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Using the uniaxial tension test to satisfy the hyperelastic material simulation in ABAQUS

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Abstract. Since, hyperelastic materials, such rubber, are widely used in different life fields principally in engineering of elastomeric bearing pads. The present study aims to determine a suitable constitutive model dependent on strain energy potential which can characterize hyperelastic material behavior through uniaxial tension test only. Built-in ABAQUS software constitutive hyperelastic models are used to fit the experimental results of the uniaxial tension test, check the stability and obtain the material coefficients. The used models are that of Mooney-Rivlin, Polynomial, Neo-Hookean, Yeoh and Ogden. The results revealed that Polynomial, Ogden and then Yeoh models are convenient to fit the hyperelastic behavior of the rubber material while Mooney-Rivlin and Neo-Hookean models have a slight ability of fitting limited to the early stage of the linear behavior of the material.

1. Introduction

Hyperelastic behavior represents the ability of materials to preserve their elasticity under both linear and nonlinear relationships between stress and strain. Thus, hyperelastic materials such as rubber can restore their original state after load releasing regardless of the deformation range. Thereby, rubber-like materials are not only artificially produced or used for considerable applications like vibration and shock isolation industry [1,2], but also some human and living tissues behave as hyperelastic ones [3,4]. So that, simulation of rubber-like materials is of significant importance for manufacturing, engineering and medicine fields. Significant attention is paid into the simulation of elastomeric bearing pads which are vibrations isolator and loads transfer from superstructures into substructures of bridges. Rapidly, simulation processes of the rubber-alike materials can be facilitated by finite element analysis (FEA) techniques built-in miscellaneous aided software [3,5]. FEA processes can adopt multiple constitutive models to accomplish the simulation even when each model requires private coefficients on value and type.

In addition to explicitly input coefficients, the material coefficients that implicitly input by test data are acceptable in FEA programs. However, the problem be facing the analyst is how to obtain the data essential to produce the coefficients required to fully defined models [6].

ABAQUS, as FEA software, is capable of fully defining the material hyperelastic models by coefficients input directly or through test data input which are processed to simulate the material behavior and produce its coefficients [7,8]. Uniaxial, biaxial and planar (pure shear) tension tests data can be input and represented in ABAQUS besides volumetric tension and compression changes also. In probable, only one or maybe two types of tension test data of the material are on hand [1,6-9]. Furthermore, volumetric compression data are not provided for incompressible materials. Where a rubber is highly constrained by rigid steel laminated bridges bearing pads, the rubber exhibits deformations but



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approximately without volumetric changes [1-3,6,7]. In the present study, chloroprene rubber sample is simulated in ABAQUS for two aims. Firstly, representing and comparison the test data of the uniaxial tensile of the rubber sample with curves produced from application of hyperelastic material models of polynomial, Reduced Polynomial and Ogden. Secondly, obtaining the rubber sample coefficients to be adopted for behavior analysis at next or another simulation process. Off course the local target of the current simulation study is the elastomeric bearing pads in bridges, but the target can be globalized to cover another engineering and industry and medicine applications.

2. Hyperelastic Models in ABAQUS

Depending on strain energy potential, several hyperelastic constitutive models are built-in ABAQUS, therefore; rubber-like and elastomeric (rubber) material can be easily modeled. The strain energy potential function fall into two parts for deviatoric and volumetric strains [5-9].

$$U = U_{dev} + U_{vol} \quad (1)$$

Where U is the strain energy potential, U_{dev} is the deviatoric (shear) strain energy potential which involves the change in shape without change in volume, while U_{vol} is the volumetric (dilatational) strain energy potential which involves the change in volume without change in shape.

The volumetric strain energy potential has unique mathematic expression in almost hyperelastic models as explained below:

$$U_{vol} = \sum_{i=1}^N \frac{1}{D_i} (J_{el} - 1)^{2i} \quad (2)$$

Where: N , D_i , J_{el} are material constants, represent strain energy potential order, compressibility index and elastic volumetric strain of the material respectively.

Generally, it is common to deal with rubber materials for most works as incompressible and set D_i into zero. So, a lot of focusing on hyperelastic models is awarded to the deviatoric strain potential [1-9]. The mathematic expression of the deviatoric strain potential is different form model to other according to invariant-based (polynomial) models commonly defined in term of invariants (\bar{I}_i) or stretch-based (Ogden) models commonly defined in terms of principal stretch ratios ($\bar{\lambda}_i$) [1,3,5-10].

2.1. Polynomial models

It is invariant-based type of strain energy models was firstly proposed by R.S. Rivlin in 1951 [11] and so that it is indicated as the generalized Rivlin hyperelastic mode. It is generally formed as:

$$U_{dev} = \sum_{i+j=1}^N C_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j \quad (3)$$

Where: \bar{I}_1, \bar{I}_2 are the first and second invariants of the deviatoric strains. C_{ij} is material constant, describes its shear behavior.

If the strain energy potential order set into one ($N = 1$), the Mooney-Rivlin model is obtained and its form is:

$$U_{dev} = C_{10} (\bar{I}_1 - 3) + C_{01} (\bar{I}_2 - 3) \quad (4)$$

For particular forms of the polynomial model, specific coefficients are set to zero. If all C_{ij} with $J_{el} \neq 0$ are set to zero, the reduced polynomial form is obtained:

$$U_{dev} = \sum_{i=1}^N C_{i0} (\bar{I}_1 - 3)^i \quad (5)$$

If the strain energy potential order of the reduced polynomial model is set into three ($N = 3$), the Yeoh model is obtained [12]. Whereas, additional reducing into ($N = 1$) leads to obtain to the Neo-Hookean model [13].

2.2. Ogden models

It is stretch-based type of strain energy models was proposed by R.W. Ogden in 1972 [14]. This model is the frequently used for rubber components like O-ring and seal analysis [a comparison among]. The generalized form of this model is:

$$U_{dev} = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} (\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3) \quad (6)$$

Where: $\bar{\lambda}_i$ is the principal stretch ratio, μ_i and α_i are material constants, describe its shear behavior.

3. Experimental Work

The experimental work of the present study consists of preparation and testing a hyperelastic material which is chloroprene rubber in term of uniaxial tension and then feeding the stress-strain values in form of test data into ABAQUS to simulate the material behavior depending on.

3.1. Material used

The material used in the present study is a layer of synthetic chloroprene rubber (CR). The material was cut as a sample from laminated elastomeric bearing which is reinforcing steel sheets are totally covered with rubber complies with EN 1337-1 [15]. The sample mechanical properties of the sample were tested in Baghdad Central Laboratory/National Center for Laboratories and Building Research. The results are listed in table 1.

Table 1. Nominal mechanical properties of the tested rubber.

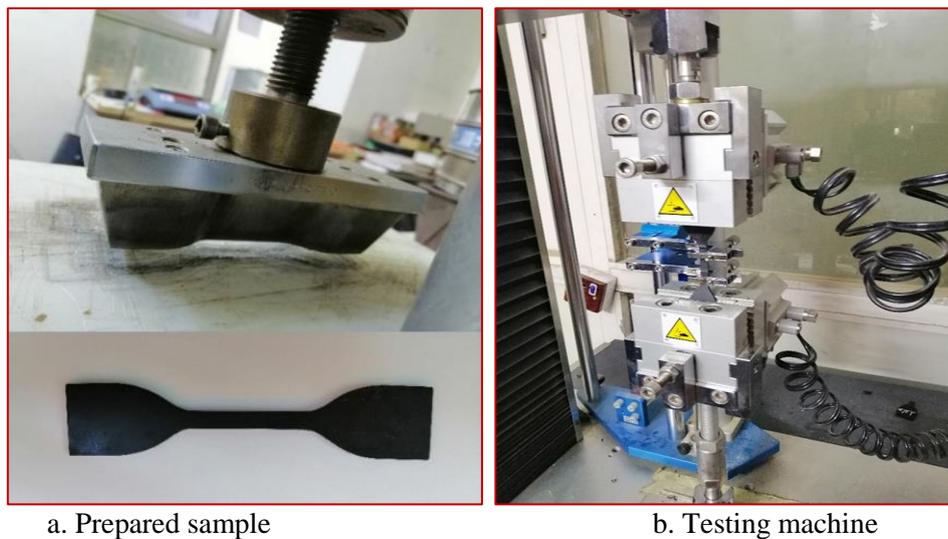
Material	Test	Result	ASTM Designation	Reference
	Hardness limits	66	D2240	[16]
Synthetic	Shear Modulus (MPa)	1.215	D4014-03	[17]
Chloroprene	Tensile Strength (MPa)	15.77	D412-06a	[18]
Rubber (CR)	Ultimate Elongation (%)	320	D412-06a	[18]
	Compression Set (%)	23	D395-14	[19]

3.2. Sample preparation

The sample has been prepared according to ASTM D412-06a [18] which uses dumbbell Die C specimen as shown in figure 1.a below. The average thickness of specimen is (2.85mm) which checked by three measures were two at each end of the reduced section and one at its center.

3.3. Testing procedure

At beginning, general checks were done on the machine and the testing ambient. The next step was fixing the sample ends in the testing machine shown in figure 1.b to carry out a uniaxial tension test. The initial gauge length (L_0) to measure the longitudinal stretches of the sample equals (70mm). The test begun with a speed of grip separation was (5 mm/min) to observe the load-displacement curve readings according to the test specification [18]. Displacements with their corresponding loads were recorded manually using mobile camera to capture the computer screen during the test progress. Testing process has been continued until the sample rupture. The test was carried out in Baghdad Central Laboratory/National Center for Laboratories and Building Research.



a. Prepared sample

b. Testing machine

Figure 1. Testing preparing.

3.4. Test results

After recording of axial applied loads and corresponding longitudinal displacements from the uniaxial tension test, stress-strain results were calculated and listed as in table 2. These experimental results have been input into ABAQUS as the test data of the rubber to simulate its hyperelastic behavior.

Table 2. Test results of stress-strain.

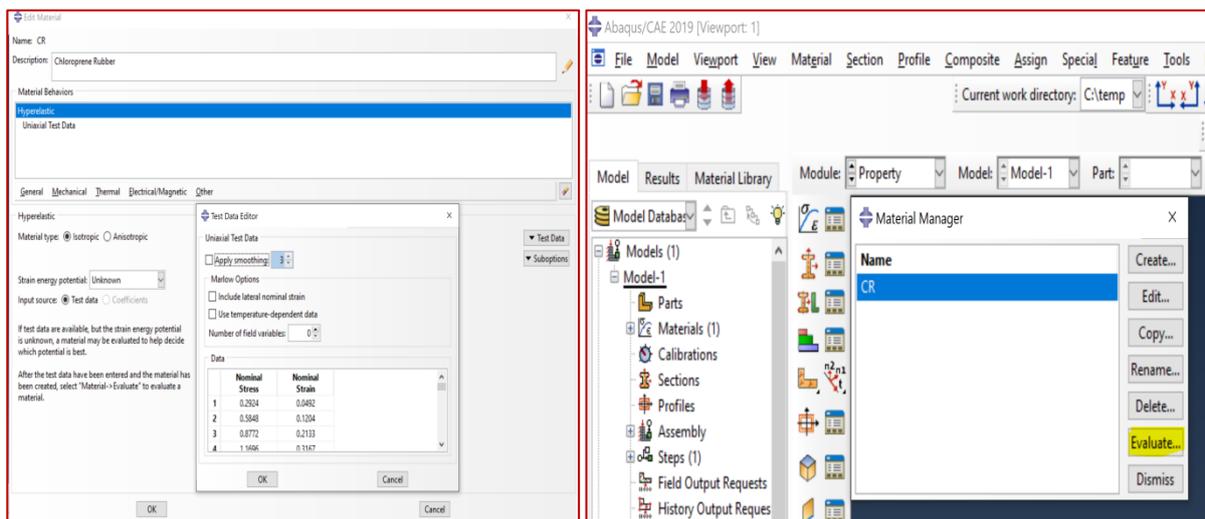
Force (F) N	Extension (ΔL) mm	Stress (σ) MPa	Strain (ϵ) %	Force (F) N	Extension (ΔL) mm	Stress (σ) MPa	Strain (ϵ) %
5	3.442	0.2924	0.0492	95	98.808	5.5556	1.4115
10	8.425	0.5848	0.1204	100	102.797	5.8480	1.4685
15	14.928	0.8772	0.2133	105	106.394	6.1404	1.5199
20	22.167	1.1696	0.3167	110	109.96	6.4327	1.5709
25	29.508	1.4620	0.4215	115	113.433	6.7251	1.6205
30	36.653	1.7544	0.5236	120	116.856	7.0175	1.6694
35	42.651	2.0468	0.6093	125	120.083	7.3099	1.7155
40	49.0000	2.3392	0.7000	130	123.469	7.6023	1.7638
45	54.512	2.6316	0.7787	135	126.999	7.8947	1.8143
50	59.899	2.9240	0.8557	140	130.365	8.1871	1.8624
55	65.118	3.2164	0.9303	145	133.637	8.4795	1.9091
60	69.943	3.5088	0.9992	150	136.928	8.7719	1.9561
65	74.579	3.8012	1.0654	155	140.153	9.0643	2.0022
70	78.972	4.0936	1.1282	160	143.472	9.3567	2.0496
75	83.394	4.3860	1.1913	165	146.861	9.6491	2.0980
80	87.387	4.6784	1.2484	170	150.262	9.9415	2.1466
85	91.232	4.9708	1.3033	175	153.557	10.2339	2.1937
90	95.236	5.2632	1.3605	178	156.181	10.4094	2.2312

4. Simulation work

The simulation work was done by ABAQUS through plotting the stress-strain curves for the test data and five selected constitutive models. The stress-strain curve of the test data represents the realistic behavior of the rubber while the five curves created by Mooney-Rivlin, Polynomial, Neo-Hookean, Yeoh and Ogden models are trial to fit the realistic one. Basically, ABAQUS reanalyze the test data using one of the selected models at each fitting time to produce the material coefficients, check the model stability and plot the stress-strain curve. By this way, five material coefficients packages and five stress-strain curves were additionally plotted. Thus, to clarify which model is more convenient to fit the rubber behavior, the five fitting curves of the constitutive models are comparable with the realistic curve came from test data.

4.1. Behavior definition

In present study, ABAQUS CAE/2019 version is utilized. The hyperelastic behavior of rubber is defined into ABAQUS through Properties Module from Material Manager followed by Create, Mechanical, Elasticity and then Hyperelastic [7]. At last, Test Data button was selected to input the experimental stress and strain values as shown in figure 2.a. Then, Mooney-Rivlin, Polynomial, Neo-Hookean, Yeoh and Ogden models were selected to fit the test data. The curve fitting was done through Evaluate button found in the Material Manager menu [7] as shown in figure 2.b.



a. Test data input

b. Data evaluation option

Figure 2. Curve Fitting in ABAQUS.

4.2. Behavior fitting

After evaluation process completion, uniaxial six stress-strain curves were plotted as shown in figure 3.a; one of them is the realistic which belongs to the test data while the rest five plots are fitting curves which belong to the constitutive models. The chloroprene rubber behavior represented by Test Data curve inside the plot are composed of linear segment at first stage and then transforms to nonlinear. It is clear from figure 3.a that, the 1st order models (Mooney-Rivlin and Neo-Hookean) are almost limited to linear behavior and thus they were inconvenient to fit the chloroprene rubber behavior. However, slight fitting to Test Data curve can be achieved at small values of strain not exceed about 30% for Mooney-Rivlin curve and about 15% for Neo-Hookean curve. On other hand, Yeoh-model which is 3rd order reduced polynomial model exhibited a good convenience to fit the Test Data curve while Ogden of 3rd and Polynomial of 2nd order curves are hidden under the realistic curve of the Test Data because of full fitting among them. That is to say, Ogden model and polynomial Model can reflect excellent simulation to the chloroprene rubber behavior.

Besides plotting of the uniaxial stress-strain curves, ABAQUS can adopt the uniaxial tension test data to plot the stress-strain curves for biaxial tension, planar shear and direct shear illustrated in figure 3.b-d despite of absence of their pertaining test results. Since the test data of the uniaxial tensile are indirect values for lateral dimensions of the rubber, this can indicate an advantage of material simulation in ABAQUS which can predict the correlated behavior of the material depending on indirect input data.

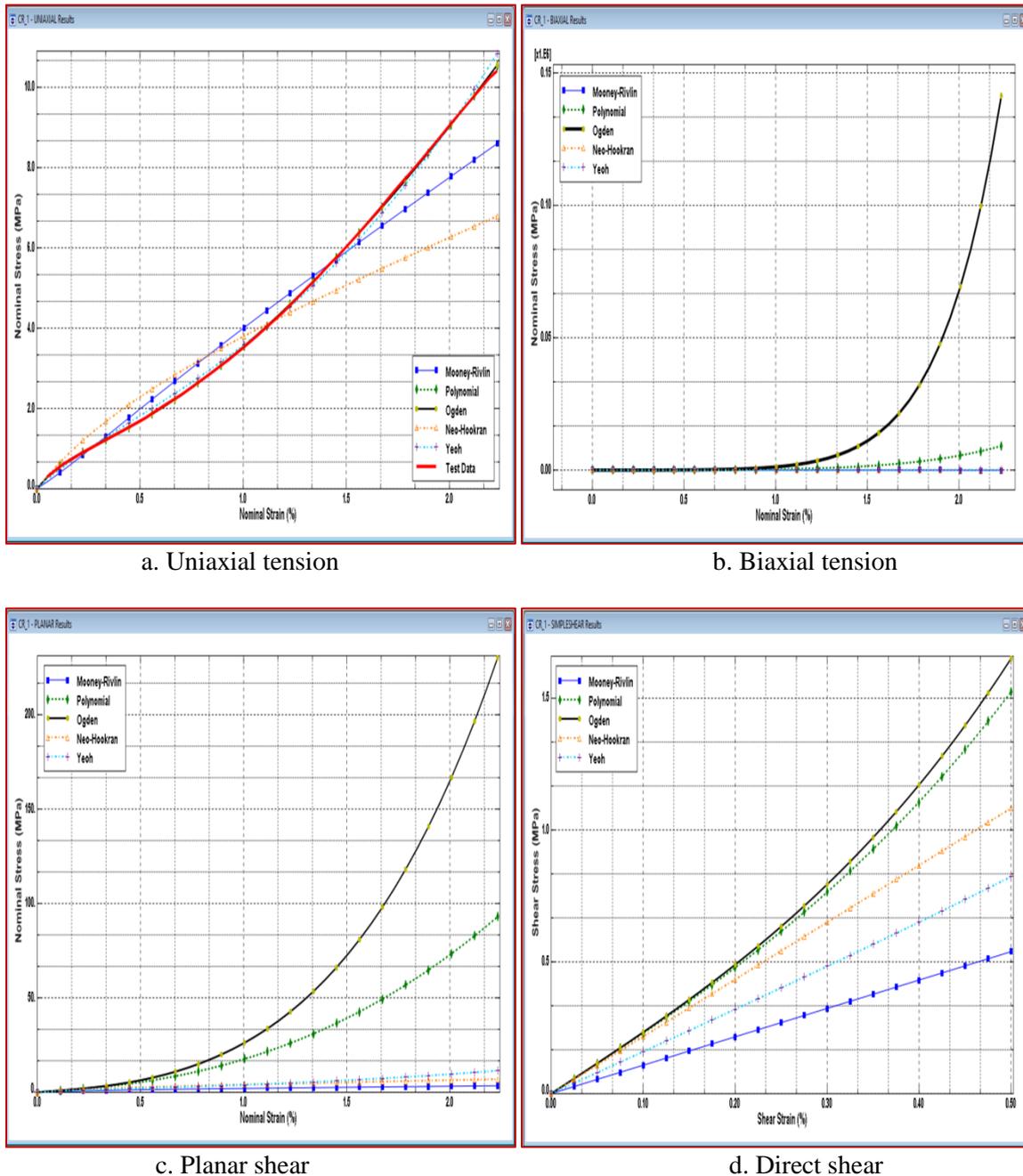


Figure 3. Simulation result curves from ABAQUS.

4.3. Material model stability

In addition to curve fitting done, the ABAQUS dialog box of Material Parameters and Stability Limit Information appeared. The contents of the dialog box are listed in Table 3. The stability check is essential because if the deformation is more complicated, it is expected that the material will be unstable at the strain levels indicated and thus, the simulation may not converge [2,6,7].

Table 3. Material coefficients and stability checks for hyperelastic constitutive models.

Constitutive Model	Stable Check	Material Coefficients			
		Deviatoric		Volumetric	
Mooney-Rivlin	Unstable	$C_{10} = 1.7439$	$C_{01} = -1.2054$	-	$D_1 = 0$
Polynomial	Stable	$C_{10} = -1.3911$	$C_{01} = 2.5235$	-	$D_1 = 0$
		$C_{20} = -1.4069$	$C_{11} = 0.1974$	$C_{02} = 0.6006$	$D_2 = 0$
Neo-Hookean	Stable	$C_{10} = 1.0829$	-	-	$D_1 = 0$
		$C_{10} = 0.7950$	-	-	$D_1 = 0$
Yeoh	Stable	$C_{20} = 5.6035$	-	-	$D_2 = 0$
		$C_{30} = 1.6121$	-	-	$D_3 = 0$
Ogden	Stable	$\mu_1 = -2.3527$	$\alpha_1 = 1.1080$	-	$D_1 = 0$
		$\mu_2 = 1.3602$	$\alpha_2 = 2.3333$	-	$D_2 = 0$
		$\mu_3 = 3.2809$	$\alpha_3 = -5.4789$	-	$D_3 = 0$

4.4. Material coefficients obtaining

The material coefficients produced by the constitutive hyperelastic models are demonstrated in the dialog box of Material Parameters and Stability Limit Information mentioned before. These coefficients represent the material constants and being divided into deviatoric and volumetric for each model as listed in Table 3 above. The deviatoric coefficients are C_{ij} , μ_i and α_i while the volumetric coefficient is D_i which is always produced equal zero because there is no input volumetric data from experimental test. Now, the material coefficients produced by the convenient model(s) can be used as input data to define the material properties at another analysis and even design consequent process.

5. Results reliability

Depending on the plotted curves illustrated in figure 3.a and the values listed in table 3, the present results can be compared with previous researches. The present study is compatible with the researches when they remarked that Ogden model agreeable and is better than Mooney-Rivlin and Neo-Hookean model in fitting the hyperelastic behavior of rubber. Also, simple fitting with Mooney-Rivlin and Neo-Hookean models at linear deformation for the hyperelastic material can be got [3,5,9,10] but this simple fitting is more in Mooney-Rivlin model than Neo-Hookean model [5]. Moreover, the present study confirmed that Yeoh model is superior to neo-Hookean model and leads to rational fitting of hyperelastic material behavior [1]. To increase the convenience of the model toward fitting the nonlinearity of the material, more material coefficients are required [5,10] and by increasing the model order (N), its accuracy to simulate the hyperelastic behavior of the rubber can be enhanced [2]. The present results revealed that Ogden model with six deviatoric coefficients produced attains more accuracy to fit the rubber behavior than Yeoh model with three deviatoric coefficients produced while the two models are of 3rd order, but Ogden model is not preferable than Polynomial model of 2nd order with five deviatoric coefficients produced. That to say, both Ogden and Polynomial models are convenient to simulate the hyperelastic rubber material but the Polynomial model can attain excellent convenience with less material coefficients.

6. Conclusions

From the results of the present study; the following can be remarked; simulation of hyperelastic rubber material can efficiently done through uniaxial tension test to produce the material coefficients beneficially to define the material behavior for next analysis or design works such as elastomeric bearing pads. By increasing the material coefficients, its nonlinear behavior can be well defined, thus the fitting accuracy of constitutive model will enhance. Yeoh, Ogden and Polynomial models are convenient as constitutive models to simulate the hyperelastic behavior of rubber material in ABAQUS as FEA program.

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