Investigation of the influence of vertical force on the contact between truck tyre and road using finite element analyses

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Abstract. In the modern context of automobile integration with the emerging technologies of the interconnected society, the interaction between tyre and road is an element of major importance for automobile safety systems such as the intelligent tyres, as well as for passenger comfort, fuel economy, environmental protection, infrastructure and vehicle durability. The tyre-road contact generates the distribution of forces exerted on each unit area in the contact patch, therefore the distribution of contact stresses on three orthogonal directions. The numerical investigation of stresses distribution in the contact patch requires the development of finite element models capable of accurately describing the interaction between tyre and rolling surface. The complex finite element model developed for the 11R22.5 truck tyre has been used for investigating the influence of vertical force on the distributions of contact stresses. In addition to these contributions, the paper presents aspects related to the simulation of truck tyre radial stiffness. The influence of tyre rolling has not been taken into consideration, as the purpose of the current research is the investigation of tyre-road contact in stationary conditions.

1. Introduction

The integration of the modern automobile in the evolution of the increasingly interconnected human society depends on the development of emerging smart technologies such as the intelligent tyre systems [1]-[8]. In this progressively complex context, the interaction between tyre and road is an element of crucial importance not only for automobile safety and fuel economy, but also for passenger comfort, environmental protection, durability of vehicle and infrastructure [9]-[11]. The tyre-road contact is concretized through the distribution of forces exerted on each unit area in the contact patch, therefore the distribution of contact stresses, which can be decomposed on three orthogonal directions.

The experimental research of tyre-road contact stresses distributions involves complex measuring equipment, embedded in the rolling surface [12]-[15] or mounted inside the tyre [16]. The numerical investigation of the distribution of contact stresses throughout the contact patch surface requires the development of finite element models capable of accurately describing the tyre behaviour and the interaction between tyre and rolling surface [17]-[21]. Several complex measuring systems, as well as numerous finite element models have been developed in the University POLITEHNICA of Bucharest for the investigation of tyre-road interaction [1], [12], [21]-[24].

Taking into consideration the non-uniformity and anisotropy that generate the highly non-linear behaviour of tyres, the finite element model of a radial truck tyre has been developed with particular attention to the complexity of the tyre structure and multitude of different components. The complex
finite element model developed for the 11R22.5 truck tyre has been used for investigating the influence of vertical force, applied in stationary conditions, on the distributions of contact stresses.

In addition to these contributions, the current paper presents aspects related to the numerical simulation of tyre radial stiffness. The influences of rolling speed and rolling conditions have not been taken into consideration, as the purpose of the current research is the investigation of tyre-road contact in stationary conditions. Furthermore, the results presented in this paper are obtained taking into account constant inflation pressure and zero degrees camber angle for the radial tyre model.

2. Finite element model of radial truck tyre
The finite element model for investigation of the contact between truck tyre and road has been developed using Abaqus software. The profile coordinates have been measured on the exterior contour of an 11R22.5 truck tyre as well as on the exterior and interior contours of a corresponding truck tyre section. The 3D model shown in Figure 1 has been created accordingly [22], taking into consideration the components of real tyre structure, including the tread profile with circumferential grooves, the shape and position of beads, the real position and orientation of cord layers, and the different types of rubber components.

![Figure 1. Perspective view of the 3D model compared to the image of the real tyre section](image)

The finite element model includes the surface type elements for modelling the rebar layers, which have been defined with angle, spacing, section area and material properties, as well as the volume type elements for the different types of rubber components in the tyre structure [25]. Due to the orientation of belt plies, the model of tyre section is not symmetrical, and therefore the entire section has been modelled instead of using a symmetrical model for only half of the tyre section, which would have allowed reducing the number of elements and nodes [23]. The circumferential meshing is non-uniform, as it can be seen in Figure 2, in view of increasing the resolution in the contact patch [24], while maintaining a relatively small model size: 43214 nodes and 50441 elements.

Linear elastic properties have been attributed to the cord materials and bead materials [26], while hyperelastic behaviour has been defined using neo-Hookean model for the different types of rubber components [27]-[30]. Boundary conditions have been defined using a rigid body for modelling the
rim, with all degrees of freedom suppressed excepting rotation around tyre axis, and a rigid planar
surface representing the road, with one translational degree of freedom allowed on vertical direction.

Figure 2. Three-dimensional tyre model with non-uniform circumferential meshing [31]

Tyre inflation pressure has been defined on the interior surface of the model, and subsequently road
contact has been applied, with friction coefficient corresponding to real conditions [32],[33].

3. Steady-state analyses with vertical force applied between tyre and road surface
The steady-state analyses performed on the finite element model of the 11R22.5 truck tyre, with
inflation pressure and with vertical force, allowed simulating the contact between tyre and road and
obtaining the contact patch shape.

The contact patch shape resulting from the finite element analyses performed at 780 kPa inflation
pressure with 20234 N vertical force has been compared, as shown in Figure 3, with the contact patch
print determined experimentally in corresponding conditions. The tyre-road contact model is validated
by the good similarity of these results, although there are some small differences of shape which can
be explained by the mounting position with small camber angle of the real truck wheel. It can also be
noticed that some ribs in the tread profile of the real tyre have very thin transversal sipes, which have
not been included in the finite element model, because of limited meshing density.

Figure 3. Contact patch shape of the truck tyre model at 780 kPa inflation pressure,
compared to the contact print obtained experimentally
The radial stiffness curve of the truck tyre model shown in Figure 4 has been determined from the finite element analyses performed at 800 kPa inflation pressure, for a wide range of vertical loads. The highlighted point represents the radial stiffness obtained experimentally at 800 kPa inflation pressure, for a single value of vertical load, corresponding to the truck load in the road test conditions. It can be seen that the measured stiffness is relatively similar to the simulated value, but the real tyre stiffness is slightly higher than that of the finite element model. The radial stiffness of the tyre model tends to increase when the vertical load is higher [34], as it can be seen from the shape of the curve.

![Radial stiffness curve of the truck tyre model at 800 kPa inflation pressure, compared to the value of radial stiffness obtained experimentally](image)

**Figure 4.** Radial stiffness curve of the truck tyre model at 800 kPa inflation pressure, compared to the value of radial stiffness obtained experimentally

The influence of vertical force on the shape of contact patch and on the distributions of contact stresses on three orthogonal directions obtained from simulations is presented in Figure 5; the comparison has been made between the results obtained at two different values of vertical force, 20445 N and 10223 N, applied in stationary conditions. The simulations have been performed on the finite element model of the 11R22.5 truck tyre with 780 kPa inflation pressure and 1° camber angle.

The dimensions of the contact patch are strongly influenced by the vertical force applied on the tyre model. The shape of the contact patch under smaller vertical load is closer to a circular shape. The distributions of normal and lateral stresses are symmetrical with respect to the lateral plane containing the contact patch centre, while the longitudinal stresses are antisymmetrical with respect to this plane [35]. The symmetry of the distributions of normal and longitudinal stresses with respect to the longitudinal plane containing the contact patch centre is slightly affected by the camber angle. In stationary conditions, the maximum values of lateral stresses are located on the edges of tread ribs, and the global distribution of lateral stresses tends to be antisymmetrical with respect to the longitudinal plane containing the contact patch centre.

The values of longitudinal stresses are significantly smaller in the case of the lower vertical force, and the values of lateral stresses are also reduced in this case. The maximum values of normal stresses are approximately the same for the two different values of vertical force, and in both cases they are located at the contact patch centre. However the high values of normal stress are applied on a much smaller area of the contact patch in the case of the lower vertical force.
Figure 5. The distributions of contact stresses in [N/m²] for finite element tyre model with 20445 N vertical force (left) and 10223 N vertical force (right) at 780 kPa inflation pressure: a) longitudinal stresses, b) lateral stresses, c) normal stresses
4. Conclusions
The finite element model developed for the 11R22.5 truck tyre has allowed investigating the contact patch shape and dimensions, as well as the tyre radial stiffness. These parameters have been used for finite element model validation against experimental results.

The influence of vertical force applied in stationary conditions on the distributions of contact stresses has also been emphasized by the results of finite element analyses. The dimensions of the contact patch are strongly influenced by the vertical force applied on the tyre model. The vertical force has negligible influence of on the peak values of normal stresses, but changes significantly the area of the contact patch on which the high values of normal stress are applied. The distribution of lateral stresses is also related to the vertical force applied on the tyre model, while the effect on the values of longitudinal stresses is even more significant, with major consequences on vehicle stability and safety.

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