Numerical Modeling in Tire Mechanics

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Abstract:

The contribution has its focus on several aspects of the description of tire features through finite element modeling. It is starting with the formulation of rubber material properties. Material characteristics, which have to be taken into account depending on the focus of analysis, are introduced. Geometrical nonlinearities, i.e. large strain, nonlinear elasticity, softening, inelastic and dissipative features are of importance and influence certain tire properties. An important simulation feature is the steady state rolling framework. In this case, the finite element discretization is fixed in space and the material is considered as flowing through the mesh. This approach is computationally very efficient and represents the real loading conditions of the tire. During the design process, various structural aspects need to be investigated in order to obtain an optimal product. Tire mechanical properties which are in the reach of current computing facilities are shown.

Keywords:

Constitutive modeling, rubber material, tire mechanics, moulding, steady state rolling, durability, friction, material force method, tire-pavement-interaction

1 Introduction

The tire structure is a quite complex and highly challenging construction for mechanical modeling and numerical simulation. Nowadays, computational mechanics has reached an advanced level of description which allows a relatively accurate prediction of tire features. The finite element method (FEM), which is the standard approach in this numerical field, represents an efficient simulation tool for structural analysis. Moreover, hardware has developed to a sufficient standard for the solution of these large and highly nonlinear boundary value problems. In continuum mechanics, advances have been made in the formulation of rubber material properties. Constitutive approaches have to be taken into account depending on the focus of analysis. The tire needs to be designed according to optimized requirements with respect to footprint pressure and shape, wear, rolling resistance, durability as well as tire characteristics (forces, moments). Thus, the intention is to give a general overview on the current simulation capabilities in rubber characterization and, especially, in advanced tire mechanics in order to show the benefits for the design process.

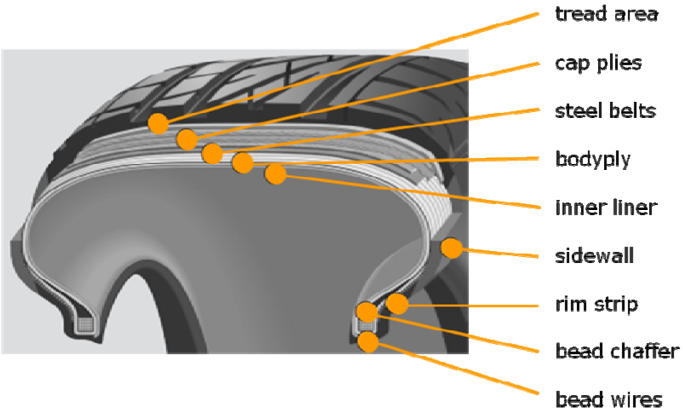

Figure 1: Main tire components

The constitutive parts of the tire are a larger number of natural or synthetic rubber components and reinforcing fibres out of steel or polymeric material. Figure 1 identifies the main constituting parts of a passenger car tire (PC tire).

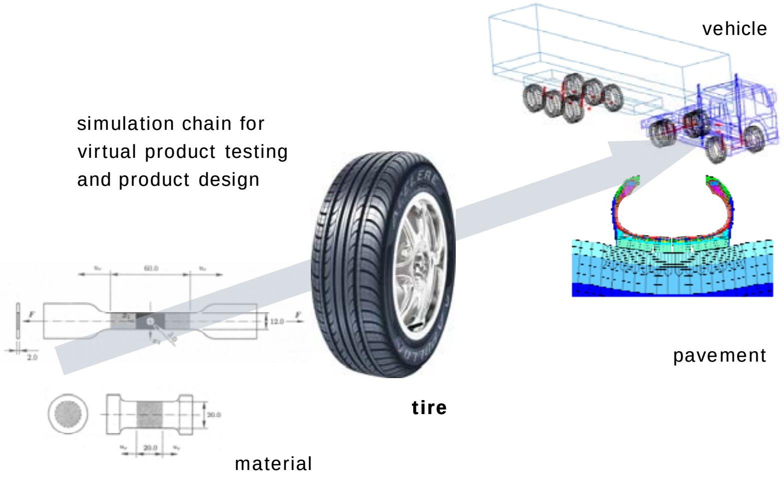

Figure 2: Simulation chain

The tire cannot be considered as a standalone product. In fact, it is the transmitter of forces generated by the motion of the vehicle and, therefore, it has to be seen in conjunction with the features of the car and it influences the vehicle dynamics properties as well. Moreover, the interaction between tire and pavement influence both, the driving behavior as well as the loading of the pavement. Thus, the tire needs to be described starting at material and constitutive level and ending up in the consideration of the full operating environment formed by vehicle and pavement. At the end, a simulation chain can be envisaged for virtual product testing and product design (Figure 2) including the production process.

2 Constitutive Modeling

Tire structures consist mainly of two classes of material components: elastomers and reinforcing cords. The appropriate description of the materials from a continuum mechanical point of view is depending strongly on the physical features of the structure which need to be captured. Besides, predictive capabilities of the constitutive formulation are required, i.e. out of a certain identification of the free model parameters; a reliable prediction of the genral structural behaviour should be possible.
Main underlying property of an elastomer is the hyperelastic behaviour. Marckmann, Verron [11] evaluated a large number of published approaches and concluded, that the extended tube model (see Kaliske, Heinrich [6] and Figure 3) has predictive capabilities. In Figure 3, the results of Yeoh's model and of the extended tube model are presented, where the material parameters have been identified according to the uniaxial test and, subsequently, pure shear and equibiaxial experiments have been accomplished. The extended tube model is founded on physical considerations of the polymer chains being linked at the network nodes to other chains and being confined by surrounding chains.

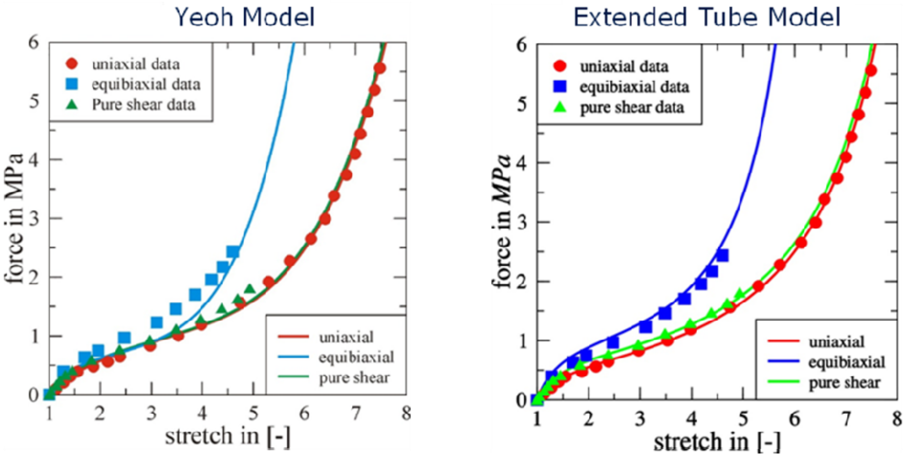

Figure 3: Models for rubber elasticity

Modeling of the inelastic features of filled elastomers, which are employed in tire production, bases on phenomena like viscoelasticity, rate-independent inelasticity and damage characteristics. A physically inspired nonlinear viscoelastic approach has been proposed by Bergström, Boyce [1] and an accompanying FE-implementation is shown in Dal, Kaliske [3]. Beyond the rate-dependent dissipative features, strong rate-independent properties are found, which go back to slipping of the polymer chains on the filler surface (see Kaliske, Rothert [5], Netzker et al. [14]). An endochronic plasticity model without an explicit yield surface and with an intrinsic time scale as depicted in Figure 4 is capable of representing the rate-independent inelastic material response. Once, rupture of filler and polymer chain is observed (Kaliske et al. [7]), the stiffness of the material is reduced and, thus, softening is found. After some load cycles of preconditioning, the softening effect is mostly reduced.

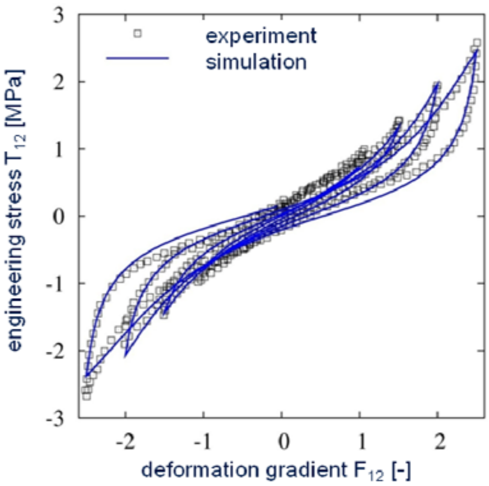

Figure 4: Endochronic plasticity formulation

3 Tire Moulding Simulation

The raw material of tire production is uncross-linked natural or synthetic rubber. Furthermore, the uncross-linked rubber compounds comprise several additives, like e.g. sulphur, oil, carbon black and flexibilizer. After mixing all these components, the designed rubber compound is obtained and can be formed in order to get the designated shape within the producing device. During the forming process, uncross-linked rubber is pressed into a mould under high inflation pressure of the bladder and under temperature. After moulding, the pressure is kept constant and the temperature is rising until the inmoulded rubber compounds are completely cross-linked. During cross-linkage, rubber changes its properties significantly as well as the product obtains its required and final features.

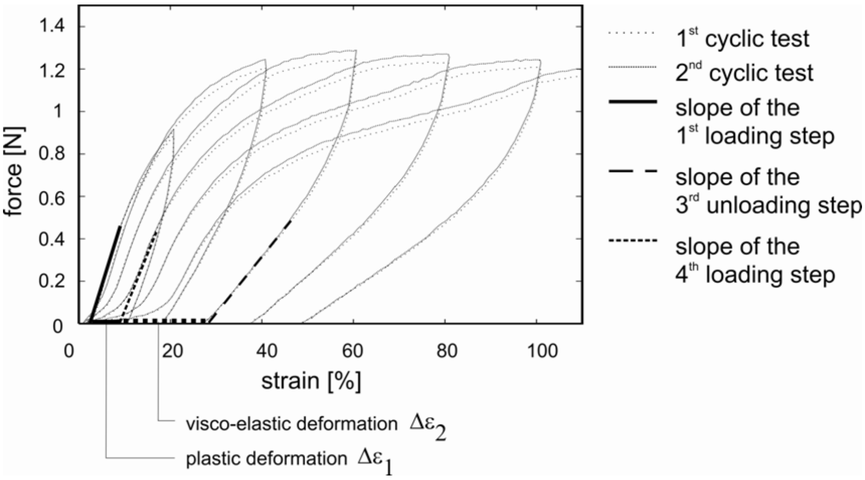

Figure 5: Cyclic test of uncured rubber material

Currently, research is under way to understand, to investigate and to describe the mechanical characteristics of uncured rubber material in order to simulate the forming process using the FEM (see also Kaliske et al. [9]). Extensive material tests show the elastic, viscous and plastic parts of the material response (Figure 5). An appropriate material description has been developed and implemented into a FEM code. The elastic part of the model is represented by a nonlinear elastic model. For the inelastic portion of the formulation, the theory of the fractional calculus is used, which can be represented by a rheological fractional element. This theory is based on a fractional time derivative. First FEM forming simulations are carried out (Figure 6) where the green tire as well as the bladder are discretized. Due to the axisymmetrical discretization, only circumferential groves are taken into account.

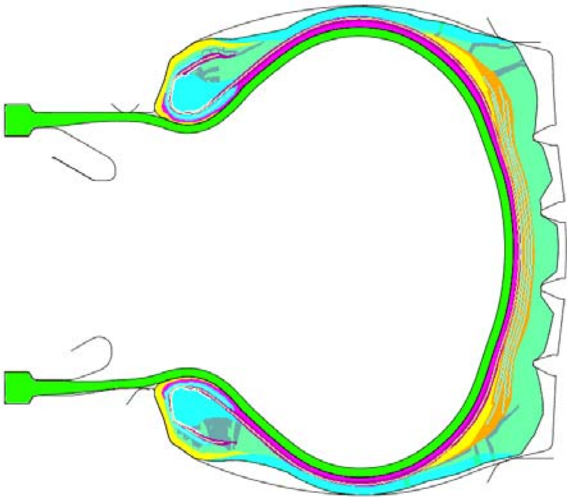

Figure 6: Moulding of truck tire 315/80 (bladder, tire, mould)

4 Rolling Tire Approach

The FE-model of the tire is directly developed out of the 2D CAD drawing of the cross-section. This way, we obtain a 2D geometry which is discretized by axisymmetrical elements. Thus, loading situations like moulding, inflation and free spinning of the tire can be investigated by an efficient 2D discretization which nevertheless leads to a 3D state of deformation due to the reinforcements. 2D axisymmetrical elements with an out of plane degree of freedom have to be used. In the next step, the fully 3D geometry is generated out of the 2D case (see Figure 7) which serves as basis for complex numerical tire simulations under various loading situations.
An important simulation condition for tires is the steady state rolling description. In this case, the FE-discretization, i.e. the elements, are fixed in space and material is considered as flowing through the mesh. This approach is computationally very efficient and represents the real loading condition of the tire. An axisymmetrical description of the structure is prerequisite for this approach.

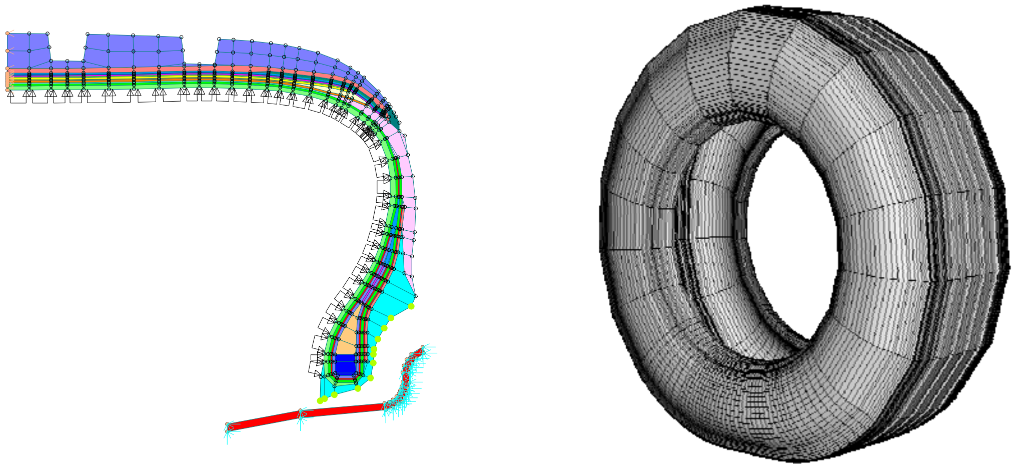

Figure 7: Axisymmetrical and three-dimensional tire model

Figure 8 shows the footprint normal pressure distribution of a free rolling and a cornering tire. If rolling over an obstacle is subject of the investigation, a transient time-dependent simulation needs to be chosen. An explicitly rolling tire is seen in Figure 8. In this case, a fine and constant discretization in circumferential direction is required which leads to small time steps in order to ensure a stable explicit time-stepping procedure. Adaptive discretization of the geometry (Figure 7) is restricted to static and steady state simulations.

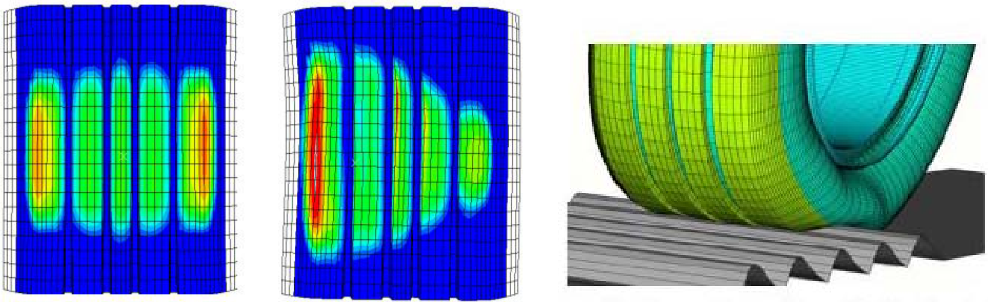

Figure 8: Footprint pressure of steady state rolling tire (free rolling, cornering) and transient rolling tire

Significant tire mechanical properties are computed out of the (steady state) rolling tire. Usually, the simulation is based on an elastic material characterization. Inelastic effects like rolling resistance, heating of tire at high speed due to dissipation or changing tire contours as a consequence of the material’s history cannot be captured by an elastic steady state formulation. For this type of description, a non-local material history consideration is needed which might lead to a total modification of the FE-data structure of the problem’s coefficient matrices.

5 Durability Investigations

Reliability and durability of industrial products are significant features in order to meet quality and safety requirements. Especially the tire is a safety relevant part of the vehicle. All forces of the driving maneuver are transmitted via the tire and the quite small contact patch to the pavement surface.
A number of criteria based on strain energy density, stresses or strains are in use to access durability. A more rigorous physical basis is given for considerations founding on fracture mechanics. After the Firestone tire failure (see Govindjee [4] for further details), a significant amount of attention has been drawn to fracture investigations of tires.

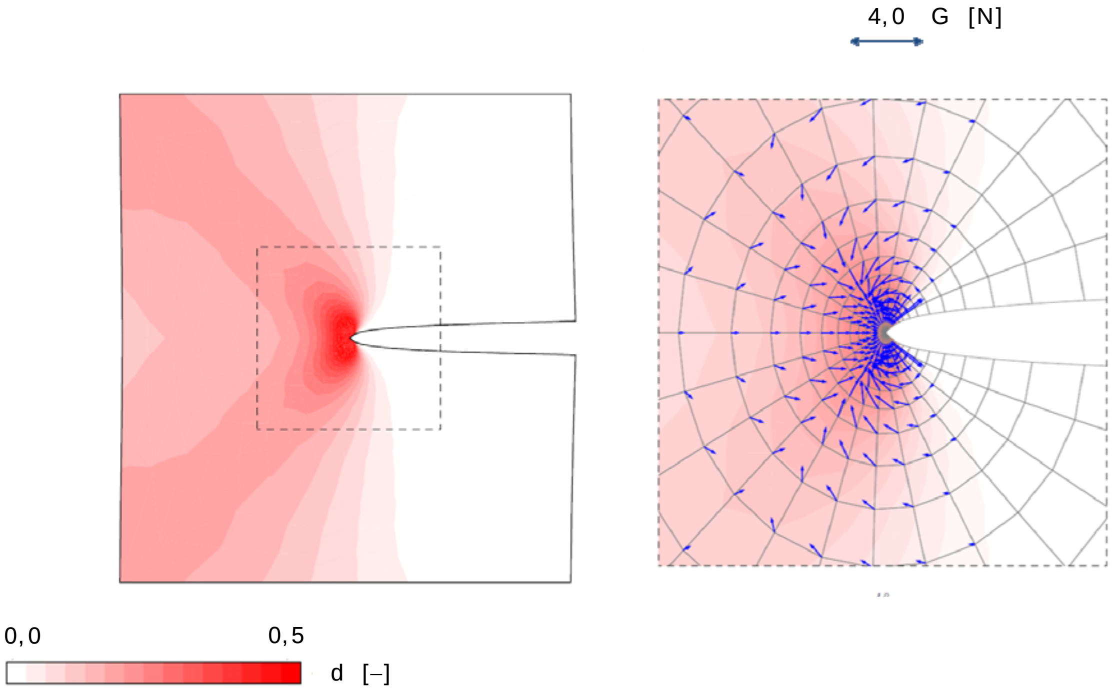

Figure 9: Field of damage variable and material nodal forces based on Eshelby stress tensor

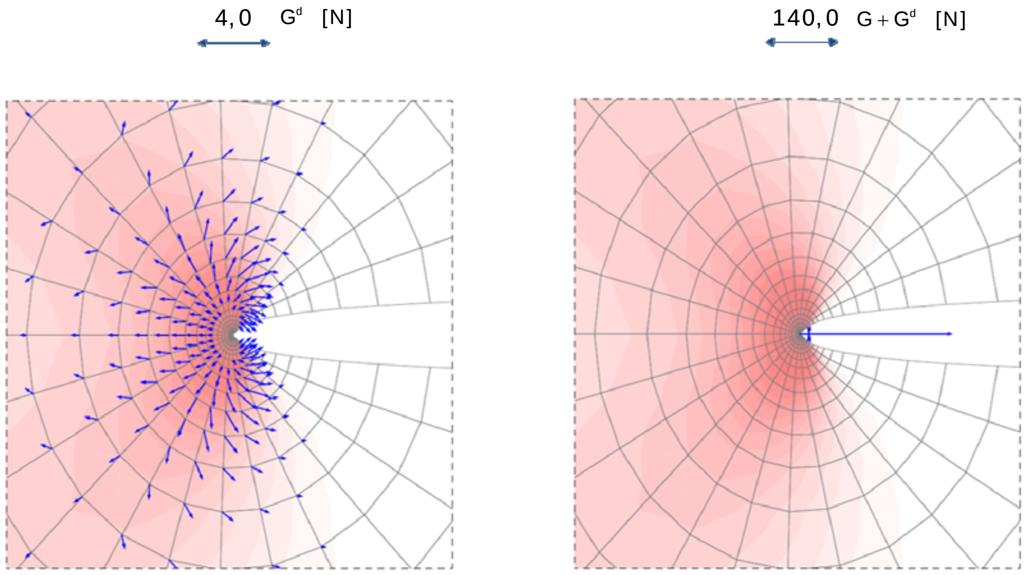

Figure 10: Material nodal forces based on damage variable and sum of material nodal forces

Investigations using traditional fracture mechanical methods like the J-integral (Rice [16]) or the material force approach (Braun [2]) yield the energy release rate for an evaluation of fracture sensitivity. For example, Figure 9 shows a cracked plate which is made out of irreversible softening rubber material. The field of the damage variable is depicted (Figure 9, left). The material force method can be evaluated with respect to inelastic material formulations taking the material derivative of the history variable into account (see Näser et al. [12], [13] among others). The component computed out of the Eshelby stress tensor (Figure 9, right) and the contribution originated in the history damage variable (Figure 10, left) yield as the sum of both parts (Figure 10, right) the material equilibrium. The large crack tip nodal material force vector can be interpreted as the crack driving force. The length of its projection onto the crack direction is finally equivalent to the energy release rate.

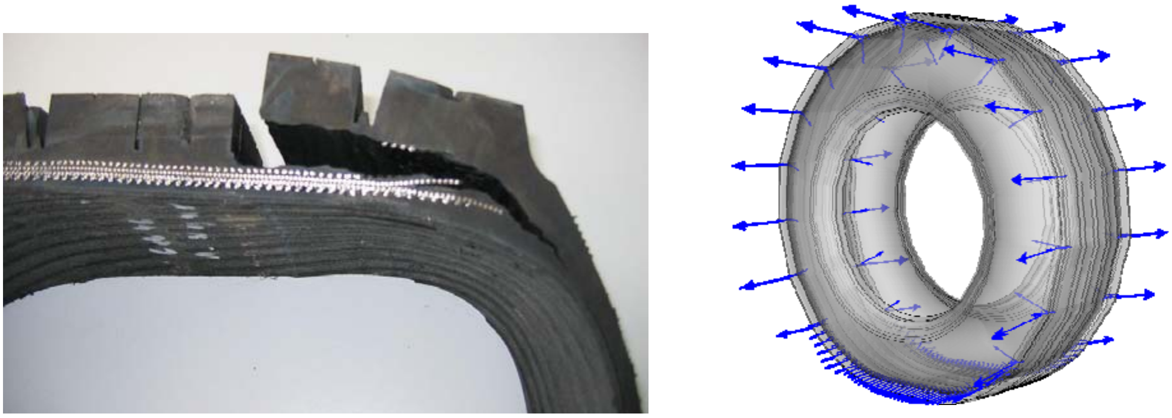

Figure 11: Failed tire and material nodal force distribution in circumference

As can be seen in Figure 11, cracks within the tire may start growing from the belt edges into the center part and become unstable and cause sudden failure of the structure. Reasons might be the large difference in stiffness at the belt edge and the production process.

The circumferential distributions of material nodal forces, which can be seen as being equivalent to crack driving forces, are shown in Figure 11 (see also Näser et al. [13]). From the length of the material force vector, the energy release rate and the J-integral can be computed. In contrast to energy density or stress and strain based criteria, an assumed crack geometry needs to be discretized. By computing the material nodal forces, a clear separation of the different energy contributions is possible in order to distinguish contributions associated with crack advancement and parts associated with dissipation coming from the inelastic material properties like viscoelasticity (Näser et al. [12]). In combination with the so-called Paris plot (Paris et at. [15]), where the crack growth rate as function of the energy release rate is depicted, a physically based life time prediction of the tire could be developed (see Näser et al. [13] for further details).

6 Tire-Pavement-Interaction

In the scientific literature, no complex 3D and coupled modeling of the tire-pavement-system has been reported so far. Usually, one of the components, either pavement or tire, is strongly simplified. Thus, the outcome of the investigation is limited due to the modeling constraints. With an approach at hand coupling fine discrtizations of both parts via the contact patch (see Figure 12), these restrictions can be overcome. A realistic sensitivity study for both coupled subsystems leading to the relevant influence factors can be achieved. A structural understanding of the mechanics of the coupled system will be developed and give insight into detailed parts of the subsystems.

The mechanical impact of tires on pavements is usually modelled as a spatially stationary load distributed over a certain contact area. To eliminate the drawbacks associated with a simplified modeling of the pavement loading, it is aimed to use a steady state rolling formulation for the tire as well as a steady state transversal moving discretization for the pavement structure. This formulation permits to use FE-models for pavements that are based on a Lagrangian approach, and requires additionally an Eulerian formulation to account for the relative displacement between tire and pavement materials during rolling of the tire.

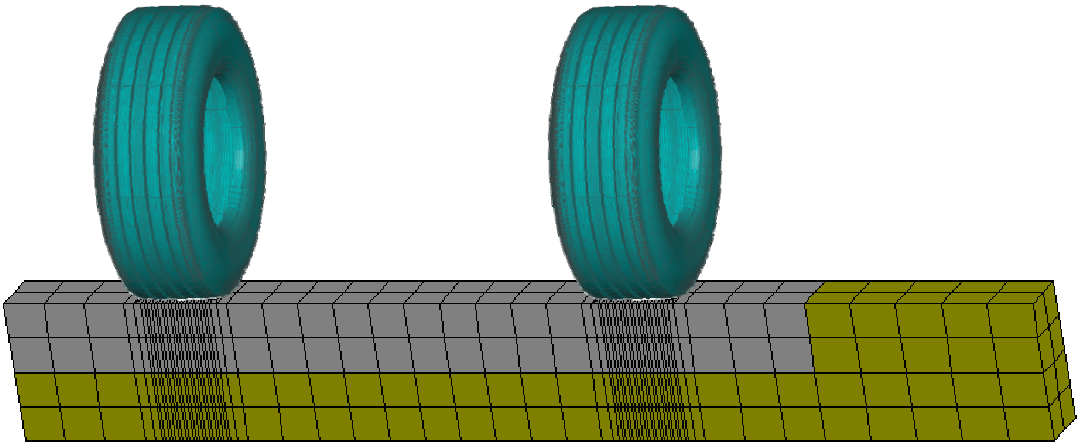

Figure 12: Tire-pavement-model

The resulting vertical stresses are shown in Figure 13 after consideration of tire and temperature loading of the pavement construction (Kaliske et al. [8]). As the mechanical properties of the pavement (stiffness, strength, inelasticity) are very sensitive to temperature, which changes during day and night, summer and winter strongly, an one sided coupled thermo-mechanical investigation is used.

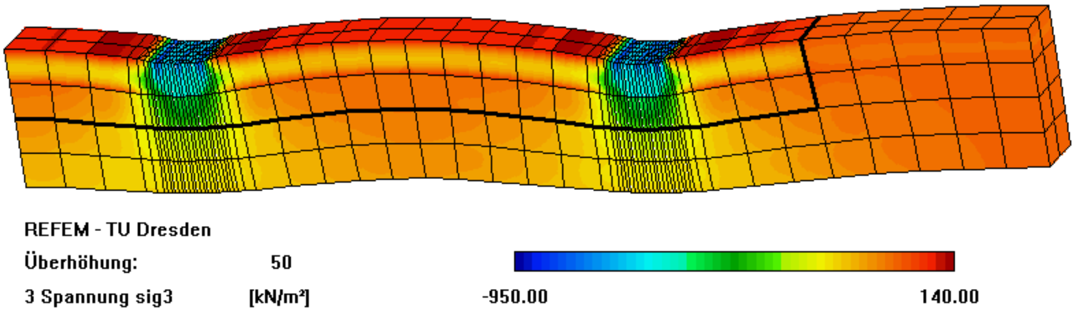

Figure 13: Vertical pavement stresses at tire and temperature loading

7 Robust Tire Design

So far, a sharp deterministic description has been the goal of the development. In order to obtain a full and realistic picture of the structural behavior, uncertainties, related to varying material or geometrical features need to be captured as well. Thus, a modeling of the used data by a non-deterministic approach has to be carried out. Hence, a fuzzy or fuzzy-stochastic analysis may be used, which maps uncertain structural input parameters onto an uncertain system response. Within the fuzzy FE-analysis, the identification of the variation of an uncertain fuzzy system response is an optimization task. Therefore, the FEM tire simulation is the fundamental deterministic solution of the fuzzy analysis and has to be carried out repeatedly several times within a run of the fuzzy analysis.

3D FEM tire simulations as described above are computational too time consuming for an implementation into the fuzzy FE-analysis. A more efficient approach is the application of metamodels (like e.g. neural networks) which approximate the response surface of the 3D FEM tire simulation.

Finally, the quantification of the variation of all uncertain parameters leads to a robustness measure. On this basis, robustness can be defined as the ratio of all uncertain structural input parameters and all uncertain system responses. A high variation of the uncertain structural input parameters and a minor variation of the uncertain system responses leads to a higher robustness.

Information on robustness of a tire design can be used to optimize the development process and will lead to a better understanding of more and less important input parameter for a robust tire design (see Kaliske et al. [10] for further details).

8 Summary

Future challenges in numerical tire simulation lie among others in the field of expanding the mechanical description not only by the temperature field but to consider chemical processes, i.e. ozone aging, change of material nature during the curing process or to consider fluid-structure-interaction during hydroplaning. Not only multi-physical phenomena but also multi-scales in time and length will bring further physical knowledge into the simulation procedures.

Thus, the tire structure is reliably accessible by current theoretical-numerical approaches and computational codes. Nevertheless, due to the complexity of the structure and its manifold influence factors, research in tire mechanics will go on steadily in order to provide new simulation tools and deeper insight into the structural behavior.

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