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Finite element stress and strain analysis of a solid tyre

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Analysis and modelling

ABSTRACT

Purpose: In this work, a finite element model of a solid tyre was constructed to simulate the loading condition. The solid tyre being modeled constitutes of three rubber layers with different properties and steel wires. Only hyperelastic property is considerd for the rubbers. The validation of FE prediction against experimental results was undertaken. An example of how arrangement of rubber layers in solid tyre can affect the distribution of strain energy density and deflection under loading was also carried out using FE analysis

Design/methodology/approach: A finite element model of a solid tyre was constructed to simulate the static compressive loading condition. The solid tyre being modeled constitutes of three types of rubber of components and steel wires

Findings: The 3D FE model for static loading analysis of solid tyre constructed in this study can give reasonably good prediction of load-deflection behaviour of a real solid tyre. It can also be deduced that the distributions of analysis parameters such as strain energy density and Von Mises stress given by the FE analysis are acceptable and can be used to improve the design of solid tyres. The tyre made entirely with the rubber of the same hyperelastic property as the tread layer can give more flexible deformation and thus more comfortable ride with lesser risk to damage due to heat generation.

Practical implications: Finite element analysis, as has been demonstrated, can be used to predict the performance of the solid tyre when such variations are made. The results from finite element anaysis can be used to determine the optimum thickness of each layer for green tyre (unvulcatised tyre) building

Originality/value: In the solid tyre manufacturing point of view, improving the load bearing performance by changing thickness of each solid tyre layer or make a variation in layers arrangement is the least problematic and can be done effectively without changing the mould or rubber compounds.

Keywords: Design; Solid tyre; Finite element analysis

1. Introduction

Solid tyre is one of the important engineering parts used widely in heavy industry. Forklift trucks used for handling heavy materials and goods often use solid tyres. Solid tyres mostly consists of layers of the various rubber compounds of varying thickness to form a composite structure. Steel rings are also used as reinforcing components in solid tyres. Solid tyres usually face the major problems of failure due to heat build up and riding comfort. In order to improve design of solid tyres, it is necessary to be able to predict the mechanical behaviour of the tyre under applied load. Also stress-strain and strain energy density distribution developed should be analysed. This can lead to the identification of locations at risk to damages and also results in a guidance for components and compound formulations optimisation.

Finite element analysis (FEA) is a powerful and economical method that has been used widely for engineering design purpose. There are some previous work by others FEA of solid tyres, for example [2]. In this work, a finite element model of a solid tyre was constructed to simulate the loading condition. The solid tyre being modeled constitutes of three rubber layers with different properties and steel wires. Only hyperelastic property is considerd for the rubbers. The validation of FE prediction against experimental results was undertaken. An example of how arrangement of rubber layers in solid tyre can affect the distribution of strain energy density and deflection under loading was also carried out using FE analysis.

2. Finite element analysis of a solid tyre

A 3-D finite element model was constructed using ABAQUS finite element package to simulate the static load bearing conditions and to study the load-deflection characteristic. In the present study, a tyre model has an outer diameter of 518 mm, 218 mm inner diameter and a tyre width of 144 mm. For reason of symmetry and economy in the numerical calculations, only one quarter of the tyre model was constructed. The FE model comprising of a solid tyre and a rigid floor is shown geometrically in Figure 1. In the present study, the tread geometry is not included and the floor is assumed frictionless. The tyre under analysis is held rigidly at the points of contacts to the rim and the rigid floor is pushed upward against the tyre with a force representing one quarter of a load which the tyre must be borne in service. The solid tyre model is constructed of three solid rubber layers; namely base layer, middle layer and external layer and reinforcing steel rings as shown in Figure 2. Each rubber layer has different hardness and mechanical properties. The base layer is the hardest layer for good grip contact to the rim. The middle layer is the softest layer to increase flexibility of the tyre.

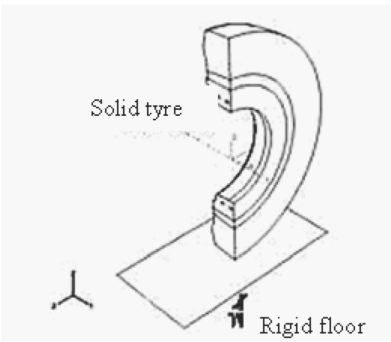

Fig. 1. FE model comprising of a solid tyre (1/4 of real geometry) and a rigid floor

The rubber materials were modeled as hyperelastic materials characterised by the Polynomial (N=2) strain energy function. The strain energy function constants for each material were found using uniaxial tensile test data, biaxial test data and pure shear test data. The last two tests data were generated from uniaxial data using the method of "Constant true Young's Modulus with varying Poisson's ratio" devised by Turner and Brennen (1990).

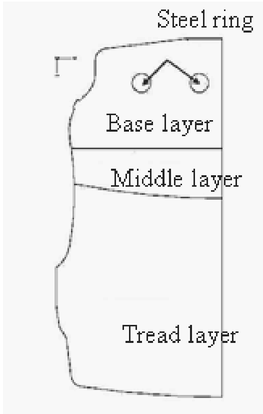

Fig. 2. Components in the solid tyre model

The eight nodes brick C3D8RH elements were used for modeling rubber layers and C3D8R elements were used for steel rings and rigid element was used for the rigid floor. The 3D finite element model of the solid tyre was generated by revolving the axisymmetric model as in Figure 3 about its axis of revolution [4] and the 3D model obtained from the revolution is shown in Figure 4. The part of tyre that contain the anticipated contact region and its vicinity are discretised by a finer mesh than the remaining part.

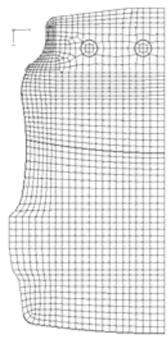

Fig. 3. 2D axisymmetric FE model of the solid tyre

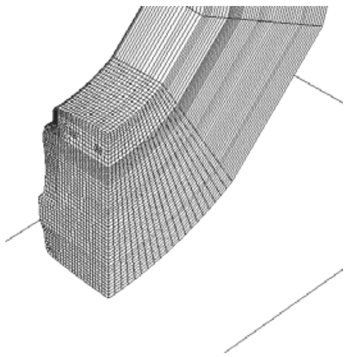

Fig. 4. Revolved 3D FE model of the solid tyre

Load-deflection validation

The load-deflection experiment was performed at the testing laboratory of Mouldmate Co. Ltd. to verify the FE simulation result. In the experiment, the tyre with the same geometry as described in the FE model was fitted to a wheel and pressed against a rigid plate using a hydraulic arm. The pressing load was increased from zero to 25%, 50% , 75% and 100% of the full load used was 14 kN. The loading conditions used were the same as in the FE simulation. The deflection in the loading direction of the wheel center and the displacement in the lateral direction of at a point in the part of the greatest width near to the contact area were measured by means of dial gauges. The arrangement of the dial gauges is shown in Figure 5.

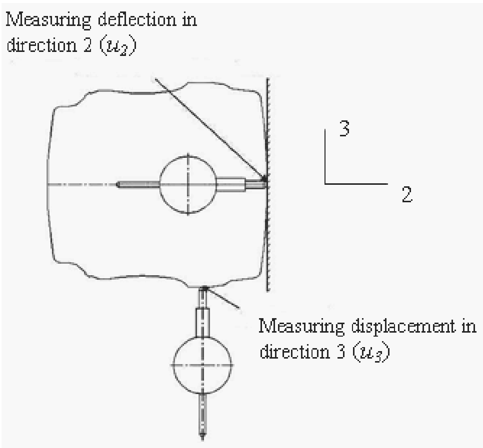

Fig. 5. Arrangement of dial gauges of measuing deflections

The load-deflection results obtained experimentally are compared with the FE simulations as shown in Figure 6. It could be drawn from the figure that the experiment and simulation results are in good agreement with acceptable discrepancy. Thus It can be said that the finite element model constructed can give trustworthy analysis and can be used for further design analysis.

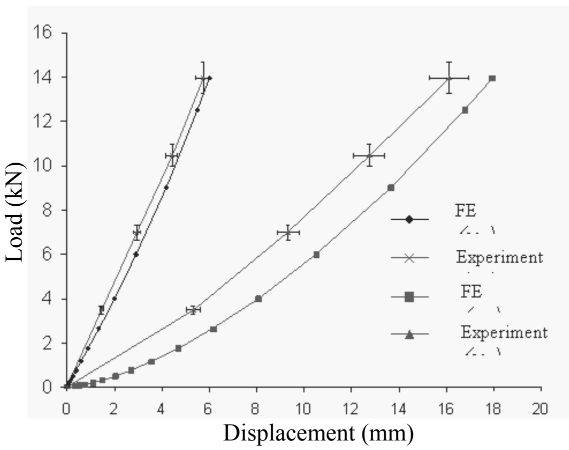

Fig. 6. Comparison of the load-deflection results obtained from the experiments and the FE simulations

Distribution of strain energy density and stress

The distribution of strain energy density and Von Mises stress over the half tire cross section obtained from FE analysis were examined. These parameters are generally important in mechanical design stage. The distribution of strain energy density shown in Figure 7 indicates that strain energy density is concentrated in the middle region of the tread layer which is undergoing large deformation. This region of high strain energy density is the same as "hot region" where temperature rises extensively leading to heat blow out failure during endurance tests (Moldmate Co. Ltd., Priveate communication). Thus area of high strain energy density can be related to the area with high heat generation. To reduce the risk of failure due to heat build up, the strain energy density should be kept minimum. Figure 8 shows that regions of high Von Mises Stress is in the middle region of the tread layer and also apparently in the shoulder area of the base layer. This indicates high distortional stress in this area which could affect the gripping contact to the rim.

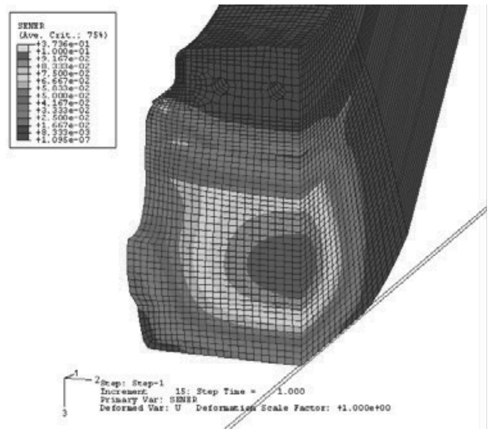

Fig. 7. Distribution of strain energy density obtained from FEA

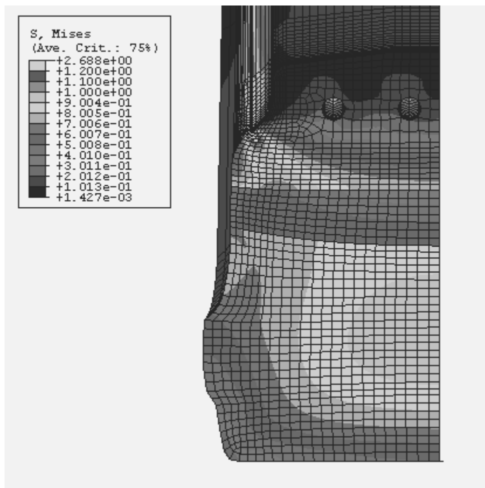

Fig. 8. Distribution of Von Mises stress obtained from FEA

Variations of rubber layers arrangement

An investigation on the effect of variations of rubber layers arrangement was carried out by means of FE analysis. Two simplest variations were chosen as examples. In one variation, the solid tyre is entirely made of the material with the hyperelastic property of the tread layer. The other variation, the tyre consisted of 2 layers, with the middle layer replaced by the tread layer. These arrangements can be practically done easily without a change in tyre geometry or rubber compound ingredients. Plot of strain energy density along the centre vertical line of the cross section vs. the normalised distance from the rim for the three design variations is shown in Figure 9. Deflections under the full load of three design variations are shown in Table 1.

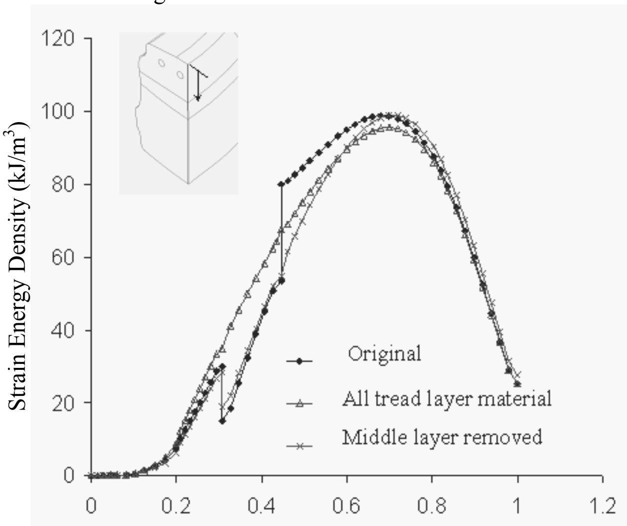

Fig. 9. Plot of strain energy density along the centre vertical line of the cross section from the rim for the three design variations

Table 1.
Deflections at full load of various tyre designs

Design variation	Deflection at full load (mm)
1. Original design	17.82
2. All tread layer material	18.37
3. Middle layer replaced with tread layer	17.31

It can be seen from Figure 9. that the maximum strain energy density on the centre vertical line of the design entirely made of tread layer material is the lowest comparing to the other two designs thus lesser heat generated, whilst its deflection at full load is the maximum indicating more flexible tyre and more comfortable ride. On the other hand, the design with the middle layer replaced with tread layer the tyre is less flexible and thus ride is less comfortable. This hints that the better tyre design can be achieved though having rubber layers with similar hyperelastic property as the tread layer. Nevertheless, other properties such as viscoelasticity and thermal properties should also be considered in the design stage.

3. Conclusions

The 3D FE model for static loading analysis of solid tyre constructed in this study can give reasonably good prediction of load-deflection behaviour of a real solid tyre. It can also be deduced that the distributions of analysis parameters such as strain energy density and Von Mises stress given by the FE analysis are acceptable and can be used to improve the design of solid tyres. Investigation of variation tyre models with different rubber layers arrangement was also undertaken. The tyre made entirely with the rubber of the same hyperelastic property as the tread layer can give more flexible deformation and thus more comfortable ride with lesser risk to damage due to heat generation.

In the solid tyre manufacturing point of view, improving the load bearing performance by changing thickness of each solid tyre layer or make a variation in layers arrangement is the least problematic and can be done effectively without changing the mould or rubber compounds. Finite element analysis, as has been demonstrated, can be used to predict the performance of the solid tyre when such variations are made. The results from finite element anaysis can be used to determine the optimum thickness of each layer for green tyre (unvulcanised tyre) building.

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