FINITE ELEMENT MODEL OF RADIAL TRUCK TYRE FOR ANALYSIS OF TYRE - ROAD CONTACT STRESS

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Distribuția eforturilor tri-ortogonale din pata de contact pneu-drum prezintă importanță deosebită pentru siguranța automobilelor. Au fost investigate eforturile din pata de contact utilizând un model cu elemente finite al unui pneu radial de autocamion realizat în ABAQUS. S-a ținut seama de anizotropia structurii datorată diferitelor tipuri de cauciucuri şi straturilor de cord. Au fost efectuate analize ale umflării, contactului static şi rulării. A fost studiată deformarea modelului de pneu sub efectul forței verticale. S-au obținut distribuțiile eforturilor în condiții statice şi de rulare. Au fost analizate valorile şi orientările eforturilor din pata de contact în condiții de tracțiune şi frânare.

The distribution of tri-orthogonal stresses in tyre-road contact patch has a major influence on automotive safety. Theoretical investigation of tyre-road contact stresses was performed using a finite element model of radial truck tyre developed using the ABAQUS software. The anisotropy of tyre structure due to different rubber compounds and reinforcement layers was taken into account. Analyses of tyre inflation, static contact and steady state rolling were performed. The deflection of tyre model under vertical load was studied. Distributions of contact stresses in static and rolling conditions were obtained. Magnitudes and orientation of contact stress distributions in braking and traction conditions were analyzed.

Keywords: finite element, tyre-road interaction, contact patch stress, truck tyre

1. Introduction

The importance of tyre-road contact resides in the fact that all forces acting on a vehicle are applied in the contact patch, with the exception of aerodynamic forces. The forces applied in the contact patch have a major influence on the automotive safety, as they determine vehicle stability and manoeuvrability.

The tyre-road contact forces are distributed on the contact patch area, but their distribution is not uniform [1]. Therefore, global forces are the resultant of contact patch stresses on each element of contact patch area [2]. Forces on an element of contact patch area can be divided into components on three orthogonal

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directions [3], Fig. 1. Tri-axial forces on each unit area of contact patch represent the normal, longitudinal and lateral stresses in the tyre-road contact patch [4].

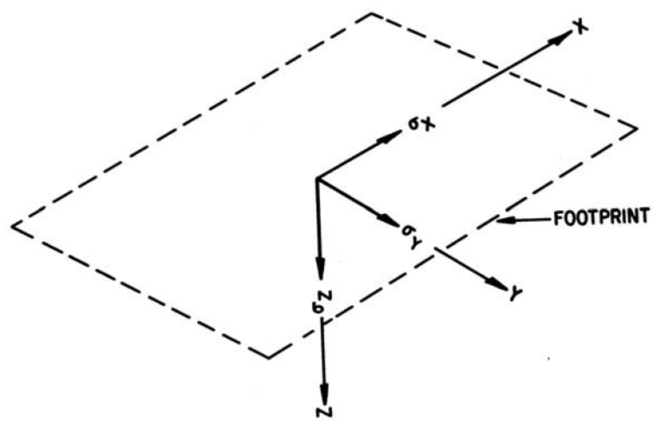


Fig. 1. Directions of tri-axial stresses on element area of tyre-road contact patch [3]

The theoretical investigation of tyre-road interaction can be performed using finite element models or analytical models (lumped parameter models, empirical or semi-empirical models). Analytical models are limited in regard to contact stress distributions: lumped parameter models do not provide the distributions of stresses throughout the length and width of tyre-road contact patch area, while the empirical or semi-empirical models deal only with global forces in the contact patch. The requirements of finite element models mainly concern computational resources. The evolution of these models is related to the development of computing capacity and finite element codes [5].

2. Finite Element Tyre Model

2.1 Model Geometry

In view of numerical investigation of the tyre-road contact stress distributions, the finite element model of a radial truck tyre has been developed using ABAQUS software.

The model geometry was defined using the coordinates measured on a section of a 9.00R20 tyre. A bi-dimensional model of tyre section was developed, as shown in Fig. 2. Only the circumferential grooves in the tread were taken into account [6], [7]. Although the major part of the section is symmetrical, there are also unsymmetrical reinforcement layers which do not allow only one half of the tyre section to be modelled.

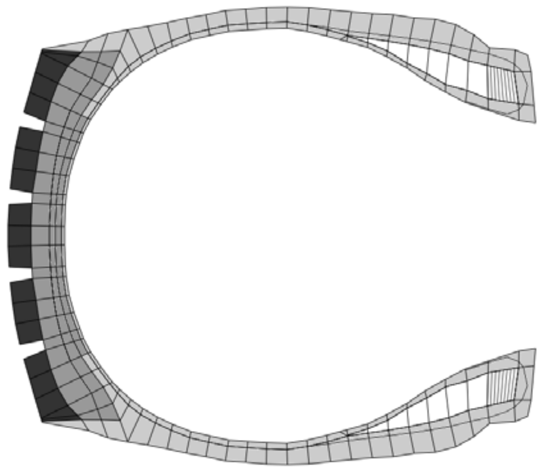


Fig. 2. Bi-dimensional model of 9.00R20 tyre

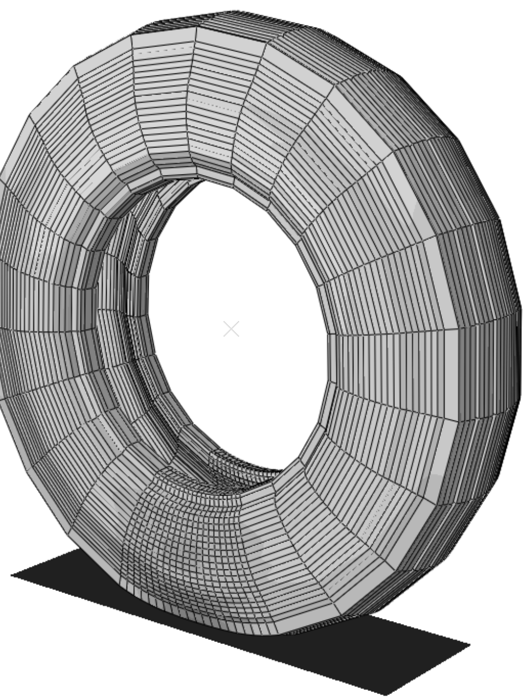


Fig. 3. Tri-dimensional model of 9.00R20 tyre

The anisotropy of tyre structure due to existence of different rubber compounds and various reinforcement layers was taken into account. Two types of elements were used [8]: for rubber parts the element type was solid 4-node axisymmetric, hybrid, with twist; for reinforcement layers the element type was surface 2-node axisymmetric, with twist. The solid elements were grouped into sets corresponding to the areas of tread, undertread, sidewalls, and bead filler, shown in Fig. 2. The rebar layers were defined taking into account the cross section area, spacing and angle of cords and they were considered embedded in solid elements.

The tri-dimensional tyre model was generated by revolving the bi-dimensional model about the rotation axis. The 3D model shown in Fig. 3 has 40 sections with 19922 nodes and 16201 elements. The sections are spaced unequally around the symmetry axis, so that the mesh is fine in the contact patch region and coarse in the rest of the model [9]. The ABAQUS software provides a combined lagrangian-eulerian algorithm which allows tyre rolling to be simulated using a model with uneven mesh density, in order to reduce the number of elements [10].

2.2 Materials

Different materials with hyperelastic properties were modelled to represent the various rubber components within the tyre. The hyperelastic behaviour was described through strain energy potential, as presented in [11], [12]. The required parameters were mentioned in [13] for each type of rubber component. The steel and polyamide cords were defined with linear elastic properties [7].

2.3 Boundary Conditions

The tyre nodes corresponding to the rim assembly were connected through a rigid body to a reference node representing the rim, defined at the origin of the coordinate system. This rigid body was subsequently used to set the appropriate restraints for the fixed or rotating wheel.

The road surface was created as a rigid body consisting of a plane analytical surface with a reference point in close proximity to the tyre. Contact was defined between the outer surface of tyre tread elements and the road surface, with appropriate friction coefficient and limited slip.

A uniform pressure of 650 kPa was applied on the internal surface of the tyre. A displacement was applied on the road surface in view of obtaining road contact. Then, a 15 kN force was applied on the same surface to simulate real conditions of loaded tyre.

To analyse different tyre rolling conditions, a translation velocity of 10 km/h was applied, together with rotational velocities ranging from 5.5 rad/s (equivalent to braking conditions) to 5.8 rad/s (corresponding to traction).

2.4 numerical analyses

The analyses were performed using ABAQUS Standard [8], [14]. The first simulation was steady state analysis of tyre inflation performed on the 2D tyre section model. In this analysis, all degrees of freedom of the rim were restrained and the uniform inflation pressure was applied on the internal surface of the tyre section. The inflation analysis was performed on the 2D model because it requires less computational time than the 3D model. The results of the 2D model analysis can be used in further analyses on the 3D model, which can be executed without repeating the inflation step. The subsequent analyses were performed on the 3D tyre model.

The static contact analysis included a step in which the road surface is displaced towards the tyre so that they come into contact, followed by a step in which the prescribed vertical force is applied on the tyre by the road. In this analysis, the translational degrees of freedom of the rim were restrained. All degrees of freedom of the road, except for the vertical displacement, were restrained. Finally, a steady state rolling analysis was performed on the 3D tyre model, on which the longitudinal translation velocity was applied. Various rotational velocities were applied in different steps, so that braking conditions, free rolling conditions and traction conditions are achieved consecutively. The boundary conditions applied in the previous analysis were maintained.

3. Results

3.1 Shape of Inflated Tyre

The inflated contour of 2D tyre model superimposed on the initial shape and the magnitude of inflated shape displacements are shown in Fig. 4. The deformations are large in the area of sidewalls and very small in the tread area, due to reinforcement layers under the tread.

3.2 Tyre Deflection under Vertical Load

The shape of the 3D tyre model in contact with the road surface under the 15 kN load and the magnitude of tyre vertical displacements is shown in Fig. 5. The normal displacement measured in the centre of the contact patch under the abovementioned load is 24.4 mm.

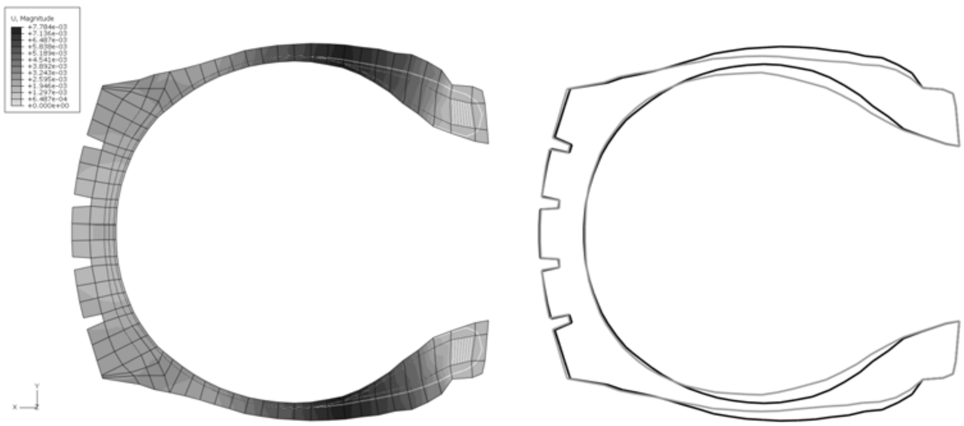


Fig. 4. Displacements and contour of inflated 2D tyre model

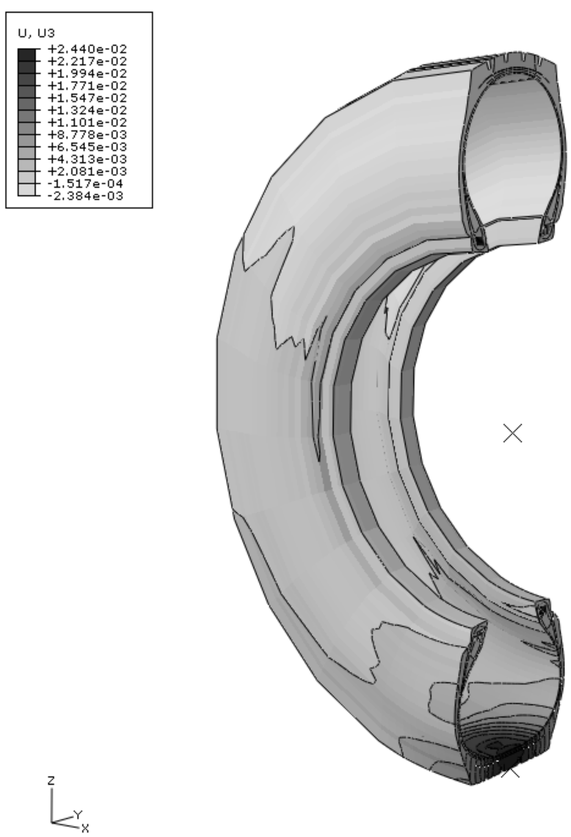
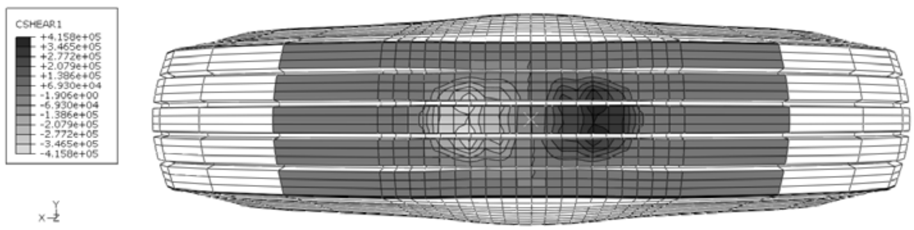


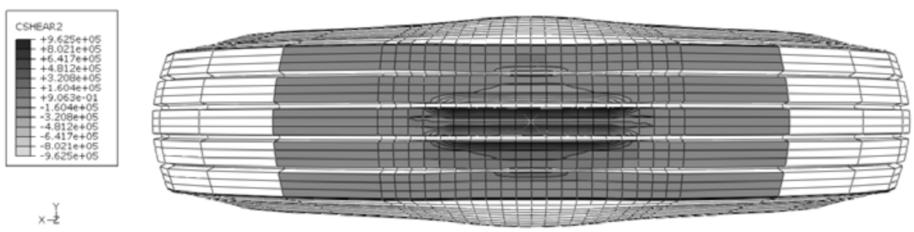
Fig. 5. Displacement of 3D tyre model under vertical load

3.3 Stress Distributions

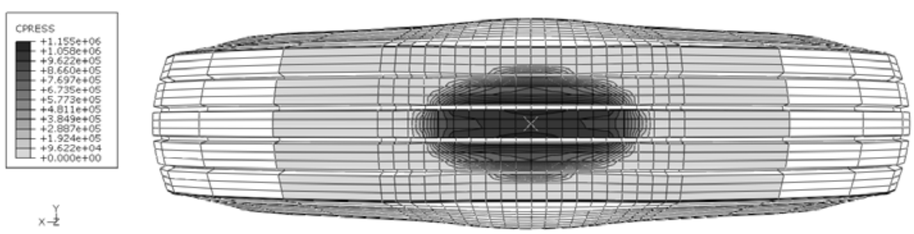
The distributions of contact patch stresses applied by the 3D tyre model on road surface in static conditions under 15 kN vertical load are shown in Fig. 6.



a) longitudinal stress



b) lateral stress



c) normal stress

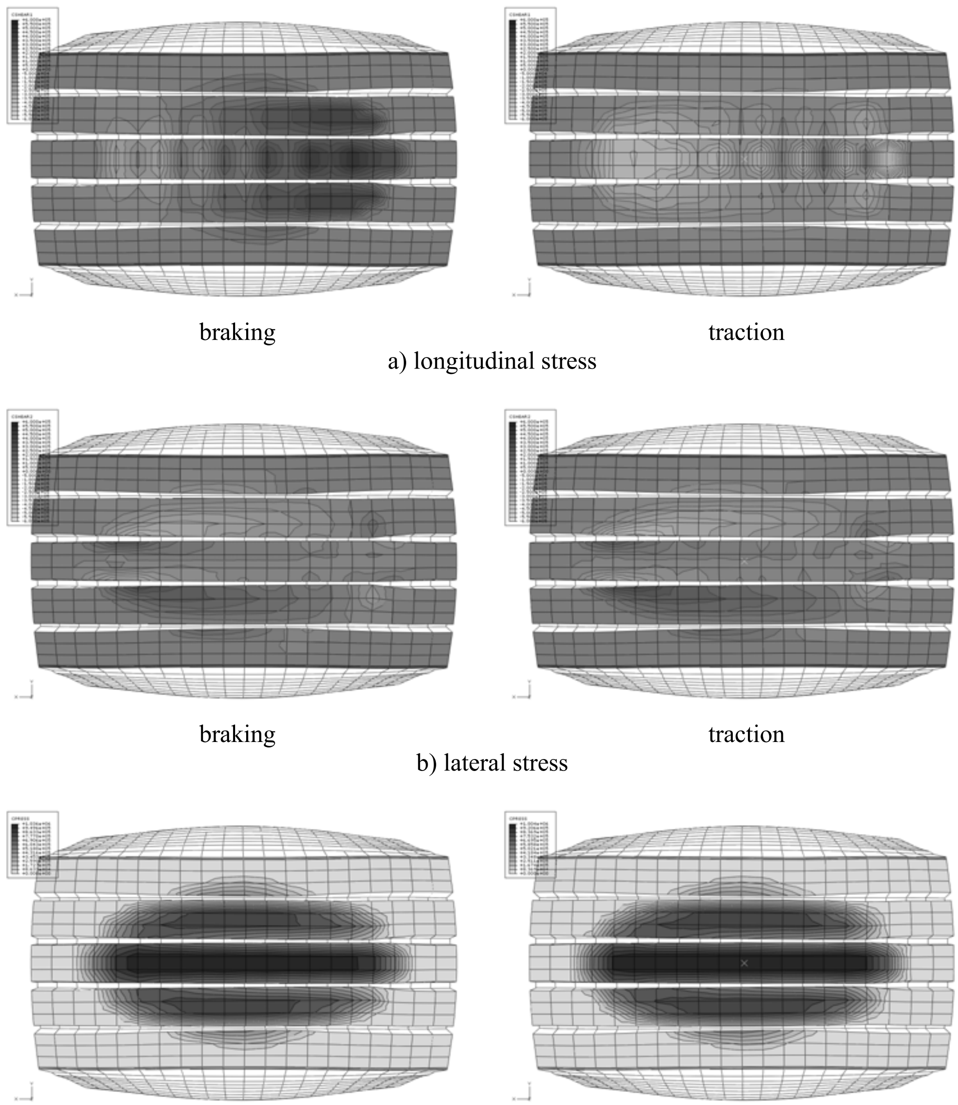
Fig. 6. Contact stress distributions of 3D tyre model in static conditions

The distribution of longitudinal stress is anti-symmetrical with respect to the YZ plane. The longitudinal stress decreases very much near the centre of the contact patch, and the orientation is towards the YZ plane.

The distribution of lateral stress is anti-symmetrical with respect to the ZX plane. The lateral stress increases near the grooves in the tread profile. The lateral stress is overall oriented towards the ZX plane, however on the centre rib the orientation is inverted locally, in the direction of the adjacent grooves.

The distribution of normal stress illustrates the quasi-elliptical shape of the contact patch. This distribution is symmetrical with respect to both YZ and ZX planes. The highest values of normal stress are found on the centre rib near the grooves and they exceed substantially the internal pressure of the tyre.

Fig. 7 shows the distributions of stresses in the contact patch of 3D tyre model in case of steady state rolling, for both braking and traction conditions.



braking traction

a) longitudinal stress

braking traction

b) lateral stress

braking traction

c) normal stress

Fig. 7. Contact stress distributions of 3D tyre model in rolling conditions

The distributions of lateral and normal stresses are very similar in braking and traction conditions. However, they differ from the distributions obtained in static conditions. The distribution of longitudinal stress is strongly influenced by the rolling conditions. In braking conditions the longitudinal stress obtained for the tyre model on the road surface is oriented mainly in the rolling direction, with a very small stress value in the opposite direction, near the leading edge of the contact patch. On the contrary, in traction conditions, the longitudinal stress is opposite to the rolling direction, with the exception of very small areas in the trailing extremity of the contact patch.

4. Conclusions

Finite element analysis was used for investigating the tri-axial stresses in the tyre-road contact patch. The 2D tyre model allowed simulating tyre inflation with reduced computational resources. The vertical load step provided the deflection of 3D tyre model under the applied force, as well as the distributions of contact stresses in static conditions. Distributions of contact stresses in braking and traction conditions were obtained from the steady state rolling analyses. Subsequently for the validation of the finite element model experimental results are to be used. Upcoming research using the finite element model of the 9.00R20 tyre aims at investigating the influence of tyre functional factors and construction parameters on contact patch stresses, and the consequences on the active safety of heavy vehicles.

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