially for tensile tests. Some discrepancies were observed between experimental and simulations in the case of compression tests. However, to determine the compressive modulus it is necessary to carry out experimental test according to the test standards to verify the characteristics of elastomers.

Key words: dielectric elastomers; mechanical tests; hyperelastic behaviour; finite element method (FEM).

1. Introduction

Polymers have many advantages such as low manufacturing cost, lightweight, compliant nature, fracture tolerant, can be made in different shape or size, easy handling etc. They are used in various applications including toys, footwear, electronics, coatings, paints, adhesives, tires, packing and encapsulating materials etc.

Mechanical testing of soft materials, such as polymers, elastomers and bio-materials, presents considerable challenges that do not arise when characterizing metals and ceramics. Soft elastomers, mostly polyurethanes, silicones and acrylics, are interesting candidates as dielectric materials in electroactive polymer (EAP) actuator technology (Carpi *et al*., 2008).

Dielectric elastomers (DEs) consist of a thin polymer film sandwich between two compliant electrodes. When a voltage is applied across the electrodes, the electrostatic forces from the opposite electric charges create a pressure, called Maxwell stress, which squeeze the film in thickness direction and expand it in area. Thus, the dielectric elastomers enable electromechanical transduction being used as actuator and sensor: the voltage can deform the elastomer, and the deformation changes the capacitance of the elastomer film (Carpi *et al*., 2008; Carpi *et al*., 2010; Brochu & Pei, 2010; Kornbluh *et al.*, 2012).

The specific requirements for DE materials depend on the actuator type and its foreseen applications. Elastomer materials for sound generation, for instance, require primarily materials with fast response speed at high frequencies without large strains (Pelrine *et al*., 2001; Heydt *et al.*, 2006). In contrast, for pumps, materials with a relatively low response speed may also be sufficient, but large strains are obligatory (Pimpin *et al*., 2004; Niklaus *et al*., 2010; Loverich *et al*., 2006; Piyasena *et al*., 2009). Furthermore, for both cases high efficiency is required, which means that the actuator should have low mechanical and electrical losses (Kornbluh *et al*., 2000).

Elastomers are hyperelastic materials with a nonlinear stress-strain behaviour. Measuring the mechanical properties of thin elastomer films, and understanding the effects of scale, microstructure, and process parameters on their mechanical behaviour, is essential for designing and modeling of dielectric elastomer actuators and sensors with high performance and sufficient reliability (Michel *et al*., 2010; Valenta & Bojtos, 2008; Cianchetti *et al.*, 2009).

In this paper a comparison is made in terms of mechanical behaviour of some elastomer films subjected to uniaxial tension and compression tests. Stress-strain curves were recorded and elastic modulus was calculated for both mechanical tests. Finite element method (FEM) was used in order to simulate the large deformations and validate with experimental data.

2. Experimental Part

Materials used in this work were provided by "Petru Poni" Institute of Macromolecular Chemistry, Iaşi, România. PDMS/SiO_2/TiO_2 composites with different thickness were synthesized using solvent free sol-gel technique (Alexandru *et al*., 2010).

Uniaxial tensile tests were performed on dumbbell-shaped specimens (DIN 53504-S3A:1994) using a TIRA 2161 apparatus, at room temperature. All specimens were tested according to ASTM D412 and ISO 37 at extension rates of 50 mm/min until mechanically broken (Cârlescu *et al*., 2012). Because rubber-like materials such as elastomers shows viscous properties which appear as creep or stress relaxation, uniaxial stress relaxation tests were performed at an extension rate of 20 mm/min for strains up to 100% (Cârlescu *et al*., 2014a).

Uniaxial compression tests were realized on circular specimens with 7 mm diameter at loads up to 15 N and velocity of 0.6 mm/min in room conditions. The compressive forces and displacements were recorded using a universal mechanical tester UMT2-CETR. The specimens were horizontally placed and pressed with a circular indenter from copper. The surfaces were lubricated with oil in order to reduce the friction forces that can influence the measurements (Cârlescu *et al*., 2014a).

3. Results

3.1. Experimental Results

Stress-strain data from uniaxial tension and compression tests showed a non-linear elastic response of specimens in terms of large strains at small applied stresses. The elastic tangent modulus was calculated from the slope of stress-strain curves at small strains (10%) where Hooke's law is still valid (Cârlescu *et al*., 2012). Fig. 1 shows the stress-strain curves recorded in both tension and compression tests.

The values of tensile modulus of about 1 MPa was found to be in agreement with those reported in literature by other researchers for PDMS (Michel *et al.*, 2010; Scott *et al.*, 2004; Cazacu *et al.*, 2009).

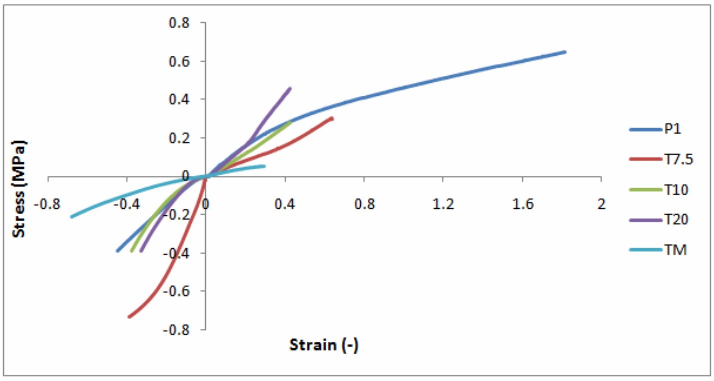


Fig. 1 − Stress-strain curves of specimens.

The compressive modulus was found to be quite similar with tensile modulus and in agreement with those reported by Li *et al.* (2011) using the universal mechanical tester UMT-CETR. Table 1 listed the tensile and compressive modulus calculated for all specimens tested.

Table 1
Elastic Modulus for Tension and Compression Tests

Specimen	Tensile modulus [MPa]	Compressive modulus [MPa]
P1	1.4	0.918
T7.5	0.484	0.257
T10	0.624	0.51
T20	0.817	0.732
TM	0.242	0.154

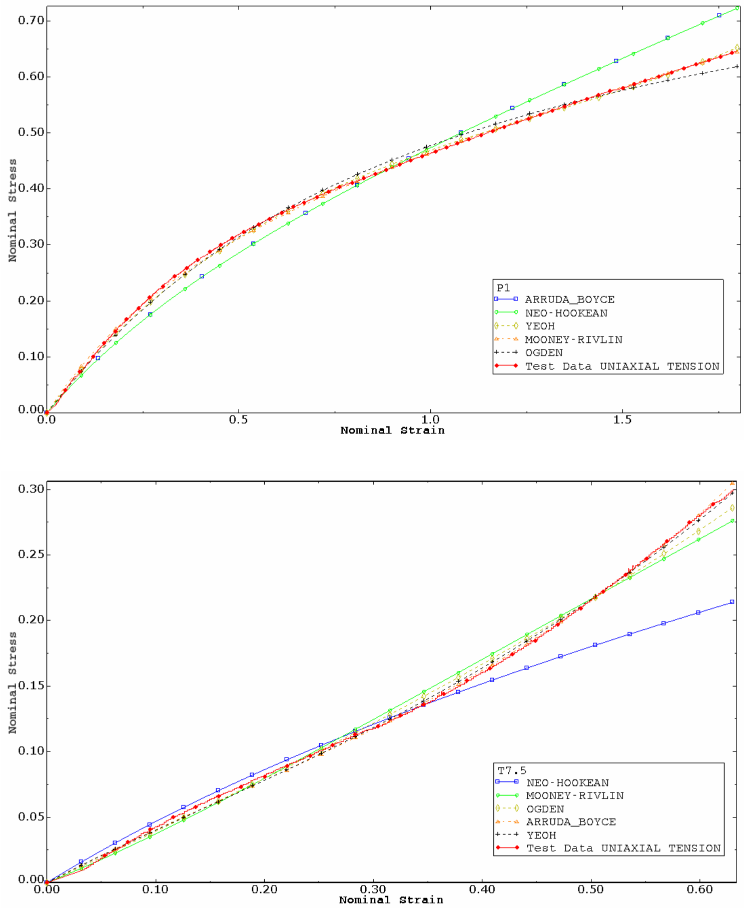
3.2. Model Fitting

Experimental data obtained from tests are useful to calibrate constitutive models in order to accurately reproduce mechanical behaviour of the material in FEM simulations (Cârlescu *et al.*, 2014b).

Rubber-like materials exhibit very large strains, with strongly non-linear stress-strain behaviour. Furthermore, their stress–strain relationship is suitable to be derived from a strain-energy density function; for this reason they are usually referred to as hyperelastic materials. A number of constitutive models are available in literature that has been proposed based on a phenomenological approach or on the intricacies of the micromechanics (Hoss, 2009; Steinmann *et al.*, 2012; Khajehsaeid *et al.*, 2013; Oscar, 2009).

Stress-strain curves data were fitted with various hyperelastic models such as Neo-Hookean, Arruda-Boyce, Mooney-Rivlin, Yeoh and Ogden that are implemented in FEM commercial codes like ABAQUS. Fig. 2 shows the fitting of experimental data with different hyperelastic models. From the fitting procedure the material coefficients were calculated (Cârlescu *et al*., 2014b) that are listed in Table 2.

From Fig. 2 it can be observed that experimental data fits very well with hyperelastic models, even at large strains. Mooney-Rivlin, Ogden and Yeoh perform very well when calibrated with uniaxial tension data while Arruda-Boyce and Neo-Hookean is acceptable. However, the fitting procedure in ABAQUS gives us also the stability information of hyperelastic models for each specimen mechanical behaviour.



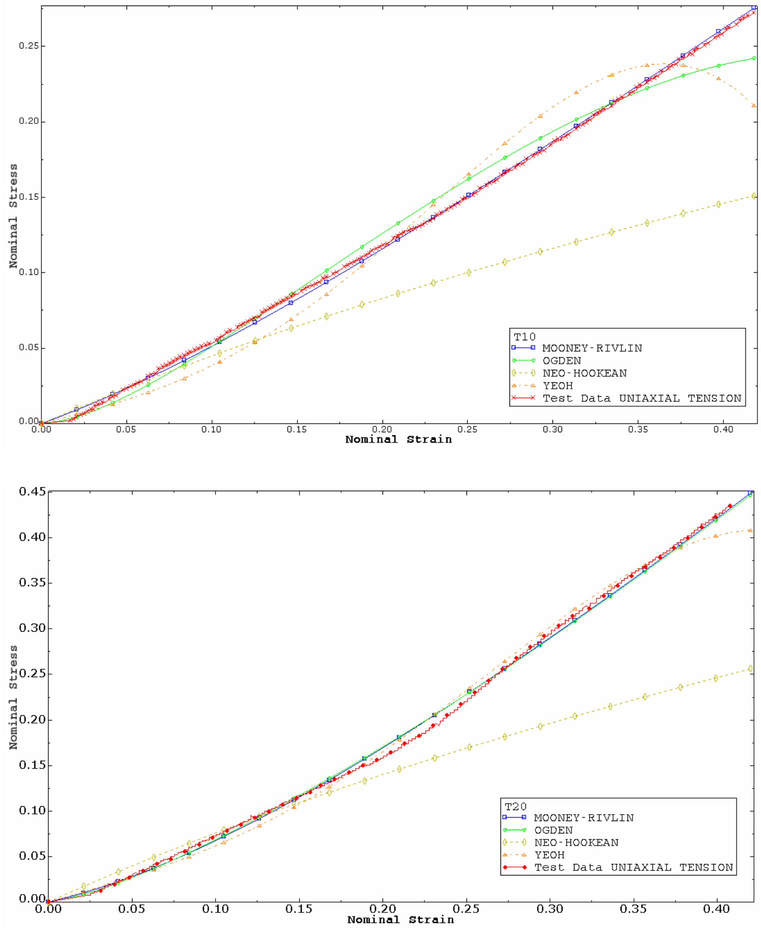


Fig. 2 − Fitting experimental stress-strain data with different hyperelastic models in uniaxial tension.

Table 2

Hyperelastic Material Coefficients for PDMS Specimens Under Uniaxial Tension

Probe	Hyperelastic model	Material coefficients [MPa]
P1	Mooney-Rivlin	C_{10}=8.979769991E-02 C_{01}=8.642347373E-02
	Ogden (order 2)	μ_1=0.406090611 α_1=1.47380052 μ_2=-0.117635868 α_2=-4.46220887
	Neo-Hookean	C_{10}=0.135269270

Table 2
Continuation

Probe	Hyperelastic model	Material coefficients [MPa]
P1	Yeoh (order 3)	C_{10}=0.154688363 C_{20}=-6.42342332E-03 C_{30}=4.190435286E-04
	Arruda-Boyce	μ=0.270538534 λ_m=5191.09574
T7.5	Mooney-Rivlin	C_{10}=0.197002599 C_{01}=-0.141885266
	Ogden (order 2)	μ_1=0.157393915 α_1=4.10432343 μ_2=-2.965492791E-02 α_2=-10.6701816
	Neo-Hookean	C_{10}=8.528426198E-02
	Yeoh (order 3)	C_{10}=7.164376205E-02 C_{20}=2.597573388E-02 C_{30}=4.022738977E-04
	Arruda-Boyce	μ=4.548108790E-02 λ_m=1.01591808
T10	Mooney-Rivlin	C_{10}=0.342777658 C_{01}=-0.273841338
	Ogden (order 2)	μ_1=0.494401326 α_1=6.14124479 μ_2=-0.467966817 α_2=-16.1902630
	Neo-Hookean	C_{10}=8.205763276E-02
	Yeoh (order 3)	C_{10}=5.013334856E-02 C_{20}=0.378703839 C_{30}=-0.478465458
T20	Mooney-Rivlin	C_{10}=0.665942686 C_{01}=-0.599016868
	Ogden (order 2)	μ_1=0.547068431 α_1=7.62771583 μ_2=-0.504562927 α_2=-18.6998560
	Neo-Hookean	C_{10}=0.114442766
	Yeoh (order 3)	C_{10}=6.806060418E-02 C_{20}=0.543818666 C_{30}=-0.595844295

3.3. Numerical Simulation

Finite element method (FEM) is suitable to study the large deformations of rubber-like materials using a non-linear constitutive law and an iterative approach (Hoss, 2009; Steinmann *et al.*, 2012; Khajehsaeid *et al.*, 2013; Oscar, 2009; Sasso *et al.*, 2008).

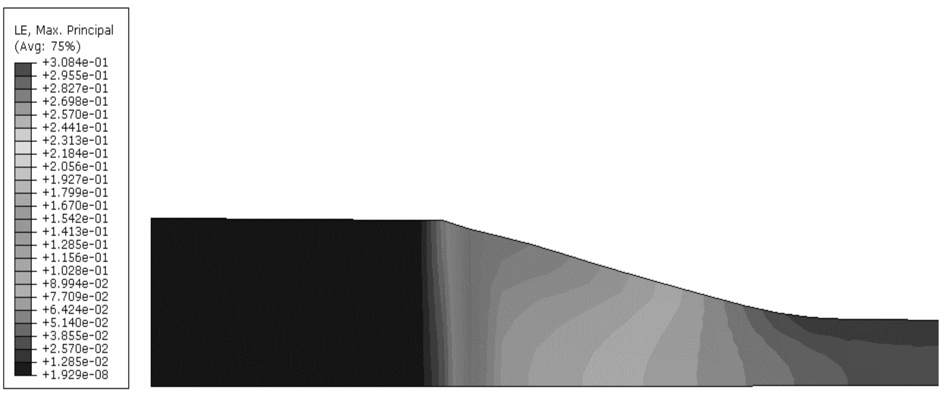
In this section, two simulations are described. They were carried out in ABAQUS/Standard to reproduce the uniaxial stretching test on dumbbell specimen and the compression test on circular specimen. In all of them the material is characterized with stable hyperelastic models that were calibrated by experimental data from uniaxial tension test.

In the dumbbell stretching simulation, standard 8-node linear brick hybrid elements (C3D8RH) with reduced integration are used to model the rubber specimen and double planar symmetry is applied in order to reduce the number of elements to process. The top widest part was hold fixed and a fixed displacement was applied to the nodes belonging to the bottom widest part of the specimen, the areas that in real test are fastened between the clamping of the traction machine.

The stresses and strains along the axial direction at nodes in the central section were compared with experimental data (Fig. 3). It is important to mention that ABAQUS gives the true stress-strain (σ_{true}-ε_{true}) so for comparison the experimental data (σ_{exp}-ε_{exp}) were converted using the eq. (1):

$$\varepsilon_{true} = \ln(1+\varepsilon_{\exp})$$
$$\sigma_{true} = \ln(1+\sigma_{\exp}) \tag{1}$$

Fig. 3*a* shows the contours of logarithmic strains on uniaxial tension.



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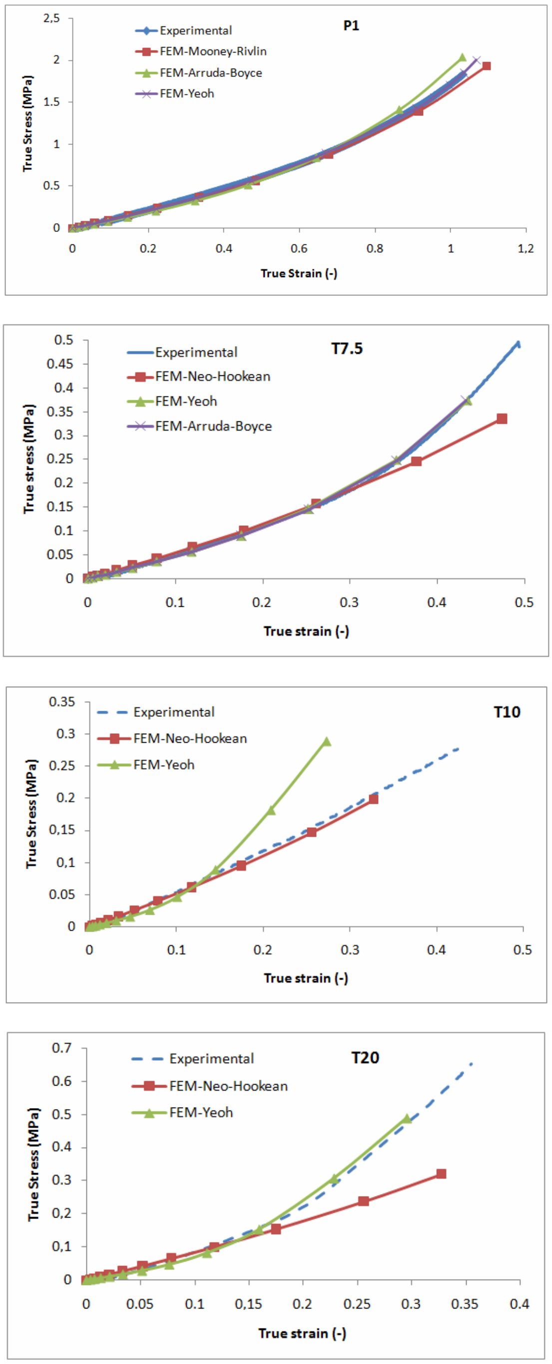
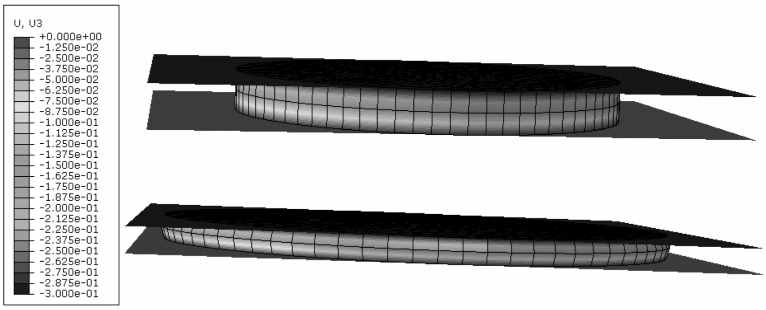


b

Fig. 3 − FEM simulation of uniaxial tension on dumbbell specimen (*a*); A comparison between numerical and experimental data (*b*).

The compression test on circular specimen was simulated using also standard 8-node linear brick hybrid elements (C3D8RH) with reduced integration. Fig. 4*a* depicted the FEM model of specimen placed between two rigid plates. The bottom plate is fixed while a fixed displacement is applied to the upper plate. Interaction properties between the surfaces of specimen and the two plates were set as “hard contact” for normal behaviour and a friction coefficient of 0.1 was chose for tangential behaviour. The reaction force at the bottom plate and the displacement of upper plate were compared with experimental data (Fig. 4*b*).



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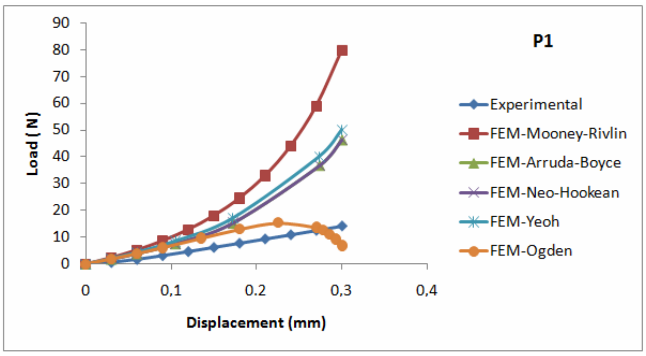

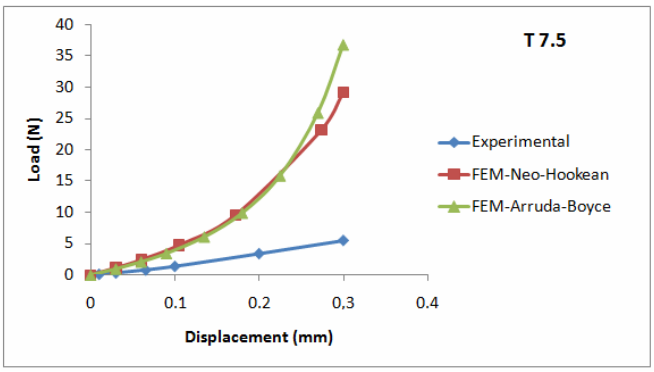

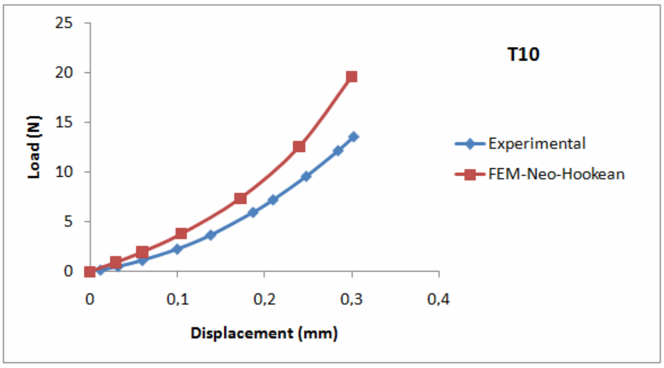

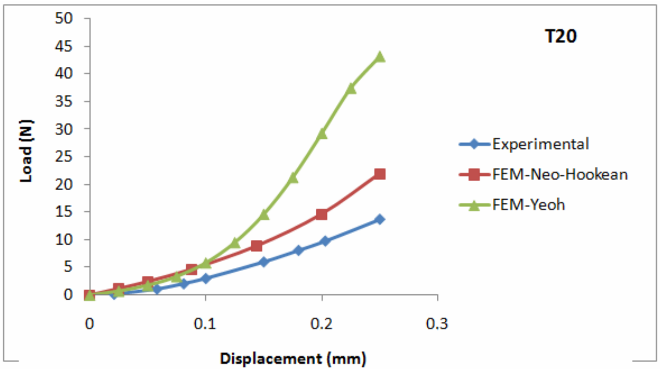

b

Fig. 4 − FEM model of compression on circular specimen (*a*); A comparison between numerical and experimental data (*b*).

In all analyzed deformational states, considering global entities like load and total displacement, the fitted models give a stable analytical description of the material stress-strain response and a good agreement between numerical and experimental data, even at large values of strains. We can also conclude that the stability of hyperelastic model is important to calibrate the material.

Some discrepancies were observed between experimental and simulations for compression test. These discrepancies may be due to the specimen's geometry that need to be resized, according to ASTM D395.

4. Conclusions

In this work, a procedure of rubber-like materials characterization is given by means of mechanically test method applied in uniaxial tests. Experimental data from the tests were processed in order to calibrate hyperelastic constitutive models of the material behavior. The fitting procedure is performed in ABAQUS involving uniaxial test data, in order to obtain a set of material parameters that fits stress-strain response in a tensional state as general as possible. Among the models available in literature and implemented into commercial FEM codes like ABAQUS, Mooney-Rivlin, Ogden, Arruda-Boyce and Yeoh were found to be most accurate. Depending on the stability limit information of hyperelastic models, they give a good description of the material response. Furthermore, their implementation into ABAQUS shows good agreement between simulation and experimentation for tension state and some discrepancies in compressive state due to the experimental test procedure.

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CARACTERIZARE MECANICĂ ŞI SIMULARE CU ELEMENTE FINITE LA TRACŢIUNE ŞI COMPRESIUNE UNIAXIALĂ A UNOR ELASTOMERI DIELECTRICI

(Rezumat)

Elastomerii dielectrici (ED) au fost dezvoltaţi ca muşchi artificial pentru diverse aplicaţii, precum mecanisme moi, elemente optice, suprafeţe haptice, microvehicule, senzori şi actuatori, micropompe fluidice şi dispozitive de stocare a energiei. Ei prezintă proprietăţi superioare materialelor piezoelectrice, electrostrictive sau aliajele cu memoria formei, şi anume, deformaţie mare indusă electric, densitate mare de energie, răspuns rapid, operare fără zgomot, uşori şi ieftini. Pentru a le creşte performanţa electromecanică, elastomerii sunt predeformaţi în plan cu până la 36 ori. Acest grad mare de predeformare poate duce la ruperea elastomerului şi la degradarea integrităţii dispozitivului. Dezvoltarea viitoare de traductori elastomeri dielectrici necesită metode computaţionale precise şi eficiente. Traductorii implică cuplaj electromecanic neliniar, şi sunt, de obicei, structuri hibride formate din membrane moi supuse la întindere şi materiale dure supuse la compresiune.

Această lucrare raportează o investigare sistematică a caracteristicilor mecanice ale unor filme elastomerice folosite ca strat dielectric în sisteme de actuaţie. Teste uniaxiale de tracţiune şi compresiune au fost efectuate cu scopul de a determina proprietăţile elastice ale unor elastomeri pe bază de polidimetilsiloxan (PDMS). Rezultatele au condus la un comportament neliniar elastic în ambele stări de solicitare şi la module de elasticitate apropiate. Curbele tensiune-deformaţie specifică obţinute experimental au fost aproximate cu diverse modele hiperelastice iar pentru simularea deformaţiilor mari a fost folosită metoda cu elemente finite (MEF). Rezultatele simulărilor au fost comparate cu cele experimentale şi au arătat o concordanţă bună, mai ales în cazul testelor de tracţiune. În cazul simulărilor la compresiune au fost observate anumite neconcordanţe cu rezultatele experimentale, puse pe seama neutilizării unei proceduri standard de testare a elastomerilor.