Archives of Materials Science and Engineering

Volume 108
Issue 2
April 2021
Pages 75-85

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

DOI: 10.5604/01.3001.0015.0256

Hyperelastic models for the description and simulation of rubber subjected to large tensile loading

Q.H. Jebur [a], M.J. Jweeg [b], M. Al-Waily [c,*], H.Y. Ahmad [d], K.K. Resan [e]
[a] Climate Change-Scotland, UK
[b] Al-Farahidi University, College of Technical Engineering, Iraq
[c] Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Iraq
[d] Engineering Consultant, Stress & Materials, Safran Electrical & Power, Pitstone, Buckinghamshire, UK
[e] Materials Engineering Department, College of Engineering, Mustansiriyah University, Iraq
* Corresponding e-mail address: muhanedl.alwaeli@uokufa.edu.iq
ORCID identifier: https://orcid.org/0000-0002-7630-1980 (M.A.-W.)

ABSTRACT

Purpose: Rubber is widely used in tires, mechanical parts, and user goods where elasticity is necessary. Some essential features persist unsolved, primarily if they function in excessive mechanical properties. It is required to study elastomeric Rubber's performance, which is operational in high-level dynamic pressure and high tensile strength. These elastomeric aims to increase stress breaking and preserve highly pressurised tensile strength.

Design/methodology/approach: The effects of carbon black polymer matrix on the tensile feature of different Rubber have been numerically investigated in this research. Rubber's material characteristics properties were measured using three different percentages (80%, 90%and 100%) of carbon black filler parts per Hundreds Rubber (pphr).

Findings: This study found that the tensile strength and elongation are strengthened as the carbon black filler proportion increases by 30%.

Practical implications: This research study experimental tests for Rubber within four hyperelastic models: Ogden's Model, Mooney-Rivlin Model, Neo Hooke Model, Arruda-Boyce Model obtain the parameters for the simulation of the material response using the finite element method (FEM) for comparison purposes. These four models have been extensively used in research within Rubber. The hyperelastic models have been utilised to predict the tensile test curves—the accurate description and prediction of elastomer rubber models. For four models, elastomeric material tensile data were used in the FEA package of Abaqus. The relative percentage error was calculated when predicting fitness in selecting the appropriate model—the accurate description and prediction of elastomer rubber models. For four models, elastomeric material tensile data were used in the FEA package of Abaqus. The relative percentage error was calculated when predicting fitness in selecting the appropriate model. Numerical Ogden model results have shown that the relative fitness error was the case with large strains are from 1% to 2.04%.

Originality/value: In contrast, other models estimate parameters with fitting errors from 2.3% to 49.45%. The four hyperelastic models were tensile test simulations conducted to verify the efficacy of the tensile test. The results show that experimental data for the uniaxial test hyperelastic behaviour can be regenerated effectively as experiments. Ultimately, it was found that Ogden's Model demonstrates better alignment with the test data than other models.

Keywords: Rubber, Carbon black filler, Hyperelastic models, Abaqus, FEM

Reference to this paper should be given in the following way:

Q.H. Jebur, M.J. Jweeg, M. Al-Waily, H.Y. Ahmad, K.K. Resan, Hyperelastic models for the description and simulation of rubber subjected to large tensile loading, Archives of Materials Science and Engineering 108/2 (2021) 75-85. DOI: https://doi.org/10.5604/01.3001.0015.0256

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Many manufacturing companies are indeed very interested in rubber tyres' material properties since they are linked directly to tyre performance, such as moving friction, wear, and wet grip. Rubber has several advantageous characteristics with acceptable performance at elevated strain, such as good yield strength, low creep, excellent adhesion, high corrosion, and chemical stability. In automotive components like tyres, gearbox mounts, centre bearing brackets and exhaust rubber components, elastic products are being used. The development of these highly specialised components already involves numerical simulations, like programs with finite elements. A suitable modelling approach in this context is an essential prerequisite for successful predicted results. A significant number of papers have been published in recent years that have suggested novel numerical simulations for Rubber. In data to model parts response under static load conditions, the specific non-linear hyperelasticity theory is classically invoked [1]. Alternatively, even create further advanced viscoelastic behaviour, either stress-softening models [2-7]. To explain the elasticity of elastomers, several approaches have been presented. A number of them have been shown to clarify the material's complete behaviour, i.e. to successfully reproduce experimental findings for different loads. That term completed action in the following references to the material's reaction under various loading conditions. Clearly, with both the minimum number of materials properties that should be experimental data established, the virtual simulations are those who can explain this comprehensive behaviour.

Additionally, choosing among current models is always challenging for an engineer. On the other side, several researchers have evaluated and compared hyperelastic models' ability to replicate whole elastomer behaviour. Some researchers showed the model's efficiency for considerable strain loading [8,9], particularly, or assess the model to model to define formulations [10,11] equivalence, six different models. Recently, Seibert and Schöche [12] compared particular experimental results achieved with biaxial and uniaxial extension testing. Weak predictions illustrate the risk of serial formulations and the models' biaxial response after determining the material parameters with uniaxial experimental data. Boyce and Arruda [13] were compared. Five models used Treloar's experimental results [14] aimed at three different data tests types (pure shear, biaxial and uniaxial). Further in recent times, Attard, Hunt [15] studied experimental data for uniaxial by seven separate researchers. Equibiaxial tension, tensile tension, biaxial extension, compression and shear purity and validate their model's efficacy.

To improve mechanical properties, manufacturing companies and researchers first enhance rubbers materials. It is usual to use unique materials in the compositions and revisions of current processing technologies. Different types of nanoparticles, plus crude and humanmade materials, because of their high appearance ratio and high surface energy compared to traditional fibres, polymer efficiency is greatly improved by its allotropic forms, like graphene [16], graphite [17], nanotube carbon CNTs [18], carbon black [19], and fullerene [20]. Carbohydrates (CNTs) in many applications in recent decades, CNTs and graphene have been extensively researched [21,22]. To date, nanofillers were used to strengthen composites from polymers for industrial applications, using CNTs and graphene [23]. The massive consumption of the polymers CNTs is observed to boost polymer-matrix materials' physical and mechanical properties as fillers for various polymers [24]. CNTs in different polymers are nevertheless commonly degraded; the use of CNTs in rubber products [25,26] has been reduced. The high and reversible deformability of rubber materials has gained industrial significance. Rubber materials currently contain significant carbon filler quantities, and there is a need to improve the current overall efficiency.

Due to the large surface area of rubber material, the nanoscale fillers' physical and mechanical properties can be improved by adding smaller amounts than microscale fillers.

So, the concept of the rubber-based nanoscale filler first becomes a rubber substance by improving the clay the addition of 10% layered silicate in Natural Rubber (N.R.) [27-29] indicates an improvement in the rubber modulus.

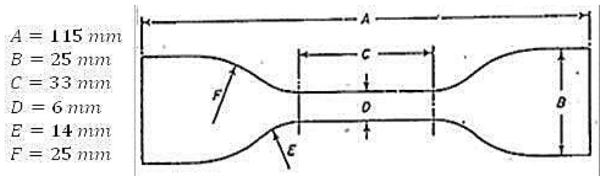
Commercial F.E. packages provide an expansive Hyperelastic Models Library for Rubber, about materials. The following models have used in Abaqus [30] HKS kit is Mooney-Rivlin, polynomial, polynomial reduced, Arruda Boyce, Yeoh, Van der Waals, Neo-Hookean and Ogden. The Mooney-Rivlin and the decreased polynomial are different. Cases of the polynomial model, while unique variants of the Neo-Hookean and Yeoh models are the reduced polynomials model. The commercial of F.E. made utilising hyperelastic models have also been contrasted with test results were obtained by Treloar [14]. Simple tension vulcanised Rubber tested by Treloar. The four predictions (Ogden, Neo-Hookean, Money Rivlin and van der Waals) were compared by Raos [31] with experimental data being performed on an SBR rubber in uniaxial, biaxial load conditions. The researcher analysed the impacts of initial strain levels used to find material parameters when full prediction spectrum of strain. The Mooney-Rivlinand Neo-Hookean models can only represent experimental results in the form of a compression when the strain line is selected appropriately and mild enlargement capable of 80%. The model's Van der Waals and Ogden included some applications with good performance. However, these models have shown some instability and resistance to strain shifts. The biaxial was also found to be susceptible tests, and reliable maintenance of the test limits were required. The hyperelastic modes were susceptible to biaxial; Ogden and Van der Waals were mainly classified as biaxial tests.

This research aims to present a systematic comparison of 4 hyperelastic models and their description of their capacity to match experimental results. After recalling simple notation, any model's layout, taken into consideration here, is briefly summarised. Then, it explains experimental methods followed to evaluate material properties. Subsequently, the parameters for contrast and the corresponding classification of models are calculated. Similarly, this work presented a typical method to use specific materials to modify existing treatment technology to enhance rubber materials' properties.

2. Experimental work

Rubber is mainly reinforced with filler particles to increase its stiffness undergoing tension. The rubber material is viscous fluid polymers that are non-linear material. It is also a cross-linked chain and undergoes a large reversible elastic deformation, and returns to its original shape with no damage. In this paper, rubber reinforcement uses filler particles that are carbon black and silica, ranging from 10 nm to 100 nm. Additionally, Natural Rubber (N.R.) reinforced carbon black (N330) filler particles with 80%, 90% and 100 % of the filler per 100 parts of natural Rubber are the materials utilised in this analysis. These percentages comply with the requirements of multinational tyre firms. The samples were prepared by combining natural Rubber, black carbon, sulphur, and oil at typical percentages to achieve the specimens' essential characteristics.

a)



b)

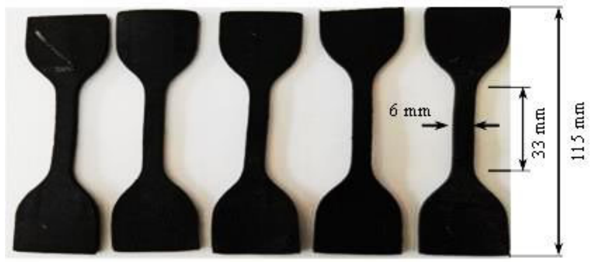


Fig. 1. The tensile test specimen dimensions, specimen thickness, t = 2 mm. a) standard ASTM D 412 [32], b) exprimental tensile test specimen

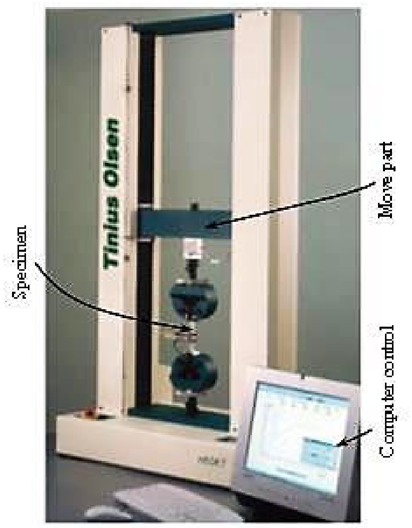


Fig. 2. Tensile test machine

Later, tensile tests were carried out corresponding to the Standard ASTM D 412; Figure 1a, [32], experiments test were repeated five times, during which average results were deducted and verified, [33-39], Figure 1b. This experiment's object is to apply a tensile force to the test sample till the specimen is rupture, pulled through to defeat during the application of the tensile load. The tensile testing machine estimates property and produces stress vs strain curve from which different values are produced, like the modulus of elasticity. Finally, as shown in Figure 2, the tensile testing machine contains an electro-mechanical test structure that regularly applies uniaxial loading to test specimens.

3. Hyperelastic models

In general, the hyperelastic models are defined in forms of strain energy potential, created as a function of strain invariants, [29] concerning strain-stress curves. These models are phenomenological, implying that there is no connection to an extracted constants to the chemical or mechanical properties of rubber materials. They consider the material's tensile properties and attempt to classify the material as an amorphous, isotropic solid, resulting in the material being defined as if the material shifts state during deformation, models can become inaccurate. Therefore, these models are better fitting for researchers, such as gum rubber, where the results of such modifications [40,41].

3.1. Ogden model

Hyperelastic models provide description and simulation of rubber tensile loading used to predict the non-linear stress-strain behaviour of materials Rubber or polymer, for example. Ogden presented the Ogden model (O-M)1972 and the density of strain energy functions for an Ogden. The information is as follows [30]

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} (\lambda_1^{\alpha i} + \lambda_2^{\alpha i} + \lambda_3^{\alpha i} - 3) \quad (1)$$

3.2. Mooney-Rivlin model

The case of Mooney-Rivlin (M-R) is derived as of the polynomial method of the hyperelastic model [30]. They were setting the parameter N =1, e.g. a first ordered polynomial. The M-R model has utilised the linear property of the invariants,

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D_1}(J_{el} - 1) \quad (2)$$

3.3. Neo-Hookean model

The Neo-Hookean model (N-H) is derived from the decreased energy potential of the polynomial strain [30]; Setting up N=1,

$$U = C_{10}(I_1 - 3) + \frac{1}{D_1}(J_{el} - 1)^2 \quad (3)$$

3.4. Arruda-Boyce model

The model of Arruda-Boyce (A-B) has the potential for the energy strain of the form, [30],

$$U = \mu \begin{pmatrix} \frac{1}{2}(I_1 - 3) + \frac{1}{20\lambda_m^2}(I_1^2 - 9) + \\ \frac{11}{1050\lambda_m^4}(I_1^3 - 27) + \\ \frac{19}{7000\lambda_m^6}(I_1^4 - 81) + \\ \frac{519}{673750\lambda_m^8}(I_1^5 - 243) \end{pmatrix} + \frac{1}{D}\left(\frac{J_{el-1}^2}{2} - \ln J_{el}\right) \quad (4)$$

4. Numerical model

A single 3-D size (1*1*1 mm) continuous reduced-integration hybrid C3D8RH part with unit dimensions can be used to evaluate hyperelastic model coefficients [30], as shown boundary conditions in Figure 3(a). Also, a single elementcan be subjected to uniaxial tensile with a 9 mm displacement in the x-direction to obtain predictions that can be directly compared to the experimental data [42-49], used to measure the coefficients – Figure 3(b).

5. Results and discussions

Uniaxial stress testing compares a strength of 80% to a hybrid rubber of 90% and 100% in the Figures 4 to 6. The elastic modulus and the extensions' material strength increase at the break with increased filling concentration for 90% and 100% fillers. Table 1 shows a parameter that is not relevant to a specific model. These were achieved by predicting mechanical properties using uniaxial tensile data carbon black (N330) filler particles with 80%. Its notable, Ogden model can achieve fitting error with 1%, while the rest models predicted parameters with higher fitting errors. The coefficient that applies to a given model is shown in Table 2. It was done with uniaxial tensile data carbon black filling particle 90% for predicting mechanical properties. Ogden's remarkable model can make a 1.7% fitting error, but the rest of the models predicted parameters with fitting errors 2.23%, 27.1% and 28.85%. Table 3 indicates that the coefficient applies to 4 hyperelastic models. It was made of carbon black filling particle with uniaxial tensile data for the prediction of mechanical properties. Again, Ogen's model could make the bets fitting error by 2.04%. Nevertheless, the rest of the models forecast 2.43%, 47.64% and 49.45% of fitting errors.

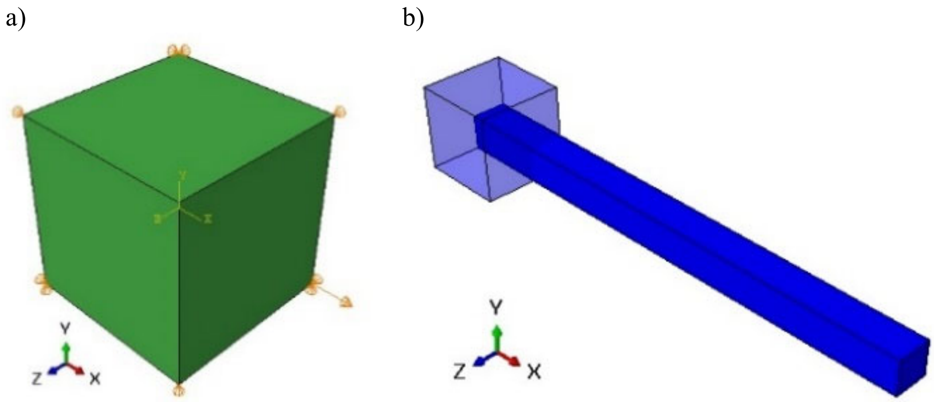


Fig. 3. Single element type C3D8RH, cubic shape: an element with boundary conditions, b unloading and a loading element

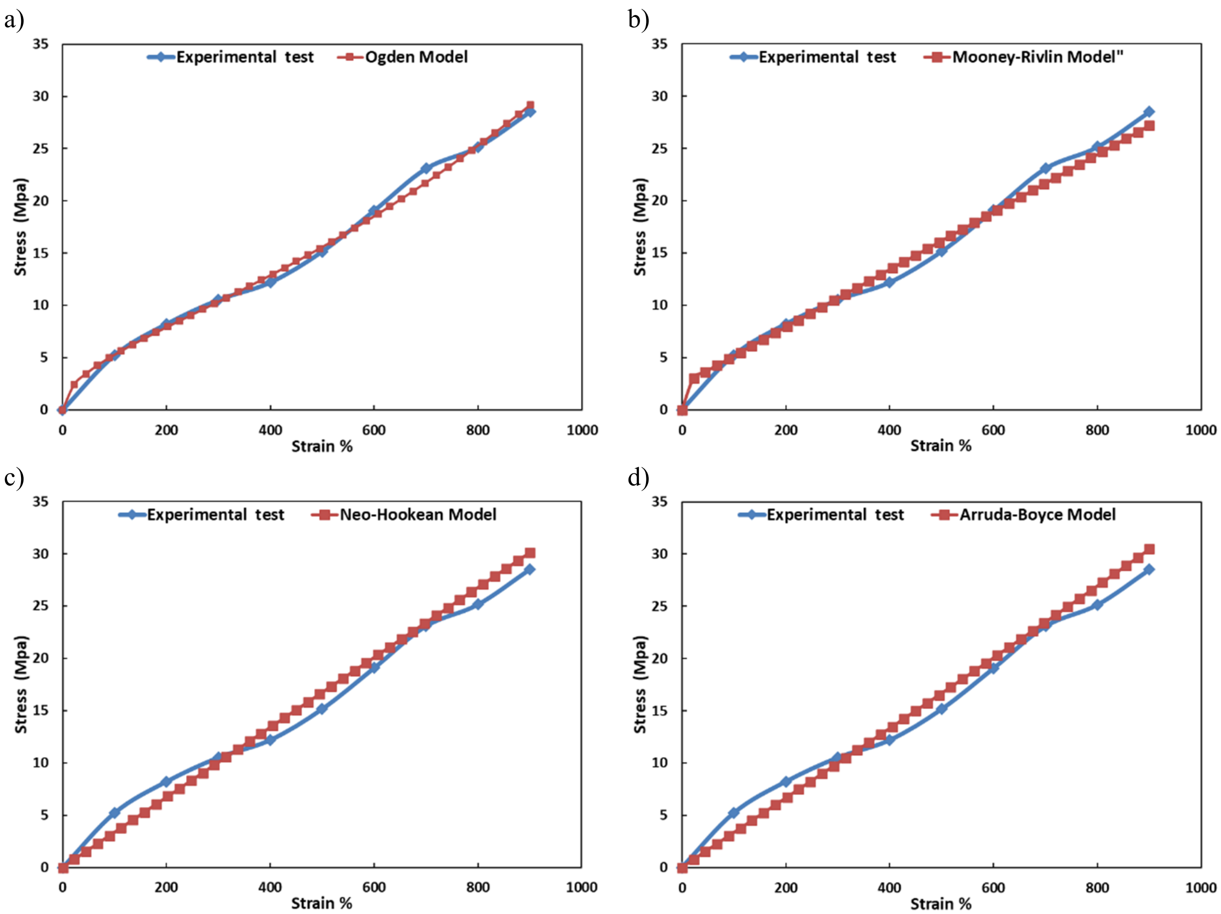


Fig. 4. Stress-Strain curve of 80% carbon black filler pphr with four hyperelastic models: a) Ogden model, b) Mooney-Rivlin model, c) Neo-Hookean model, d) Arruda-Boyce model

Table 1.
Hyperelastic parameters for hyperelastic models, data carbon black (N330) filler particles with 80%

Parameters	D	D1	D2	C10	C01	μ1	α1	μ2	α2	μ	μo	λ	Fitting error %
Model										-	-	-	
Ogden	-	0	0	-	-	1.03×10^{-5}	3.13	0.72	-3	-	-	-	1
Mooney-Rivlin	-	0	-	1.37×10^{-2}	1.17	-	-	-	-	-	-	-	2.3
Neo Hooke	-	0	-	1.67	0	-	-	-	-	-	-	-	19.1
Arruda-Boyce	0	0	-	-	-	-	-	-	-	3.30×10^{-2}	3.30×10^{-2}	2703	19.9

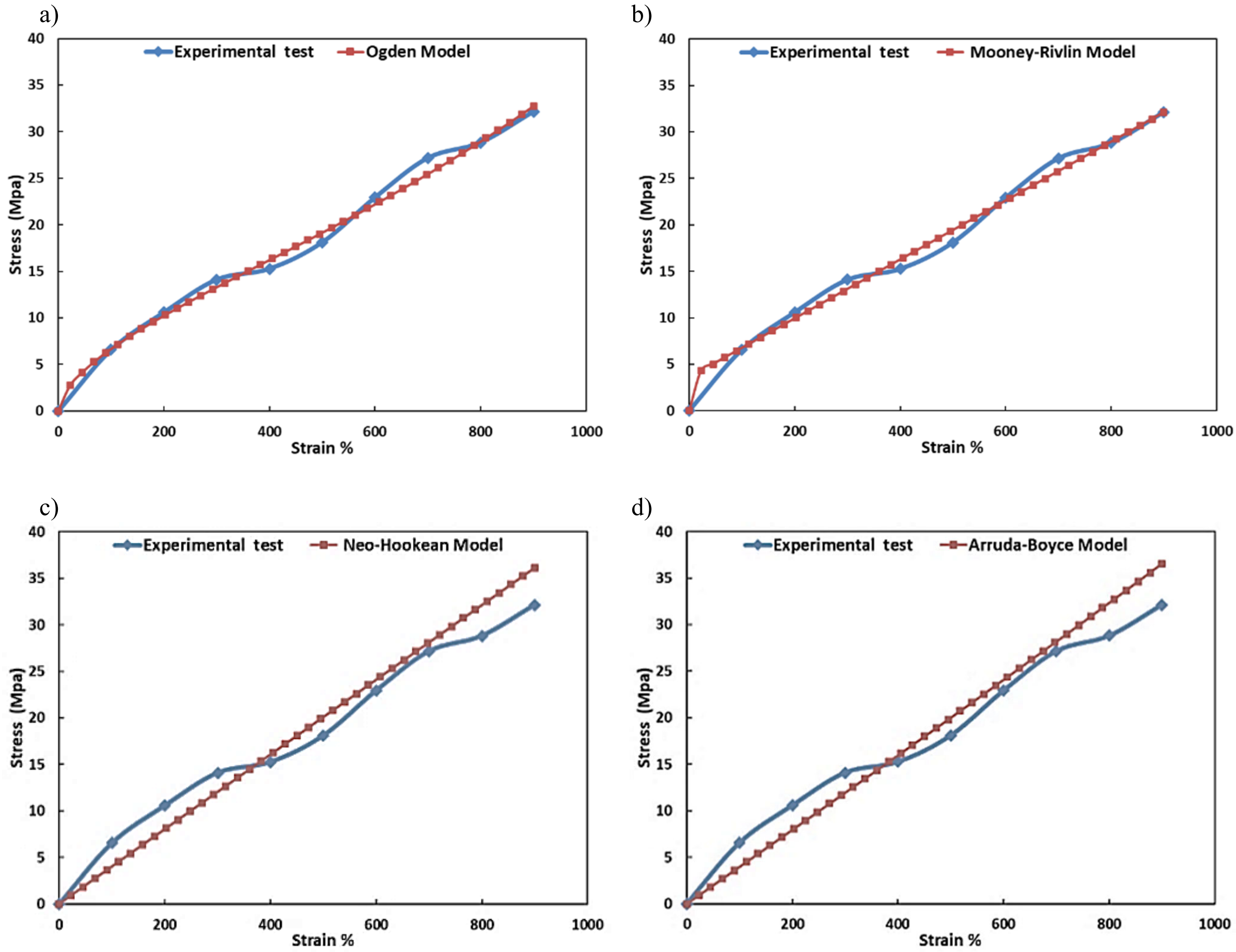


Fig. 5. Stress-Strain curve of 90% carbon black filler pphr: a) Ogden model, b) Mooney-Rivlin model, c) Neo-Hookean model, d) Arruda-Boyce model

Table 2.
Hyperelastic parameters for hyperelastic models, data carbon black filler particles with 90%

Parameters	D	D1	D2	C10	C01	μ1	α1	μ2	α2	μ	μo	λ	Fitting error %
Model										-	-	-	
Ogden	-	0	0	-	-	1.82×10^{-7}	3.66	0.65	-3.21	-	-	-	1.7
Mooney-Rivlin	-	0	-	1.58×10^{-2}	1.78	-	-	-	-	-	-	-	2.23
Neo Hooke	-	0	-	2.00×10^{-2}	0	-	-	-	-	-	-	-	27.12
Arruda-Boyce			-	-	-	-	-	-	-	3.96×10^{-2}	3.96×10^{-2}	2703	28.58

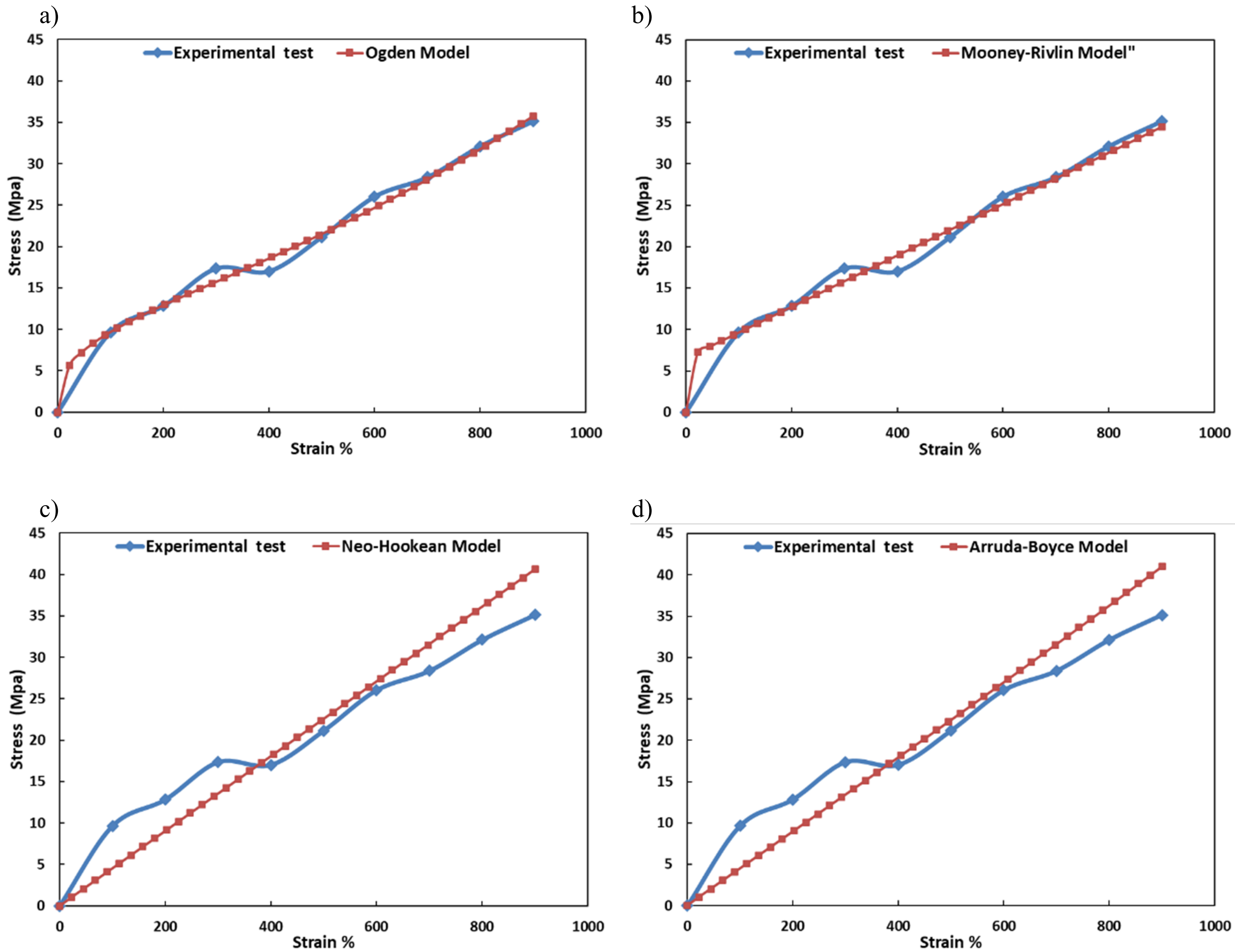


Fig. 6. Stress-Strain curve of 100% carbon black filler pphr: a) Ogden model, b) Mooney-Rivlin model, c) Neo-Hookean model, d) Arruda-Boyce model

Table 3.
Hyperelastic parameters for hyperelastic models, data carbon black filler particles with 100%

Parameters	D	D1	D2	C10	C01	μ1	α1	μ2	α2	μ	μo	λ	Fitting error %
Model										-	-	-	
Ogden	-	0	0	-	-	2.87×10^{-5}	2.99	2.46	-2.71	-	-	-	2.04
Mooney-Rivlin	-	0	-	1.55×10^{-2}	3.25	-	-	-	-	-	-	-	2.43
Neo Hooke	-	0	-	2.25×10^{-2}	0	-	-	-	-	-	-	-	47.64
Arruda-Boyce			-	-	-	-	-	-	-	4.45×10^{-2}	4.45×10^{-2}	2703	49.45

6. Conclusions

The present work demonstrates that carbon black (N330) filler particles with 80% Ogden model can predict mechanical parameters with approximately 1% fitting errors, while other models estimate parameters with high fitting errors. Experimental tensile tests were made with carbon black filling particles 90% for mechanical properties prediction. Ogden's model estimated parameters with 1.7% fitting error, while the other models calculate approximately 2.23%, 27.1% and 28.85% fitting errors parameters. Table 3 present carbon black (N330) filler particles with 100% a 2.04% fitting error in the Ogen model. However, the other hyperelastic models calculated parameters up to 2.43%, 47.64% and 49.45% fitting errors.

A helpful management study guide for measurements can help scientists and engineers, and laboratories with guidelines workers, including quality control workers, on how the machine can be described and quantified. Features for tensile testing must bring out computational development measurements. In this work, four hyperelastic models were used on how Finite Element (F.E.) simulation of linked materials utilises tensile testing. A specific experience with experimental mechanical processes monitoring, tensile testing for hyperelastic material is believed. This research also aims to familiarise the user with the recommended procedures in the future and the variables that may be applied, influencing the designed experiment's outcomes. Validation tests are strongly suggested to be carried out to gain trust in system design, and precise material property predictions demand the correct material properties.

Information on models and detailed material properties for highly extendible materials, such as Rubber, utilising traditional elastic content models tensile loading cannot be accurately modelled. These four hyperelastic models: Ogden's Model, Mooney-Rivlin Model, Neo Hooke Model, Arruda-Boyce Model, are a representation of a model that is applied in FEA packages, such as Abaqus. The hyperelastic material simulation includes data on material properties calculated under distinct stress states, large strains. The strain energy in hyperelasticity is simulated based on the deviator stress (tensile) and strain components. Models coefficients are calculated to use the least square fit from mechanical test results routines in the software for F.E. techniques for finding and presenting the input data required are mentioned in work here. Finally, It is possible to identify the material properties necessary to measure deviatoric coefficients through test data evaluated under plane stress (uniaxial tension) conditions.

Nomenclature

U	Strain energy density
λ_i (i = 1,2,3)	The principal stretches
μ_i	Material constant related to the initial shear modulus
α_i	Empirically calculated material constants
J_{el}	the elastic volume ratio
C10, C01	The material constant
I_1	The first invariant
I_2	The second invariant
c	Material constant
λ	Extensions of the deformation
N	Order of the polynomial
D, D1	Material constant

References

[1] A.N. Gent (ed.), Engineering With Rubber: How to Design Rubber Components, 2nd Edition, Hanser Gardner, 2001.

[2] R.W. Ogden, D.G. Roxburgh, A Pseudo-Elastic Model for the Mullins Effect in Filled Rubber, Proceedings: Mathematical, Physical and Engineering Sciences 455 (1999) 2861-2877.

[3] C. Miehe, J.J. Keck, Superimposed finite elastic–viscoelastic–plastoelastic stress response with damage in filled rubbery polymers. Experiments, modelling and algorithmic implementation, Journal of the Mechanics and Physics of Solids 48/2 (2000) 323-365. DOI: https://doi.org/10.1016/S0022-5096(99)00017-4

[4] J.S. Bergström, M.C. Boyce, Constitutive modeling of the time-dependent and cyclic loading of elastomers and application to soft biological tissues, Mechanics of Materials 33/9 (2001) 523-530. DOI: https://doi.org/10.1016/S0167-6636(01)00070-9

[5] G. Marckmann, E. Verron, L. Gornet, G. Chagnon, P. Charrier, P.J. Fort, A theory of network alteration for the Mullins effect, Journal of the Mechanics and Physics of Solids 50/9 (2002) 2011-2028. DOI: https://doi.org/10.1016/S0022-5096(01)00136-3

[6] A.D. Drozdov, A. Dorfmann, Constitutive Model in Finite Viscoelasticity of Particle-reinforced Rubbers, Meccanica 39 (2004) 245-270. DOI: https://doi.org/10.1023/B:MECC.0000022848.21830.c2

[7] A. Dorfmann, R. Ogden, A constitutive model for the Mullins effect with permanent set in particle-reinforced rubber. International Journal of Solids and Structures 41/7 (2004) 1855-1878.
DOI: https://doi.org/10.1016/j.ijsolstr.2003.11.014

[8] H.G. Kilian, H.F. Enderle, K. Unseld, The use of the van der Waals model to elucidate universal aspects of structure-property relationships in simply extended dry and swollen rubbers, Colloid and Polymer Science 264 (1986) 866-876.
DOI: https://doi.org/10.1007/BF01410637

[9] O.H. Yeoh, P.D. Fleming, A new attempt to reconcile the statistical and phenomenological theories of rubber elasticity, Journal of Polymer Science B 35/12 (1997) 1919-1931. DOI: https://doi.org/10.1002/(SICI)1099-0488(19970915)35:12%3C1919::AID-POLB7%3E3.0.CO;2-K

[10] M.C. Boyce, Direct Comparison of the Gent and the Arruda-Boyce Constitutive Models of Rubber Elasticity, Rubber Chemistry and Technology 69/5 (1996) 781-785.
DOI: https://doi.org/10.5254/1.3538401

[11] G. Chagnon, G. Marckmann, E. Verron, A Comparison of the Hart-Smith Model with Arruda-Boyce and Gent Formulations for Rubber Elasticity, Rubber Chemistry and Technology 77/4 (2004) 724-735. DOI: https://doi.org/10.5254/1.3547847

[12] D.J. Seibert, N. Schöche, Direct Comparison of Some Recent Rubber Elasticity Models, Rubber Chemistry and Technology 73/2 (2000) 366-384. DOI: https://doi.org/10.5254/1.3547597

[13] M.C. Boyce, E.M. Arruda, Constitutive Models of Rubber Elasticity: A Review, Rubber Chemistry and Technology 73/3 (2000) 504-523. DOI: https://doi.org/10.5254/1.3547602

[14] L.R.G. Treloar, Stress-strain data for vulcanised rubber under various types of deformation, Transactions of the Faraday Society 40 (1944) 59-70. DOI: https://doi.org/10.1039/TF9444000059

[15] M.M. Attard, G.W. Hunt, Hyperelastic constitutive modeling under finite strain, International Journal of Solids and Structures 41/18-19 (2004) 5327-5350. DOI: https://doi.org/10.1016/j.ijsolstr.2004.03.016

[16] A.K. Geim, K.S. Novoselov, The rise of graphene, Nature Materials 6 (2007) 183-191. DOI: https://doi.org/10.1038/nmat1849

[17] G. Prusty, S.K. Swain, Dispersion of expanded graphite as nanoplatelets in a copolymer matrix and its effect on thermal stability, electrical conductivity and permeability, New Carbon Materials 27/4 (2012) 271-277. DOI: https://doi.org/10.1016/S1872-5805(12)60017-1

[18] S. Iijima, Helical microtubules of graphitic carbon, Nature 354 (1991) 56-58.
DOI: https://doi.org/10.1038/354056a0

[19] J. Biscoe, B.E. Warren, An X-ray study of carbon black, Journal of Applied Physics 13 (1942) 364-371.
DOI: https://doi.org/10.1063/1.1714879

[20] H.W. Kroto, J.R. Heath, S.C. O'Brien, F.F. Curl, R.E. Smalley, C_{60}: buckminsterfullerene, Nature 318 (1985) 162-163. DOI: https://doi.org/10.1038/318162a0

[21] S. Gantayat, N. Sarkar, G. Prusty, D. Rout, S.K. Swain, Designing of epoxy matrix by chemically modified multiwalled carbon nanotubes, Advances in Polymer Technology 37/1 (2018) 176-184.
DOI: https://doi.org/10.1002/adv.21654

[22] V. Kumar, D.J. Lee, Studies of nanocomposites based on carbon nanomaterials and RTV silicone rubber, Journal of Applied Polymer Science 134/4 (2017) 44407. DOI: https://doi.org/10.1002/app.44407

[23] A.K. Geim, Graphene: status and prospects, Science 324/5934 (2009) 1530-1534.
DOI: https://doi.org/10.1126/science.1158877

[24] Q. Zhang, J.Q. Huang, Y.Z. Qian, Y.Y. Zhang, F. Wei, The road for nanomaterials industry: a review of carbon nanotube production, post-treatment, and bulk applications for composites and energy storage, Nano. Micro. Small 9/8 (2013) 1237-1265. DOI: https://doi.org/10.1002/smll.201203252

[25] S.K. Swain, A.K. Pradhan, H.S. Sahu, Synthesis of gas barrier starch by dispersion of functionalized multiwalled carbon nanotubes, Carbohydrate Polymers 94/1 (2013) 663-668. DOI: https://doi.org/10.1016/j.carbpol.2013.01.056

[26] A.M. Shanmugharaj, J.H. Bae, K.Y. Lee, W.H. Noh, S.H. Lee, S.H. Ryu, Physical and chemical characteristics of multiwalled carbon nanotubes functionalized with aminosilane and its influence on the properties of natural rubber composites, Composites Science and Technology 67/9 (2007) 1813-1822. DOI: https://doi.org/10.1016/j.compscitech.2006.10.021

[27] K. Kueseng, K.I. Jacob, Natural rubber nanocomposites with SiC nanoparticles and carbon nanotubes, European Polymer Journal 42/1 (2006) 220-227. DOI: https://doi.org/10.1016/j.eurpolymj.2005.05.011

[28] M.A. Lopez-Manchado, J. Biagiotti, L. Valentini, J.M. Kenny, Dynamic mechanical and Raman spectroscopy studies on the interaction between single-walled carbon nanotubes and natural rubber, Journal of Applied Polymer Science 92/5 (2004) 3394-3400. DOI: https://doi.org/10.1002/app.20358

[29] S. Joly, G. Gernaud, R. Ollitrault, L. Bokobza, J.E. Mark, Organically modified layered silicates as reinforcing fillers for natural Rubber, Chemistry of Materials 14/10 (2002) 4202-4208. DOI: https://doi.org/10.1021/cm020093e

[30] ABAQUS/Standard User and Theory Manuals, version 5.8, HKS Inc, USA, 1998.

[31] P. Raos, Modelling of elastic behaviour of Rubber and its application in FEA, Plastics, Rubber and Composites Processing and Applications 19/5 (1993) 293-303.

[32] ASTM D412-98a: Standard Test Methods for Vulcanized Rubber and Thermoplastic Rubbers and Thermoplastic Elastomers-Tension, ASTM International, West Conshohocken, PA, 1998.

[33] M.A. Al-Shammari, M. Al-Waily, Theoretical and Numerical Vibration Investigation Study of Orthotropic Hyper Composite Plate Structure, International Journal of Mechanical and Mechatronics Engineering 14/6 (2014) 1-21.

[34] M. Al-Waily, K.K. Resan, A.H. Al-Wazir, Z.A.A. Abud Ali, Influences of Glass and Carbon Powder Reinforcement on the Vibration Response and Characterization of an Isotropic Hyper Composite Materials Plate Structure, International Journal of Mechanical and Mechatronics Engineering 17/6 (2017) 74-85.

[35] M.A. Al-Shammari, M. Al-Waily, Analytical Investigation of Buckling Behavior of Honeycombs Sandwich Combined Plate Structure, International Journal of Mechanical and Production Engineering Research and Development 8/4 (2018) 771-786.

[36] E.N. Abbas, M.J. Jweeg, M. Al-Waily, Analytical and Numerical Investigations for Dynamic Response of Composite Plates Under Various Dynamic Loading with the Influence of Carbon Multi-Wall Tube Nano Materials, International Journal of Mechanical and Mechatronics Engineering 18/6 (2018) 1-10.

[37] H.J. Abbas, M.J. Jweeg, M. Al-Waily, A.A. Diwan, Experimental Testing and Theoretical Prediction of Fiber Optical Cable for Fault Detection and Identification, Journal of Engineering and Applied Sciences 14/2 (2019) 430-438. DOI: http://dx.doi.org/10.36478/jeasci.2019.430.438

[38] E.A. Abbod, M. Al-Waily, Z.M.R. Al-Hadrayi, K.K. Resan, S.M. Abbas, Numerical and Experimental Analysis to Predict Life of Removable Partial Denture, IOP Conference Series: Materials Science and Engineering 870 (2020) 012149. DOI: https://doi.org/10.1088/1757-899X/870/1/012149

[39] E.N. Abbas, M. Al-Waily, T.M. Hammza, M.J. Jweeg, An Investigation to the Effects of Impact Strength on Laminated Notched Composites used in Prosthetic Sockets Manufacturing, IOP Conference Series: Materials Science and Engineering 928 (2020) 022081. DOI: https://doi.org/10.1088/1757-899X/928/2/022081

[40] J.M. Allport, A.J. Day, Statistical mechanics material model for the constitutive modelling of elastomeric compounds, Proceedings of the Institution of Mechanical Engineers C 210/6 (1996) 575-585. DOI: https://doi.org/10.1243%2FPIME_PROC_1996_210_232_02

[41] Q.H. Jebur, P. Harrison, Z.Y. Guo, G. Schubert, V. Navez, Characterisation and modelling of a melt-extruded LDPE closed-cell foam, Applied Mechanics and Materials 70 (2011) 105-110. DOI: https://doi.org/10.4028/www.scientific.net/AMM.70.105

[42] M.J. Jweeg, M. Al-Waily, A.A. Deli, Theoretical and Numerical Investigation of Buckling of Orthotropic Hyper Composite Plates, International Journal of Mechanical and Mechatronics Engineering 15/4 (2015) 1-12.

[43] A.A. Kadhim, M. Al-Waily, Z.A.A. Abud Ali, M.J. Jweeg, K.K. Resan, Improvement Fatigue Life and

Strength of Isotropic Hyper Composite Materials by Reinforcement with Different Powder Materials, International Journal of Mechanical and Mechatronics Engineering 18/2 (2018) 77-86.
[44] J.S. Chiad, M. Al-Waily, M.A. Al-Shammari, Buckling Investigation of Isotropic Composite Plate Reinforced by Different Types of Powders, International Journal of Mechanical Engineering and Technology 9/9 (2018) 305-317.
[45] M.M. Abdulridha, N.D. Fahad, M. Al-Waily, K.K. Resan, Rubber Creep Behavior Investigation with Multi Wall Tube Carbon Nano Particle Material Effect, International Journal of Mechanical Engineering and Technology 9/12 (2018) 729-746.
[46] M. Al-Waily, M.A. Al-Shammari, M.J. Jweeg, An Analytical Investigation of Thermal Buckling Behavior of Composite Plates Reinforced by Carbon Nano Particles, Engineering Journal 24/3 (2020) 11-21. DOI: https://doi.org/10.4186/ej.2020.24.3.11
[47] E.N. Abbas, M.J. Jweeg, M. Al-Waily, Fatigue Characterization of Laminated Composites used in Prosthetic Sockets Manufacturing, Journal of Mechanical Engineering Research and Developments 43/5 (2020) 384-399.
[48] E.K. Njim, M. Al-Waily, S.H. Bakhy, A Review of the Recent Research on the Experimental Tests of Functionally Graded Sandwich Panels, Journal of Mechanical Engineering Research and Developments 44/3 (2021) 420-441.
[49] Q.H. Jebur, M.J. Jweeg, M. Al-Waily, Ogden model for characterising and simulation of PPHR Rubber under different strain rates, Australian Journal of Mechanical Engineering (2021) (published online).