Journal of Engineering Science and Technology
8th EURECA 2017 Special Issue August (2018) 92 - 103

NUMERICAL INVESTIGATION ON TWO-WHEELER BIAS TYRE IMPACT USING VARIOUS MATERIAL MODELS

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Abstract

This project was aimed to simulate two-wheel bias-ply tyre with ANSYS software for inflation pressure. The simulation will first be conducted by considering the tyre as a single body part, and followed by conducting the simulation with tyre layers components model with specific material properties. In current research, the simulations conducted are majority considering the bias-ply tyre as an entire single body part only. The results obtained are not as accurate as compared to measurement data. It was noticed that the inaccuracy of results is due to the inconsideration of tyre by components layer with specific material properties. Therefore, a new approach to carry out the simulation layer by layer was introduced in this project. Hyperelastic material model was chosen as the simulation model throughout the project. Mooney-Rivlin, Yeoh, Ogden, Neo-Hookean and Arruda-Boyce model are the five common hyperelastic material model. In this project, the simulation will be carried out based on Mooney-Rivlin with five parameters, Yeoh 3rd order and Neo-Hookean model only. After all, the results obtained were compared and validate with measurement data. The new approach by simulating the tyre layer by layer was the major challenges throughout the project due to the specific properties and parameters. In this case, results for layers simulation possessed higher accuracy as compared to single body simulation. Mooney-Rivlin with five parameters model was the most suitable material model, as it had higher number of parameters used. Further simulation analysis was suggested to carry on footprint test to double verify on the accuracy of models and results.

Keywords: ANSYS, Inflation pressure, Hyperelastic material model, two-wheeler bias-ply tyre,

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1. Introduction

A report on Malaysia vehicle fatalities shows that motorcyclist possesses the highest number of fatalities and was predicted to increase in future years. Among the number of fatalities, up to 8 % of it were caused by vehicles factors. If these vehicles factors could be prevented beforehand, it is believed to have a good effect on reducing the number of fatalities for motorcyclist [1].

On any type of vehicle, tyres are always the main parts contacts between vehicle body and the ground. Hence, it is extremely important to ensure the performances of tyre are always in good condition. In this project, model of 80/90-17 bias-ply two-wheeler tyre was chosen to examine the effect of inflation pressure towards a tyre. Often, finite element analysis simulation was the ideal approach to identify certain performances [2]. However, it is necessary to determine the best method of simulation for each model. Therefore, this project was aimed to identify the most suitable finite element analysis method for a two-wheeler bias-ply tyre.

In this project, two different type of methodology were introduced. Majority of finite element analysis simulation towards a two-wheeler bias ply tyre was conducted by just considering the tyre as a single layer model [3]. Despite, tyre is actually manufactured with five different layers components with unique material behaviour [4]. Ignore of each tyre layers components was believed to have affected the accuracy of current simulation results found in the market [5]. First proposal in this project was to conduct finite element analysis simulation just as the majority, which was considering the tyre model as single body layer. Secondly, new method was presented by modelling the tyre layer by layer as according to two-wheeler bias-ply geometry.

It is well aware that majority of tyre was made from rubber material. Material model used for any simulation model must then be fitted to rubber behaviour in any circumstances [6]. Hyperelastic material model was the most well-known material model that regularly utilized for any rubber-like material simulation [7]. There were several choices for the hyperelastic material model, which includes Mooney-Rivlin, Yeoh, Odgen, Arruda-Boyce, and Neo-Hookean [8]. Three material models that possessed low, medium and high strain range were chosen in this project, which were Neo-Hookean, Yeoh 3rd order, and Mooney-Rivlin with five parameters.

Components of bias-ply tyre includes tread, tread base, cord-ply, and inner liner. Tread was found to be the thickest layers among these components [9]. It was presumed that tread will be the most affected layers for a tyre performances. Since only a single layer was considered in the first approach, tread layer material was assigned as the material in this particular simulation. As for multi-layer approach, each particular material was assigned to each layer respectively. Materials constants of each layer were obtained suing curve-fitting method [10]. However, details of materials constants were not presented in this paper due to confidential information.

Numerous finite element analysis simulations were carried out in this project. Two approaches with distinct simulation model were conducted and five sets of internal pressure were tested on each model. Furthermore, each model with different internal pressure applied was tested using three different material models. The five internal pressure utilized in this project were 0.19 MPa, 0.21 MPa, 0.23 MPa, 0.25 MPa, and 0.27 MPa [3].

At the end of research, it was proved that multi-layer tyre model provided higher accuracy than single layer tyre model as predicted. Yeoh 3rd order was sufficient to provide the accurate results in this project as low pressure applied was simulated. Mooney-Rivlin, the higher order material model is recommended if higher applied pressure is simulated. Lastly, Neo-Hookean was able to provide fast prediction results if multi-layer tyre model was simulated. Yeoh material model was suggested if precise circumference results are requested in a multi-layer tyre model simulation.

2. Methods

In this section the model used for both single and multi-layer tyre simulation will be introduced. Next, the material parameters based on chosen model will be briefly discussed and meshing method will then be presented. Lastly, boundary conditions were discussed in details for the simulation of tyre inflation.

2.1. Tyre model

By utilizing the symmetrical geometry of a tyre, the model in simulation was simplified to the two-dimensional cross sectional area of tyre. Two different approaches were used for the simulation: by considering the tyre as a whole part and by considering the individual layer which make up the tyre.

2.1.1. Single-layer tyre model

A single-layered, two-dimensional tyre model was generated for single-layer tyre simulation. It was drawn according to the geometry of a cross-sectional for 80/90-17 bias two-wheeler tyre. Dimension of the outer most shell of the tyre was fully utilized for the drawing of whole-tyre simulation model. The stress-strain relationship of the tyre was assumed to be controlled mainly by the thickest layer of the tyre. Detail discussion will be given in the following section. Figure 1 shows the details of model for whole-tyre simulation.

Fig. 1. Single-layer tyre model based on 80/90-17 bias-ply tyre.

2.1.2. Multi-layer tyre model

The actual tyre is made up from the combination of multiple layers, which includes tread, tread base, two cord-ply layers and inner liner. Each layer of the tyre has different material properties. In order to achieve better accuracy of simulation result, a two-dimensional model based on the actual dimension of each layer was generated as shown in Fig. 2. From Fig. 2, it was obvious that tread occupies the thickest layer. Therefore, it was assumed that in the case of single layer tyre the material properties of the tyre was based on the material properties of tread.

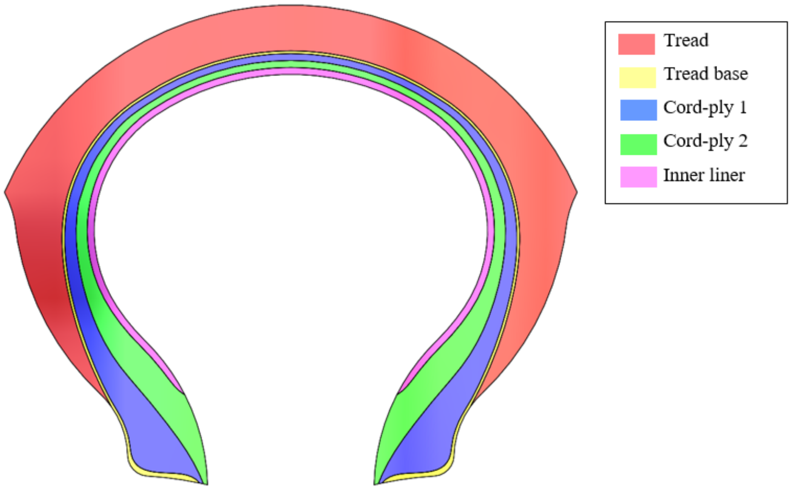

Fig. 2. Multi-layer tyre model.

2.2. Material parameters

The tyre is made up of rubber compound, which is a hyperelastic material. Stress-strain response of a hyperelastic material can be described using various hyperelastic material model by considering rubber compound to be incompressible and isotropy. Three hyperelastic material models were selected in this study, which include Neo-Hookean, Yeoh and Mooney-Rivlin. The strain energy density and material parameters of each model are shown in Table 1.

Table 1. Summary of strain energy density and material parameters for each model.

Model	Strain energy density	Material parameters
Neo-Hookean	$W = C_{10}(I_1 - 3)$	C_{10}
Yeoh	$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$	C_{10}, C_{20}, C_{30}
Mooney Rivlin	$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2 - 3)^2$	C_{10}, C_{01}, C_{20}, C_{11}, C_{02}

The material parameters were obtained using curve fitting feature in ANSYS based on uniaxial tensile testing data of each layer.

As mentioned in previous section, cross sectional model of the tyre shows that the thickest layer found in a tyre was the tread layer. Material parameters of tread layer was therefore taken into consideration for single-layer tyre model, as it was assumed to be the most affected layer towards the results due to its thickest layer dimension in bias-ply tyre. In multi-layer model, there were a total of five layers with their corresponding material parameters. For each layer, the particular material parameters were assigned to it. The simulation was repeated for three different models and the results were compared to measurement data.

2.3. Mesh convergence study

In order to verify the accuracy of the obtained results, a mesh convergence study was necessary to determine the most suitable mesh size for both simulation methods. Initially, simulation with the default meshing done by ANSYS was conducted to obtain the result as the comparison value, as it possesses the coarsest sizing. Then, simulation with finer mesh size was repeated and the percentage difference between results of each mesh size was calculated. The most suitable mesh size was determined when the simulation result approaches stable level.

2.4. Boundary conditions

To simulate the inflation process, pressure was applied normal to the inner surface of the tyre. It represented the inflation pressure of a bias-ply tyre in real situation. Then, fixed support was secured on the edge where tyre was attached to the rim. Details of boundary conditions for both models were presented in Fig. 3.

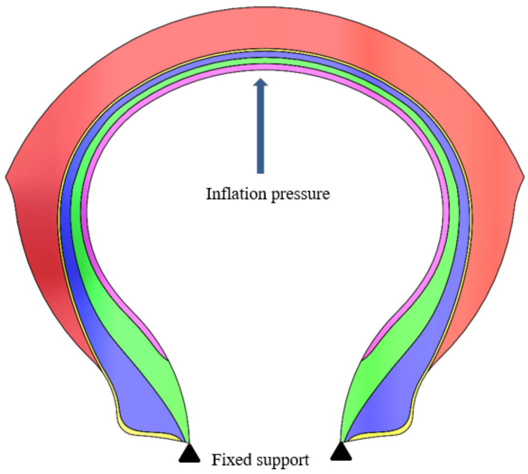

Fig. 3. Boundary conditions applied on both tyre models.

3. Results and Discussions

In this section, the mesh size determined from mesh convergence study was presented. Directional deformation in Y-axis was extracted in this study to determine the circumference of the tyre under different inflation pressure. Results obtained for both models were then compared with actual measurement data.

3.1. Mesh method and mesh size

The single-layer tyre model was meshed using hex dominant and prism shape elements as shown in Fig. 4. Both models in this study were meshed using the same meshing element.

Fig. 4. Meshed element of model.

The model was discretized using different element size starting with default mesh size. Simulations using finer mesh size were repeated and the results obtained were plotted as Fig. 5. The number of element increases as finer element size was used. As shown in Fig. 5, the results stabilize when the number of elements exceeded 10000. Therefore, mesh size of the model was selected based on the results from convergence study. Similar mesh size was used for both models.

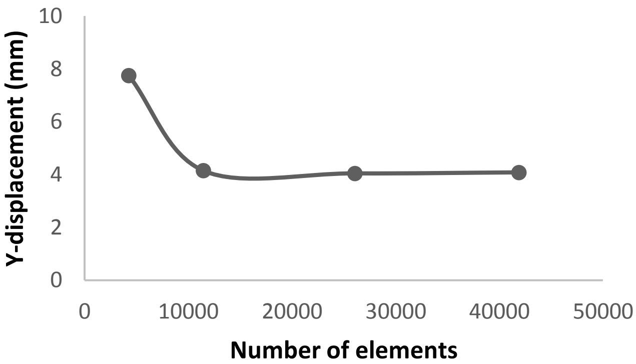

Fig. 5. Convergence study for mesh discretization.

3.2. Determination of material parameters

The material parameters for different models were curve-fitted using the data from uniaxial tensile testing for each layer. Using the obtained material parameters, the stress strain response from uniaxial tensile testing for tread and the prediction from various models were plotted in Fig. 6. For fitting purpose, the engineering strain was converted to stretch following Equation (1),

$$\lambda = \varepsilon + 1 \quad (1)$$

where λ=stretch and ε=engineering strain.

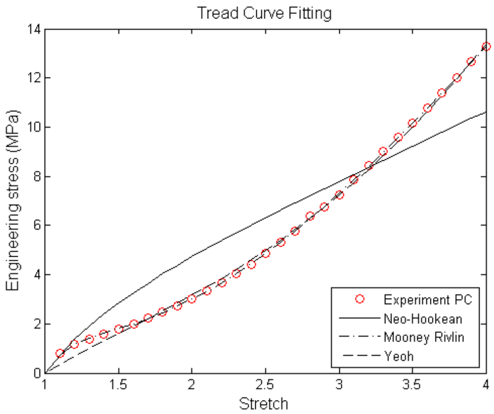

Fig. 6. Comparison of stress-strain response from uniaxial tensile testing and prediction from material models.

From Fig. 6, it was obvious that the prediction from Neo-Hookean model shows large deviation from the experimental data. The result was expected since Neo-Hookean is the simplest material models for hyperelastic material and it is only accurate at low strain. As for both Yeoh and Mooney Rivlin models, both give very good prediction as compared to the experimental data. Thus, it was estimated that the simulation results using these two models will be more accurate. Similar procedures were repeated for other layers and similar trend was observed. The curve fitting for other layers were provided in *Appendix A*.

3.3. Inflation results for single-layer tyre model

Figure 7 shows the example of tyre before and after deformation, where wireframe represents the undeformed model and the coloured regions represent the deformed model when 0.19 MPa pressure applied and simulated with Neo-Hookean material model. Maximum deformation is found at the peak of the tyre. Total deformation of the tyre is acquired from the simulation in the unit of millimeter because the deformation was found to be reasonably small.

The inflation results for single-layer tyre model under different pressures were plotted in Fig. 8. From the figure, it is observed that Neo-Hookean possessed the lowest accuracy among the simulation model followed by Mooney-Rivlin. It was noticed that Yeoh provided the highest accuracy results as validated with measurement data. This phenomenon can be explained as Neo-Hookean was the lowest order of material model utilized in this project. Result of Neo-Hookean in this simulation model was well expected beforehand.

On the contrary, results for Yeoh and Mooney-Rivlin were closer to measurement data. However, Yeoh was more accurate than Mooney-Rivlin as it possessed a smaller error gap. It was unexpected as Mooney-Rivlin had higher order than Yeoh material model used in this project. Nevertheless, it was noticed that the error gaps between all simulation results and the measurement data increases as the pressure applied increases. Hence, it was believed larger the pressure applied, the more inaccurate the results were. It was therefore suggested to utilize a higher order hyperelastic material model, such as Mooney-Rivlin nine parameters, if higher pressure is to be applied.

Based on the results, Yeoh nearly intersected with the measurement circumference for pressure applied at 0.19 MPa. Differences of displacement between Yeoh and measurement data for applied pressure at 0.21 MPa was noticed to be insignificant as well. It again proved that Yeoh 3rd order was sufficient to be used if applied pressure with maximum of 0.21 MPa is apply in a single layer tyre model simulation.

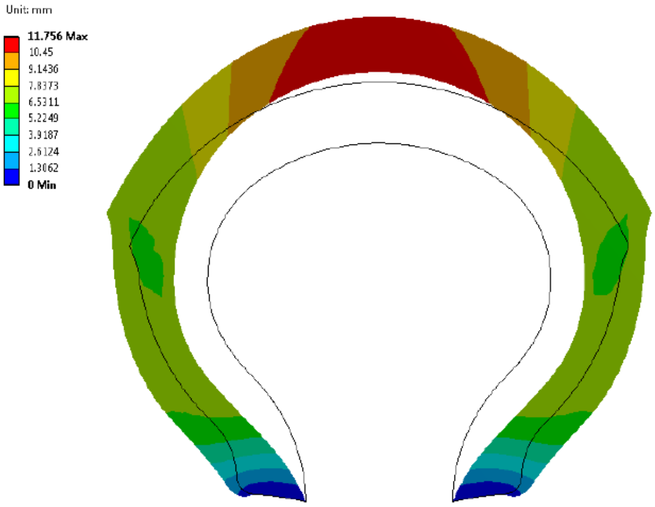

Fig. 7. Tyre model before and after deformation.

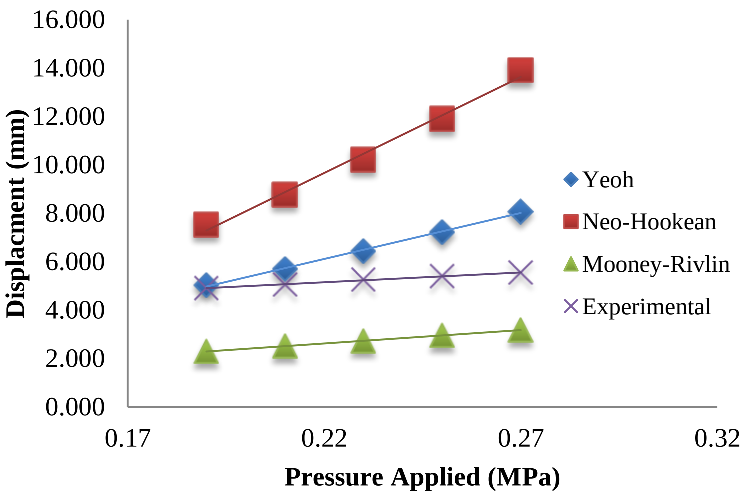

Fig. 8. Comparison of displacement with various material models for single layer tyre model.

3.4. Inflation results for multi-layer tyre model

Simulation results obtained from multi-layer tyre model were given in Fig. 9. As contrary to single-layer results, it was noticed that Mooney-Rivlin was the most inaccurate results in this simulation. Yeoh and Neo-Hookean, on the other hand, had provided almost similar outcomes regardless the difference of order for both material models. However, it was noticed that circumferences difference between all the three material models and measurement were at most 1 mm only. It proved that multi-layer model simulation did provide a better prediction as compared to single layer model.

Even though results obtained from Yeoh and Neo-Hookean material model were almost similar, Yeoh provided lesser error gaps. Yeoh in this case still was the material model that provided the highest accuracy of results. Error gap in between Yeoh and Neo-Hookean results were actually small enough to be negligible as seen from the graph. Hence, in another case, it can be concluded that Neo-Hookean was sufficient to provide an accurate result if simulation was conducted using multi-layer tyre model.

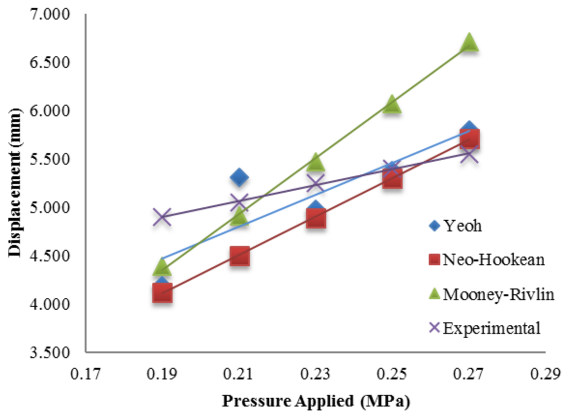

Fig. 9. Comparison of displacement with various material models for multi-layer tyre model.

3.5. Error analysis

Error analysis is necessary to provide a better insight to the analysis of simulation results. The error analysis for all cases were depicted in Fig. 10. The error was calculated using Eq. (2),

$$\text{Error Percentage} = \frac{|\text{Simulation result} - \text{Measurement data}|}{\text{Measurement data}} \times 100\% \qquad (2)$$

Based on Fig. 10, it was noticed that Neo-Hookean for single layer tyre model possessed the highest percentage difference among all simulations. Comparing Yeoh and Mooney-Rivlin for single layer model simulation, error percentage for Yeoh material model increases as pressure applied increases, whereas Mooney-Rivlin provided a more stabilized data. It was then can be said that even though Yeoh material model was able to obtain higher accuracy results if circumference data was compare, Mooney-Rivlin on the other hand provided a more consistent outcome. This phenomenon is possibly due to the higher order material model for Mooney-Rivlin than

Yeoh used in this project. Therefore, it is recommended that simulation with higher applied pressure should utilized Mooney-Rivlin instead of Yeoh.

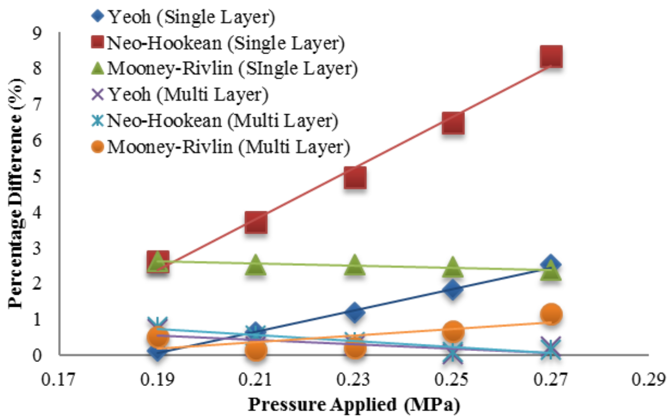

Fig. 10. Comparison of error percentage with various material models for both tyre models.

Despite the outlier noticed in Yeoh data for multi-layer tyre model, the percentage difference for Yeoh and Neo-Hookean in multi layer tyre model was almost 90% alike. In addition, both the material models have a decrement error percentage as higher pressure applied. In contrast, Mooney-Rivlin material model had an inconsistent error percentage. Neo-Hookean, hence, is suggested if the tyre model was formed layer by layer as only one material parameter is needed in this particular material model and easier to be conducted.

Moreover, it was noted that error percentage of all material models for multi-layer tyre model simulation was hardly 1%. In summarize, it is sufficient to conclude that any material model was able reliable results if tyre model was simulated with multi-layer model approach. Overall, the proved that multi-layer tyre model provided most trustworthy results as compared to single layer tyre model. Neo-Hookean material model is recommended if only quick prediction is required, whereas Yeoh material model is suggested if more precise results are needed.

4. Conclusions

Multi-layer tyre model simulation provided higher accuracy than single layer tyre model simulation. As for single layer tyre model, Neo-Hookean possesses the least accuracy material model as it is only accurate for low strain prediction. Yeoh material model provides closer results to measurement data, however, it has an increament of error percentage as pressure applied increases. Mooney-Rivlin material model in single layer model was not as accurate as Yeoh model, yet it possesses a more consistent error percentage. In conclusion, Yeoh material model is sufficient to provide reliable outcome if pressure apply is low, where Mooney-Rivlin is recommended if simulation is conducting with higher applied pressure.

For case in multi-layer tyre model, Neo-Hookean and Yeoh material model provided almost similar results. However, Yeoh is recommended if precise outcomes are needed, where Neo-Hookean is suggested if only fast prediction results are requested. In fact, all material models in multi-layer tyre model have only at most 1% of error percentage. Overall, simulation of multi-layer tyre model provided higher accuracy results as compared to single layer tyre model.

Nomenclatures

C_{01}	Material parameter
C_{02}	Material parameter
C_{10}	Material parameter
C_{20}	Material parameter
C_{30}	Material parameter
I_1	First deviatoric strain invariants of the stress tensor
I_2	Second deviatoric strain invariants of the stress tensor
W	Strain energy density

Greek Symbols

ε	Engineering strain
λ	Stretch

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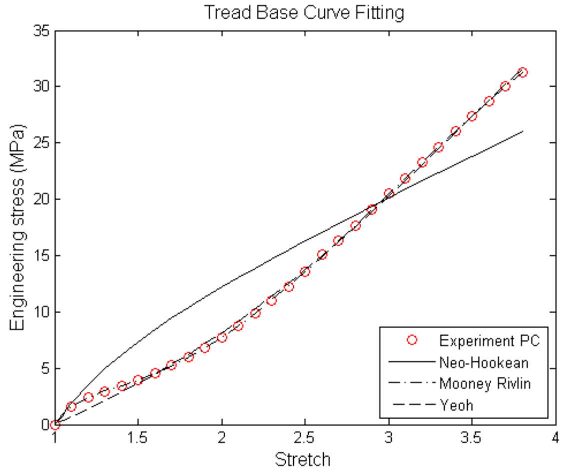
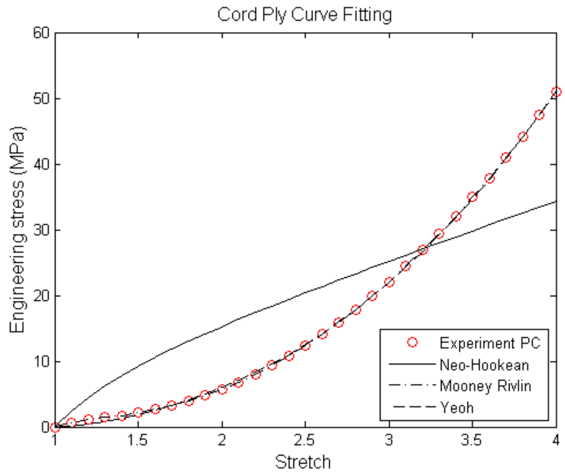
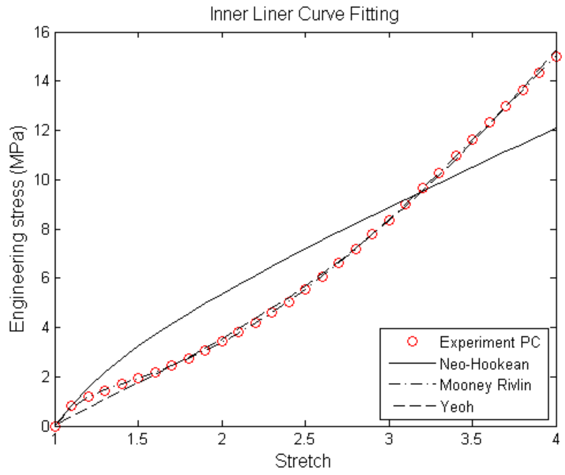
Appendix A


Tread Base Curve Fitting
Engineering stress (MPa)
Stretch
Experiment PC
Neo-Hookean
Mooney Rivlin
Yeoh


Cord Ply Curve Fitting
Engineering stress (MPa)
Stretch
Experiment PC
Neo-Hookean
Mooney Rivlin
Yeoh


Inner Liner Curve Fitting
Engineering stress (MPa)
Stretch
Experiment PC
Neo-Hookean
Mooney Rivlin
Yeoh