BULGE TEST APPLICATION IN THE CHARACTERIZATION PROCESS OF ELASTOMER MATERIALS MEMBRANES

Saúl Íñiguez-Macedo1, Alfonso Pascual-Martínez1, Jesús-Miguel Laliena-Martínez1, Rubén Lostado-Lorza2, Fátima Somovilla-Gomez2 y Marina Corral-Bobadilla2

1 Centro Tecnológico del Calzado de La Rioja | CTCR (España).

2 Universidad de La Rioja (España).

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1 Introduction

Elastomer materials exhibit a nonlinear behavior that is difficult to replicate by simple elastic models, which are generally characterized by elastic (E) and a Poisson modulus. It is necessary to introduce a different range of deformation energy functions, which must be adjusted according to the real material response. The process to obtain the constitutive parameters begins with the definition of a standardized test set. Each test provides different information, including different stress configurations, such as strain or compression. The generally used method to adjust method the registered values of strain and stress is by a curve fitting between test data and the output of the material elastic functions and varying the constitutive parameters until the minimum error [1, 2] is achieved. Previous work [3-6] has demonstrated that it is possible to use an alternative adjusting process that is known as Finite Element (FE) model updating. This process also requires a curve fitting procedure, but in this case based on the recorded pressure-displacement curves, which are much easier and cheaper to measure and quantify than strain-stress curves. From the pressure-displacement curves can the parameters be predicted by means of regression models and their corresponding optimizations based on optimization algorithms.

Taking this as a start point, the main problem is the difficulty that the initial test set introduces to the characterization process. Plane stress test specially [7], has a preparation time that makes slows the process and makes it expensive when offered as a service. The plane stress test is complex due to the test specimen’s shape (large dimensions), the preparation (the specimen must be glued with the tools, and any minimum error renders a test to be useless test) and cleaning the tools (where the rubber is glued) is difficult [8]. Trying to find a workaround and a way to validate the previous work method, the bulge test has been selected.

The aim of this work is to study the possibility of using the bulge test during the process of characterization of a rubber-like material applying the FE model updating method. The entire process has been supported on a NBR (Nitrile Butadiene Rubber) material, as this kind of rubber is used extensively in industry, i.e., for soles of footwear, in the automotive industry and the aeronautical industry, etc. [9-11].

The validation method had been based on carrying out a comparison between the bulge test response and the one simulated by the Finite Element Method (FEM). From this comparison the best type of element had been selected for study. In addition, error percentage values were obtained, to ensure the reliability of the complete process.

2 Materials and methods

This methodology has both, an experimental and an analytical part. In the experimental part, the pressure-displacement curves are recorded from the bulge test, while the analytical part of these same curves are determined by FE models based on the same test, and by regression models based on Artificial Neural Networks (ANN's), which are generated from the results obtained from the pressure-displacement curves of the FEM. Likewise, the stress at the highest point (dome of the hemisphere) is determined by means of an analytical equation proposed in the basic theory of elasticity, as well as from the FEM model.

2.1 Elastomer material characterization

The first step has been the characterization of the NBR material from which the membrane was made. This process begins with a standardized test set that includes strain, shear, compression, volumetric compression, and planar stress. This battery of tests generated a great deal of information that has been processed by Genetic Algorithms (GA) using previously trained Artificial Neuronal Networks (ANNs) to predict the material behavior [12, 13]. For this work, Mooney-Rivlin, Arruda Boyce, Gent and Ogden energy function models were used.

Parameters have been selected according to the minimum error between the experimental data and the predicted values. Each test has assigned the same weight value, defining thereby its importance into the objective function definition. After the adjustment had been completed, FE models replicating each of the five tests had simulated, including the obtained parameters, and checking the correct predictions. Finally, the parameters that best represent the material's behavior are shown in Table 1 for each energy function.

Table 1. Energy function constitutive parameters for the NBR studied

Energy deformation model function	Parameter	Value
Mooney-Rivlin	C_{10}	0.1407
	C_{01}	-0.0041
	C_{11}	0.137
Arruda-Boyce	$nk\theta$	0.897
	N	15.04
Gent	E	24.843
	I_m	307.934
Ogden	μ_1	0.4974
	α_1	3
	μ_1	-0.0791
	α_1	-2

2.2 Bulge test definition and data acquisition

After the elastomer has been characterized for each energy function of the proposed models, the bulge test was developed. In this matter, there is one fact to considered concerning this validation. The ANN and GA were validated by using FEM after the convergence of the GA. However, these models only simulated the tests that were used to train the ANN. It is interesting to prove that a different problem can be simulated with FEM using the optimum material parameters. This FE model will force the rubber to behave in non-pure strain scenarios. It will be interesting to determine the accuracy of the simulation of a future component. Due to the possibility of easily controlling the test (pressure y displacement), and acquiring an understanding of the present stresses, the validation has been undertaken by the bulge test.

2.2.1 Bulge test

The bulge test is not a normalized one test, but is widely used by other authors [14, 15]. It consists of holding a thin rubber disk (membrane) between two tightening metal tools and applying pressure to one of the faces of the disk. During the process, the disk inflates and adopts a semispherical shape. The axial symmetry of the test determines the equibiaxial, as well as the stress and strain, which is recorded in the top part of the membrane, without any expensive or complex load control system.

The bulge test does not have a standard that regulates it. The test defines the characteristics of the tools, specimens, test conditions or the way of acquiring data and obtaining results. The designed test bench (fig. (1)) consists of a system that is capable of attaching a 200mm diameter circular membrane to a steel base by means of a steel ring of 150mm interior diameter.

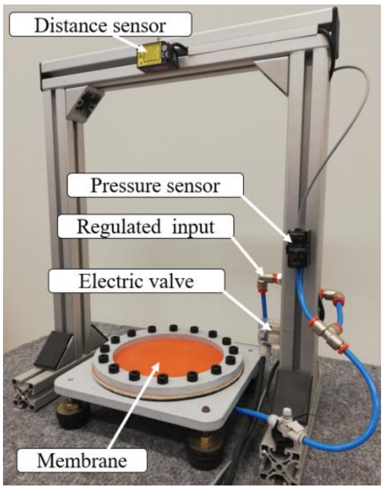

Fig. 1. Bulge test bench elements

The ring is manufactured with its inner edges rounded, in order to reduce the stress in the contact area during the deformation. The base has a central air connector that allows inflation using a regulated pressure. An electric valve is controlled by an electronic system that also records the pressure (Festo SDE5-D10-NF-Q6E-V-K) and membrane displacement (Panasonic HG-C1400). The maximum error that the Panasonic HG-C1400 contactless device presents is 0.3 mm for a measurement range between 200 and 400 mm (approximately 0.075% maximum), while the Festo SDE5-D10-NF-Q6E-V-K device presents an error of 3% when working at room temperature between 20 and 25ºC.

Both pressure and laser displacement sensors had an analogic output of 0 to 5 volts that was been read by a 16-bit ADS1115 ADC. The precision that can be obtained with such a montage is sufficient to ensure good data acquisition with a sample time of 50ms.

In this case, three rubber membranes of 2 mm width were prepared and placed attached to the test bench. A pressure of up to 340mbar was applied, and the deformation data recorded. The pressure-strain is shown in fig (2). As can be seen, the behavior of the material during the test is not linear, while the maximum displacement is 26.67 mm.

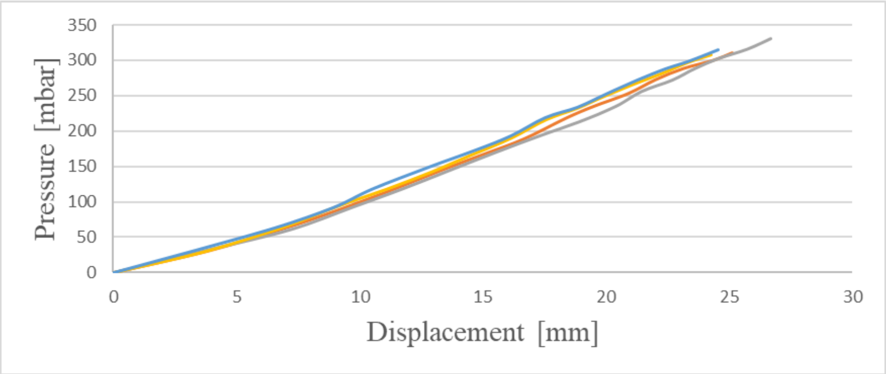

Fig. 2. Bulge test pressure-displacement curve.

The stress at the highest point of the membrane can be determined theoretically by means of Eq (1). As the membrane is very thin, the stress at the highest point (dome of the hemisphere) can be considered to be equibiaxial, while, in the rest of the contour of the hemisphere the state resembles a plane stress.

$$\sigma = \frac{pR_0\alpha_0}{2s_0\alpha} = \frac{90pa}{2s_0 \cdot arcsen\left(\frac{2h \cdot a}{a^2 + h^2}\right)} \qquad (1)$$

Where **p** is the inner pressure, **R** the membrane curve radius, **s** is the membrane thickness in the stressed situation, **s₀** is the initial thickness, **h** the high and **a** the ring radius.

2.2.2 FEM simulation

FE models were created with Mentat Marc software [16], in an effort to recreate the bulge test. However, certain simplifications were made. In the previous section, the nature of the test characteristics has been indicated, as well as the solutions that were adopted regarding the geometry of the test bench.

The FE simulation used only the geometry of the steel ring (rigid body) and the membrane (elastic body) as depicted in Fig 3. The rest of the montage only served to support the sensor kit and the air connections and added no information to the deformation process. An embedment boundary condition was applied in the contour of the rubber disk, while the pressure was defined incrementally by a ramp, which was applied uniformly over the entire inner surface of the membrane. Additionally, the mechanical contact between the disk and the steel ring also were defined.

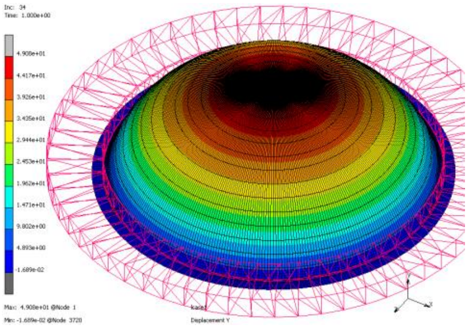

Fig. 3. Bulge test FE simulation – shell elements

Several FE models were developed considering different types of meshing (radial meshing and regular automatic meshing). These include 3D models with bricks elements and models with 2D shell elements and symmetry conditions to generate axil symmetric constructions. Regarding the mesh distribution and element size, both had been studied to ensure model precision and stability of the FE models. Fig 4 shows the difference between radial mesh and regular automatic mesh. It is clear that radial mesh produces a regular stress distribution, which was why it was selected. As a result of a mesh sensitivity analysis for the radial mesh case, it was concluded that a 5 mm mesh with 1º radial division provided the most suitability for the simulation. It should be mentioned that a mesh of this element size (5 mm) has not used in the entire model, because in the contact area it becomes inappropriate in size and should be reduced to as little as 0.5mm to achieve satisfactory results.

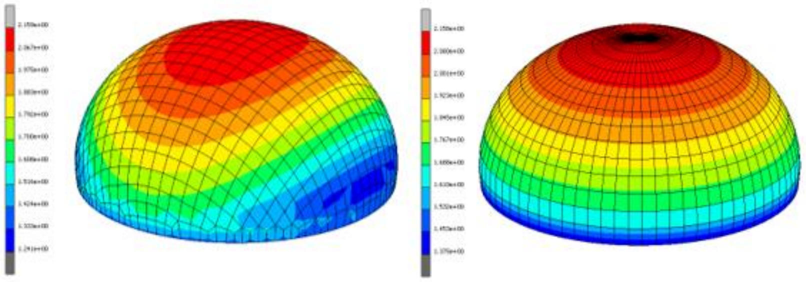

Fig. 4. Mesh type and stress distribution

Tin the end, the FE models were meshed with “Type 10” elements for the axil symmetric analysis, hexahedrons “Type 7” and pentahedral “Type 136” for the Brick cases. However, Shell models have been generated by use of quadrilaterals “Type 75” and triangles “Type 138”.

The FEM results were postprocessed to obtain each one of the results in the simulations (pressure-displacement-stresses). This data facilitated a comparison of the real test and what was carried out virtually according to the previous constitutive parameters in which the stress-strain curve is determined from very expensive extensometers.

3. Results

FE models were evaluated for the four studied energy functions. The results for the ones with Arruda-Boyce [17] parameters are shown in Table 2. This table provides a comparison of the six calculated models (σ_FEM), the theoretical stress combined with the FE models (σ_Th_FEM) and the real test (σ_Th_Test). The values of σ_FEM were determined directly from the proposed FEM models, while the values of σ_Th_FEM were calculated by means of Eq (1), using the values of h (bulge height) obtained in turn from the proposed FEM models. The value of σ_Th_Test (single value) was determined from the data of h obtained experimentally. Values are also differentiated by the pressure application method, FL (Face Load) or PC (Pressure Cavity). All FE models proposed were simulated in six computers with Intel Xeon processor, 128.00 GB (random access memory (RAM) and CPU 2.2GHz (two processors). The computational times were, for all the simulations carried out, less than 30 minutes. After post processing the FEM results, the best model was the one meshed using Shell-type elements. The shell model provided stress values (σ_FEM) remarkably close to the theoretical calculations (σ_Th_FEM), with an error of approximately 4.3%. However, the Axisymmetric models and those with Brick-type elements gave values that deviate from the theoretical ones by 34%. This precision level of the Shell models has been maintained in the three remaining energy functions (Ogden, Gent and Mooney-Rivlin). The remaining energy functions cited (considering the constitutive parameters shows in Table 1) fit more poorly than Arruda-Boyce, with an Ogden error of 20.47%, Gent 21.65%, and Mooney-Rivlin 27.14%. In Table 2 it can be seen that the shell FE model is more accurate than the others FE models. The difference between the test stress (σ_Theoretical Test) and that obtained from the shell simulation (σ_MEF) are 14.97% for shell_FL and 14.98% for shell_PC, which is considered to be a good approximation.

Table 2. Stress values of FEM models and a comparison to the real test (Arruda Boyce)

	Axi_FL	Axi_PC	Shell_FL	Shell_PC	Brick_FL	Brick_PC
σ_FEM [MPa]	1.276	1.276	0.815	0.815	1.256	1.256
σ_Th_FEM [MPa]	0.843	0.843	0.850	0.850	0.827	0.831
Error FEM-Th_FEM	33.92%	33.88%	-4.28%	-4.30%	34.10%	33.83%
σ_Th_Test [MPa]	0.938					
Error_Th_Test-FEM	26.52%	26.48%	-14.97%	-14.98%	25.31%	25.32%

The results have demonstrated that the use of the proposed characterization method based on bulge test and the FE model updating method is appropriate, and that, with the correct configuration of the model (Shell elements), it is possible mechanically characterize new elastomers such as ethylene-vinyl acetate (EVA), styrene butadiene rubber (SBR) and polyurethane (PUR) without introducing too many deviations both in the bulge test and in the FE model. The characteristic curve of the bulge test and the obtained stress distribution have shown that this characterization method could be a simpler and cheaper alternative to be used in the characterization of elastomers than other more sophisticated methods require.

4 Conclusions

The bulge test had allowed analyzing the elastomer behaviour in a non-standard test. During the test process, empirical data had been collected to compare with FE results. This process had determined that shell-type finite elements are the most suitable to mesh the FE models when simulating the bulge test, and by extension, any membrane problem, since they provide enough precision evaluating strains and stresses (error close to 15%). Shell FE models had a moderate simulation time (less than 30 minutes), which allows many simulations to be carried out without taking too much time to obtain the results. This fact, in conjunction with the one described above, remark that the use of a bulge test as a substitute for any of the original tests is possible. If done, one of the best candidates could be the planar stress test, both due to the similarities in stress behaviour plus the saving in preparation time. After the final comparison, it has been seen that the simulated and empirical data had a high degree of similarity. This characterization process can generate satisfactory results that represent the mechanical properties of elastomeric materials. The reduced error found and the computational cost indicate the possibility that the methodology suggested in this work based on the FE model updating method and bulge test could be a quicker and less expensive alternative to existing, more complex methods in the characterization of elastomers. As future work, a good start point could be to analyze the integration of the bulge test into the characterization process. An ANN model capable of providing the necessary response should be trained. With this method, the characteristic material parameters for different energy functions could be obtained in a quicker way. Another future application for this method could be the study of fatigue in elastomers. Some researchers [18, 19] have proposed this analysis through a cyclic process of inflating the test membrane until it breaks, to study then the data collected and estimate the durability of products.

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