FEA of tyres subjected to static loading

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Abstract

Structural static finite element analysis (FEA) may be used in tyre design, in order to predict and improve mechanical behaviour and durability of tyres. This paper describes the possible goals of static tyre FEA and gives special attention to various aspects of finite element (FE) model building. A short review of relevant papers is given first, followed by the description of axisymmetric and 3D models built by the authors and the results of analyses conducted using those. The accompanying comments describe how those results may be used by tyre designers.

Key words: tyre (tire), tyre design, finite element analysis (FEA)

1. Introduction

In tyre industry, there exist a constantly growing need for digital prototyping of new tyre designs, which serves as an alternative to expensive and lengthy physical prototyping. For this purpose, finite element analysis (FEA) is commonly used. In order to predict the behaviour and durability of a future tyre, detailed modelling of inner tyre structure is required. The nature and complexity of finite element (FE) tyre models depends on the chosen type of analysis, which can be static, dynamic, thermal, fluid flow etc. Usually a series of analyses is conducted, which covers the expected load cases and environmental conditions that the tyre will be subjected to during its lifetime.

Regardless of analysis types chosen, the initial tyre models are always built for structural static analysis. Static analysis is primarily used for checking the load capacity of tyre, validity of finite elements and software or the level of mesh refinement. But, it can also be used for predicting the direction in which changes in tyre design parameters influence its overall behaviour or for early detection of critical points in the structure.

We here summarize a number of papers on static analysis of tyres and also present tyre FE models and analyses results.

The goals of static tyre FEA and a short review of existing solutions

From the point of view of tyre mechanics, a static FEA may be used to analyse the first function of the tyre and the support of load (Potts [17]), in order to predict vertical stiffness i.e. the shape of load-deflection curve or to analyse footprint shape and stress distribution (Ridha and Theves [18]). It can also be used for initial evaluation of tyre durability via stresses and strains in cord or rubber components. Moreover, it is often used to predict tyre manoeuvrability through lateral stiffness or stress distribution in tyre carcass (Cho and Jeong [2]). In summary, static FEA helps in shortening the tyre design process, with raising the quality of both new and existing tyres by predicting the influence of changes in tyre construction on its behavior during service and on its durability.

Static analysis of axisymmetric tyre models is generally expected to yield results on mounting and inflation, such as stresses in bead wires, the influence of tyre geometry and rim size on cord stresses and contact pressure distribution on the tyre-rim interface, initial tyre shape after each of the two stages etc. (as described by Ridha and Theves [18]; Mancosu, [12]; Tönük [21]). Such models are valid if the loads are also of the axisymmetric nature, as the tyre geometry is. By using 3D models, one can obtain the same results as by using axisymmetric ones, as well as the results on any non-symmetric tyre loading (see Ridha and Theves [18]; Mancosu [12]; Tönük [21]; Danielson at al. [4]; Meschke at al. [13]; Hall at al. [6]; Tönük and Ünlüsoy [22]). In the case of vertical load application, the results of interest are the load-deflection curves, stresses in tyre components, footprint shape and contact stress distribution, etc. Due to overall shape and loading symmetry, only a quarter of a tyre may be modelled (Fig. 4), having in mind that this introduces some amount of error because belts angles are not symmetric with regard to two vertical planes, one containing the tyre axis and the other being normal to it. Nevertheless, in the case of static loading, this error tends to be small.

In order to describe material behaviour of structural tyre components that are composed exclusively of rubber, various authors have used either linear or hyperelastic material models. The Mooney – Rivlin form has most frequently been employed, as deformations in tyre during service rarely reach 40% (Tönük [21]) and also because of material model stability.

Description of the tyre composite cord-rubber structural components is still an area where a lot of research is to be done. Highly non-linear properties, couplings and stresses on cord-rubber interface are some of the main problems to be explored. Some researchers have focused on energy approach (Pidaparti [15]) or micromechanical approach (Kocak and Pidaparti [7]; Pidaparti at al. [16]) to define macromechanical properties of cord-rubber composites, describing rubber-cord composite as equivalent, anisotropic media. Nevertheless, the authors who used equivalent media approach, for simplicity often relied on orthotropic material definition in conjunction with solid or shell, large-strain capable finite elements, as described in Ridha and Theves [18], or Hall at al. [6]. Less then a decade ago, rebar element approach (Danielson at al. [4]; Meschke at al. [13]; Tönük [21]) gained popularity, for a number of reasons. The most important are the numerical efficiency, decrease of discretization-dependent errors (Meschke at al. [13]) and ability to define material laws and failure criteria separately (Tönük [21]). Using such an approach, it is also easier to define non-linear models for cord and rubber.

Inner tyre structure is modelled in more or less detail, where some structural components, which do not significantly influence the overall mechanical behaviour of the tyre, are often omitted or modelled together with some other component. For 3D tyre models it is a common practice to only model circumferential grooves, for the sake of simplicity, as it has been done by Tönük [21] or Hall at al. [6]. It turns out that such simplified models do not significantly change the shape of the load-deflection curves and footprints, when static loads are applied (Meschke at al. [13]; Tönük [21]), but there is a difference in vertical tyre stiffness - which is not too large, and an important difference in contact stress distribution. Furthermore, it is stated by Danielson at al. [4] that removing half of the tyre model above the horizontal plane that contains the tyre axis does not significantly alter the analysis results. On the other hand, when a detailed tread shape is to be modelled, only the part of it that may come in contact with the ground is taken into account. Whilst some authors, like Tönük [21], experimented with simplified tread shapes, other used different procedures for detailed tread modelling. Meschke, Payer and Mang [13] developed a procedure for linking fine mesh in the contact zone and the coarse one for the rest of the model. Cho at al. [3] wrote the procedure for automatic building of the fine mesh in the contact zone with transitions towards the rest of the model.

The methods for multi-objective optimization may also be included in FEA models, as it is shown in Cho at al. [2], where an axisymmetric tyre model is used to optimize the sidewall carcass contour, in order to improve tyre manoeuvrability and durability.

3. FE models

While working on tyre FEA, authors of this paper have focused on two goals: developing the FE model of a tyre (starting with tyre subjected to static loads) and defining procedures that can, on a regular basis, be used for FE modelling and analysis of any tyre. This section contains a description of the FE models developed and used for static analysis of mounting, inflation and vertical loading. For this purpose, two-dimensional (axisymmetric) and three-dimensional (3D) FEA models were built. The existing type of tyre, sized 165/70 R13, was chosen so that analysis results could be compared with experimental ones.

The purely rubber structural components were modelled using linear, mixed formulation, Hermann elements and the Mooney-Rivlin form as the material model. The material model coefficients were obtained by curve fitting, using material data from three different tests, namely uniaxial, equi-biaxial and planar tension. All the tests were performed in-house, on the uniaxial testing machine (Fig. 1). These procedures, based on work of Treloar (1958), book of Gent at al. [5], and studies of Charlton at al. [1] and Miller [14], are described by Korunović et al. [11]. The composite structural components are represented by superimposing the rebar elements for the cord and the Hermann elements for the rubber matrix.

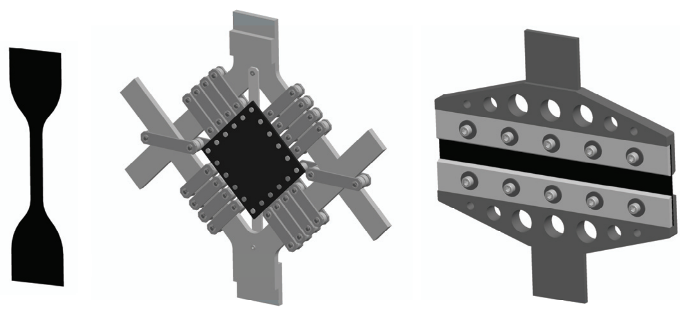


Fig. 1. Specimens and additional equipment used to obtain material data for purely rubber structural components of tyre.

To obtain geometry of the tyre profile, 3D parametric tyre CAD model (described by Stojković at al. [20]; Stojković and Trajanović [19]) was employed. Using this model, the exact geometry for any tyre dimension can easily be obtained.

3.1 Axisymmetric model

To simulate mounting and inflation processes, the axisymmetric tyre model was used. Two variations of the model were initially defined: half of tyre profile (Fig. 2) and entire profile (Fig. 3). For further analyses the second one was chosen, for two reasons. The first was to analyze the influence of non-symmetry of belts in regard to wheel plane, defined according to SAE tyre axis system (Potts [17]). The second reason was simply to have a better visualization of the results. In the end, the difference in results obtained by using the two models turned out to be negligible, and the second reason prevailed. The rebar elements have been defined for the composite structural components: belt, carcass and bead wire. For higher accuracy of the results, two belt layers have been modelled separately. The change of cord direction according to tyre deformation has been defined via user subroutines, based on the code and algorithm described in Tönük [21] and Tönük and Ünlüsoy [22]. The cord was represented using a bilinear material model and subroutines that detect whether the cord was extended or compressed in the past iteration, in order to change its modulus accordingly (based on the idea of Conor McCarty, University of Limerick). The Coulomb friction is defined between bead and rim.

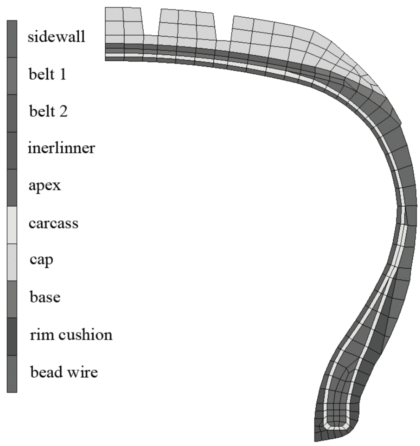


Fig. 2. Axisymmetric tyre model of a half of the tyre cross-section: structural components and finite element mesh. For accuracy purposes, the inner tyre structure is modelled in detail, although omission of some components, such as innerliner, does not significantly affect the model response. Adaptability criterion is assigned to elements in bead region, which subdivides any of the elements containing a node that comes in contact with the rigid body representing the rim. (Fig. 7).

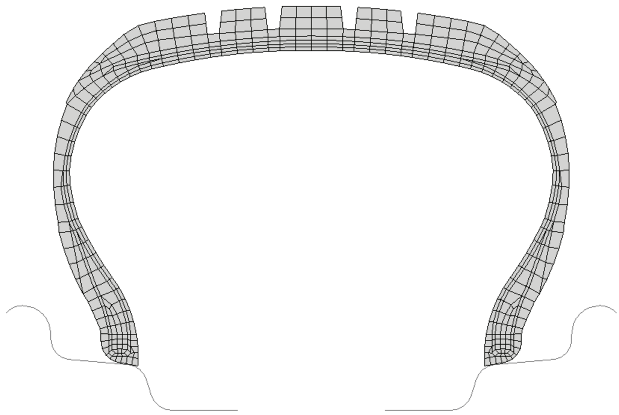
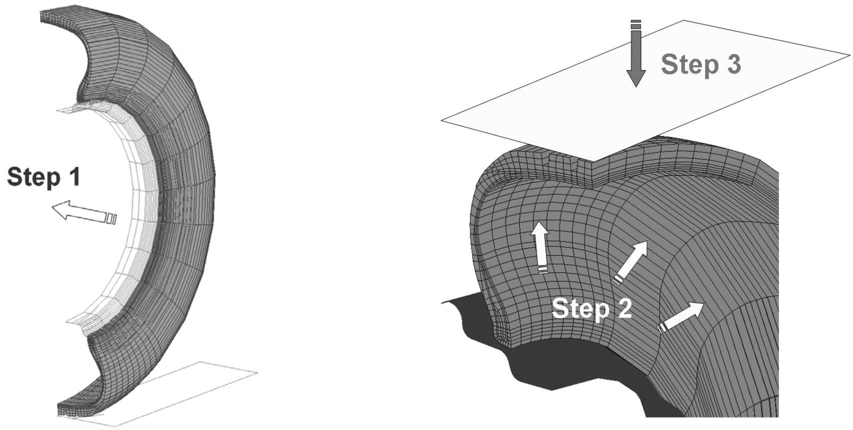


Fig. 3. Axysimmetric tyre model of the full tyre cross-section.

3.2. 3D model

For the analysis of vertically loaded tyre, a 3D FE model was used (Fig. 4). There exists a possibility to transfer axisymmetric analysis results to the 3D model, which also implies that the 3D model is built on the basis of the deformed shape of axisymmetric model. With this approach, the time needed to obtain results on vertical loading gets much shorter. This method is currently used as one of the improvements in the analysis procedure. The composite structural components were also modelled using rebar elements (Fig. 5).



(a) (b)

Fig. 4. 3D tyre model for vertical loading analysis, with the analysis steps depicted. In order to shorten the model generating procedure, only circumferential grooves were taken into account. Element density in the circumferential direction is larger in the vicinity of potential contact zone. Rim and ground are modelled as rigid bodies. (a) as in the axisymmetric model, load step 1 is related to mounting; (b) load step 2 is also similar to the axisymmetric case and represents inflation, whilst in the load step 3 the rigid body representing ground surface is moved towards wheel axis, with the resulting load acting on it being measured (a quarter of vertical load that acts on the tyre).

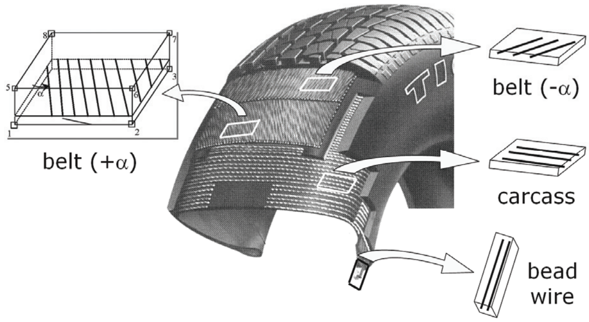
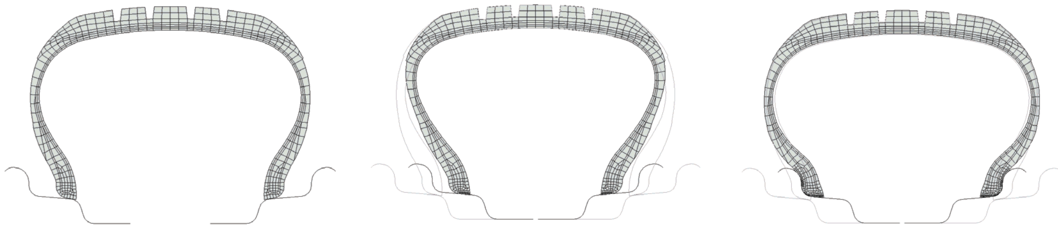


Fig. 5. Various structural components of the tyre, with schematic display of rebar elements used to model the composite ones. As in the axisymmetric model, the cord angles are driven by deformed shape of the tyre, via user subroutines.

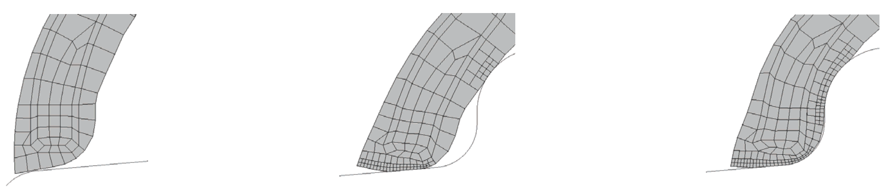
4. FEA results

The FE models described in the previous section were used to obtain the results considered to be important from designers' point of view, and which could be compared to the results in literature. Analyses results are shown and commented in the figures below (Fig. 6 - Fig. 17).



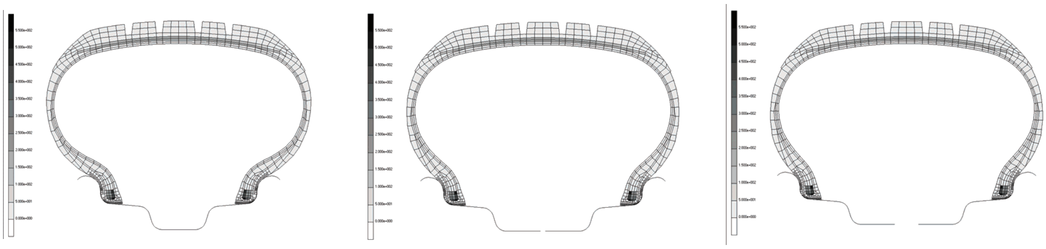
(a) (b) (c)

Fig. 6. Deformed shapes of the axisymmetric tyre model: (a) before the start of analysis; (b) at the end of the mounting load step; (c) at the pressure of 2bar (end of inflation).



(a) (b) c)

Fig. 7. Close look to bead area during the analysis, with adaptive mesh refinement: (a) before the start of analysis; (b) inflated to 0.5bar; (c) inflated to 2bar. Without adaptability, the width of inflated tyre model gets larger, bead geometry is represented less accurately, so that element edges penetrate rim surface more intensively. The finer mesh produced using adaptive refinement also produces better results for contact stress distribution.



(a) (b) c)

Fig. 8. Axial stresses in bead wire, belt and carcass of 165/70 R13 tyre mounted on 4 different rim sizes and inflated to 2bar. Rim sizes are: (a) 4J, (b) 5J (nominal) and (c) 5.5J.

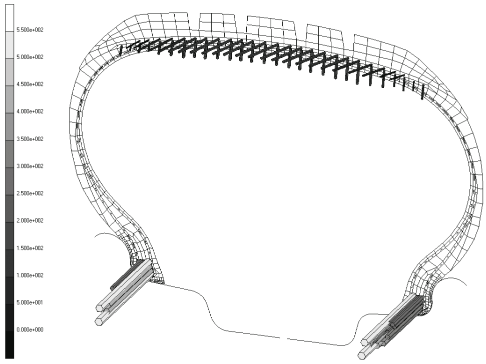
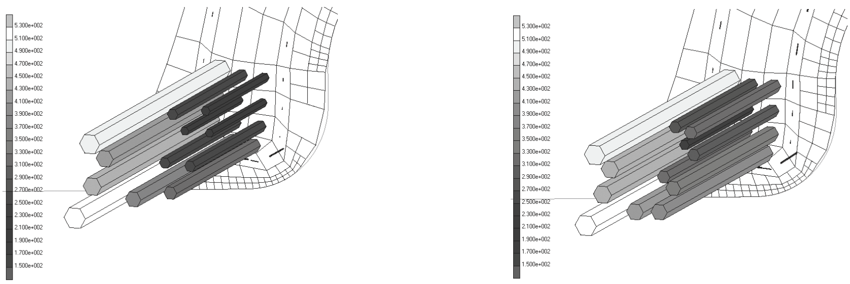


Fig. 9. Axial stresses in bead wire, belt and carcass of the tyre mounted on nominal rim and inflated to 2bar, based on the second Piola-Kirchhoff stress tensor.



(a) (b)

Fig. 10. Axial stresses in bead wire of the tyre mounted on 2 different rim sizes: (a) 4J and (b) 5.5J. This kind or result is useful for determination of the initial shape and position of bead wire and bead area, so that the stress distribution is as even as possible.

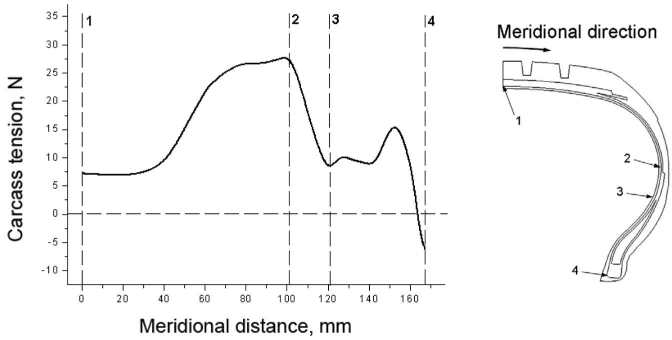
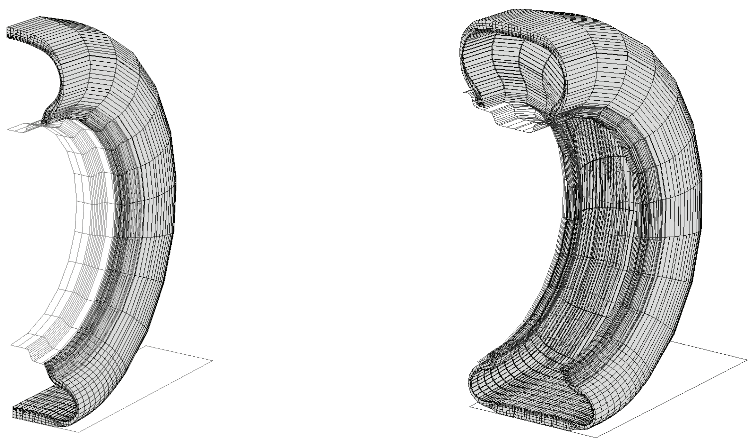


Fig. 11. Axial stress in a single wire of carcass in a tyre inflated to 2bar. This kind of result is crucial for the prediction of tyre durability and manoeuvrability.



(a) (b)

Fig. 12. Deformed shape of 3D tyre FE model for analysis of mounting, inflation and vertical loading: (a) model of a quarter of the tyre, used in the analyses; (b) fictitious model of half of a tyre, constructed by mirroring the deformed shape of model (a).

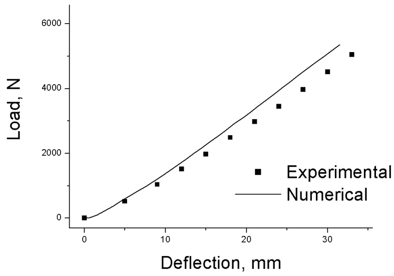


Fig. 13. Comparison of load-deflection curves obtained numerically and experimentally as a main check of the chosen modelling approach. The FE model is stiffer than the real tyre, which could be expected since the linear elements are used, and only circumferential grooves are modelled. Considering all assumptions introduced, as well as the fact that measuring equipment used was not highly accurate, the analysis results are considered to be in a good correlation with the experimental ones.

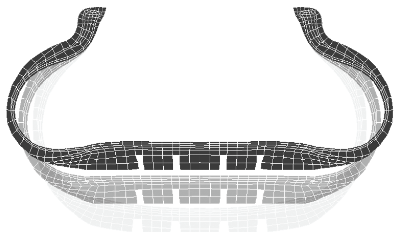
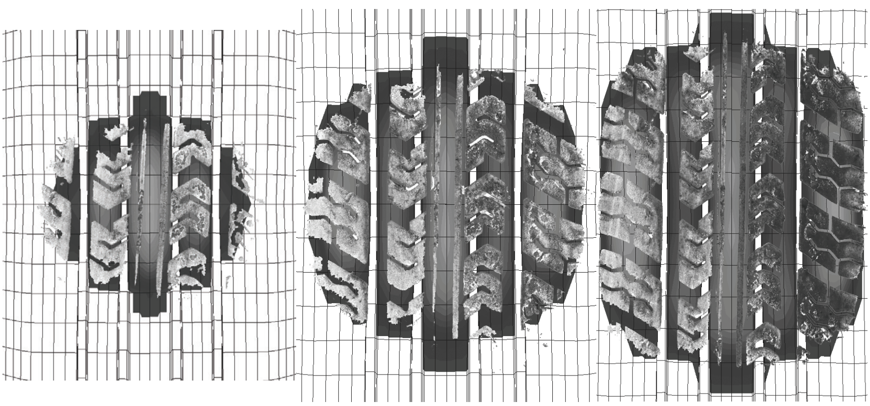
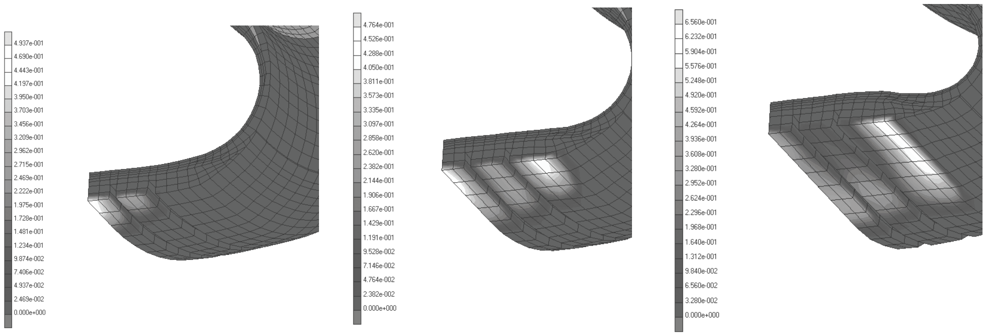


Fig. 14. Deformed tyre sections at three different load intensities, obtained using the 3D model and image editing.



(a) (b) (c)

Fig. 15. Comparison of tyre footprints obtained numerically and experimentally, as another check of the FE model accuracy. Load intensity is: (a) 1000N; (b) 2000N; (c) 3000N. Although the tyre that was experimentally tested has a different number and position of circumferential grooves (but the same inner structure) the results are in good agreement. This may point to the conclusion that tread shape does not crucially affect the shape of footprint of a vertically loaded tyre.



a) b) c)

Fig. 16. Footprint shape and contact pressure distribution for: (a) under-loaded or over-inflated tyre; (b) normally loaded tyre; (c) overloaded or under-inflated tyre. As it is often experienced in tyre service, with increasing load contact pressure shifts towards tyre shoulders and away from the footprint centre, which is often the cause of uneven tread wear.

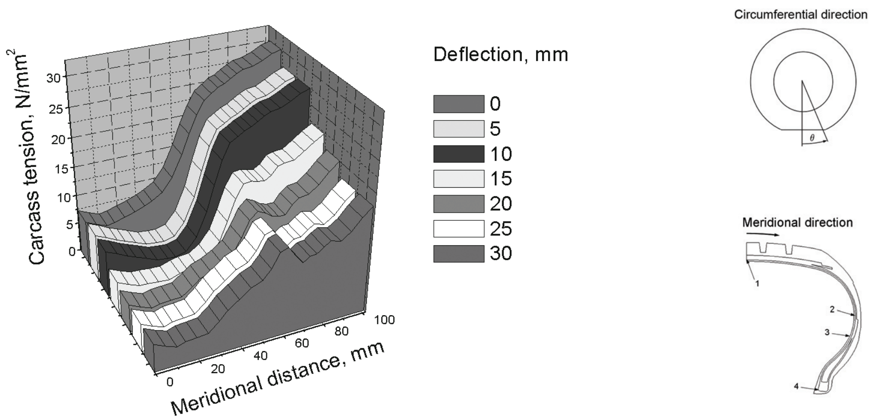


Fig. 17. Axial stress in a single wire of carcass in the tyre inflated to 2bar, sequentially vertically loaded so that deflections vary from 0 to 30mm, with 5mm increment. The curve at 0mm deflection is in good agreement with the one obtained using the axisymmetric model (Fig. 11). As load intensity grows, the curves get flatter, which means that the load is distributed more evenly.

5. Concluding remarks

The results of static tyre FEA shown in this paper indicate that it can successfully be used in tyre design in order to predict or improve tyre characteristics. FEA accelerates the process of tyre design and enables the designer to explore a variety of designs much in short time, so that the desired tyre behaviour can be tuned to known theories and experience. On the other hand, it helps in early observation of possible influences on tyre durability and mechanical behaviour, which could not otherwise be predicted.

Although dynamical and thermal behaviour, as well as time-dependent material properties such as viscoelasticity, should not be neglected when the tyre service is considered, a structural static FEA offers a good price-performance for the use in tyre design. Logical extension to static FEA tyre analysis is the analysis of steady state rolling tyre. We already have performed this extension and will report the results in a separate paper.

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