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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe werden sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.



Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

On the use of geometrically exact shells for dynamic tire simulation

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Abstract

In the present work a vehicular tire is modeled by using geometrically exact shells. The discretization is done with the help of isoparametric quadrilateral finite elements. The interpolation is performed with linear Lagrangian polynomials for the mid surface as well as for the director field. As time stepping method for the resulting DAE a modified midpoint rule is chosen. To handle the interaction with a rigid road surface, a one sided normal contact formulation is introduced. An orthotropic material model for geometrically exact shells derived from 3D continuum theory is used to describe the anisotropic behavior of the tire material. Inflation pressure is taken into account with a configuration dependent force. Some static simulations are presented and compared to measurements on a real tire.

Keywords: *geometrically exact shell, multibody dynamics, large rotations, dynamical contact, tire simulation*

1 Introduction

Acting as an interface between car and road, the tire model plays an outstanding role in dynamic simulations of vehicles. In commercial and scientific application contexts there exist several different modeling approaches for tires, depending on the use case. When the tire model has to be embedded into a multi body system (MBS) of a car, lumped parameter models of varying complexity consisting of springs and dampers are used, as well as simple data curve fits [10] in cases like real time simulation where ultimate computational performance is important. Likewise, very detailed but computationally demanding three dimensional finite element (FE) models are used for crash and misuse simulations [11]. However, a coupling of such 3D-FE tire models to MBS simulations is mostly not feasible — neither directly, nor via co-simulation — due to the large number of degrees of freedom (DOF).

Nevertheless, it would be highly desirable to have a continuum mechanics based structural model for tires available as an alternative with moderate number of DOF compatible with a direct usage in MBS simulations, and the main structural properties of a tire properly incorporated in order to be useful for practical applications. From the viewpoint of structural modeling, a good candidate for such a model are *geometrically exact shells* [12], which to the best of the authors' knowledge have not been used in tire modeling yet. This approach enables large rigid body motions, because stresses are constitutively related only to the differential invariants measuring membrane, bending and transverse shear strains. As mentioned above, the tire model should be incorporated into a multi body system. Flexible multi body dynamics with geometrically exact shells are discussed only in a few works [1, 2, 9]. By modeling the rim as a rigid body and fixing the shell on it, we get a first small flexible multi body system, which could be further extended, or already built into a slightly more complex MBS model like a quarter vehicle. To model a tire as a geometrically exact shell, a variety of features of the real physical object have to be included. An important task of the tire is the interaction with the road, hence, the shell model must be able to handle *one-sided dynamic contact* with a rigid road surface. Because of the reinforcements in the rubber matrix, an isotropic material law, often used in connection with geometrically exact shells, is not desirable for a realistic simulation. Therefore, a more complex *anisotropic material* model must be chosen and transferred to the shell. To absorb high loads, a tire is supported by inflation pressure, this leads to a configuration dependent force in continuum mechanics. For that reason, the geometrically exact shell must be able to handle so called *life loads*. In the following we will present first results, focused on first static simulations.

An outline of the present work is as follows. Section 2 illustrates the continuum mechanical theory behind the geometrically exact shell model. In Section 3 the spatial discretization and the time integration method is presented. Section 4 gives a summary of all features which are already included in the tire model. Some numerical results are shown in Section 5. A conclusion and outlook on further work is given in Section 6.

2 Continuum mechanical basics

In this section a short introduction into the kinematics of geometrically exact shells is given, with focus on the connection to three dimensional continuum theory. Let $\varphi : \omega \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be a parametrization of the midsurface. Additionally a director field $\mathbf{d} : \omega \rightarrow S^2 := \{\mathbf{x} \in \mathbb{R}^3 \mid \|\mathbf{x}\| = 1\}$ is prescribed. These two functions and the thickness variable $\zeta \in [-\frac{h}{2}, \frac{h}{2}]$ define the three dimensional configuration

$$\phi(\xi, \zeta) := \varphi(\xi) + \zeta \mathbf{d}(\xi) \quad (1)$$

of the shell, where ϕ is a mapping from the three dimensional parameter domain $\Omega := \omega \times [-\frac{h}{2}, \frac{h}{2}]$ into the three dimensional space. The covariant basis of this continuum is given by $\mathbf{g}_\alpha := \mathbf{a}_\alpha + \zeta \mathbf{d}_{,\alpha}$ and $\mathbf{g}_3 = \mathbf{d}$. Here $\mathbf{a}_\alpha := \varphi_{,\alpha}$ are the tangential vectors of the midsurface and $\mathbf{a}_3 = \frac{\mathbf{a}_1 \times \mathbf{a}_2}{\|\mathbf{a}_1 \times \mathbf{a}_2\|}$ defines the surface normal. If Greek indices are used, they represent the numbers $\{1,2\}$, and Latin indices represent $\{1,2,3\}$. The metric of the shell continuum is given by $g_{ij} := \mathbf{g}_i \cdot \mathbf{g}_j$. The contravariant basis \mathbf{g}^i is calculated by the following system of equations $\mathbf{g}_i \cdot \mathbf{g}^j = \delta_i^j$. In accordance with the theory of directed surfaces, three differential invariants are defined

$$a_{\alpha\beta} = \mathbf{a}_\alpha \cdot \mathbf{a}_\beta, \quad 2\kappa_{\alpha\beta} := \mathbf{a}_\alpha \cdot \mathbf{d}_{,\beta} + \mathbf{a}_\beta \cdot \mathbf{d}_{,\alpha}, \quad \gamma_\alpha = \mathbf{a}_\alpha \cdot \mathbf{d}, \quad (2)$$

measuring membrane deformation, spatial bending and transverse shearing of the shell continuum. The metric tensor is rewritten as $g_{\alpha\beta} = a_{\alpha\beta} + \zeta \kappa_{\alpha\beta} + O(\zeta^2)$ and $g_{\alpha 3} = \gamma_\alpha$. The unit length condition implies $g_{33} = 1$. The terms of second order in ζ are ignored, because the shell is assumed to be thin. A stress free reference configuration $\phi_0 = \varphi_0 + \zeta \mathbf{d}_0$ is defined. Its director is postulated normal to the midsurface, so the equality $\mathbf{d}_0 = \mathbf{A}_3$ holds. For the quantities of the references configuration uppercase letters are used. As \mathbf{d}_0 is normal to the midsurface, the shear term $\Gamma_\alpha = 0$ and $G_{\alpha 3} = G^{\alpha 3} = 0$ vanish. With the two parameterizations ϕ_0 and ϕ , the deformation of the shell continuum is given by $\Phi := \phi \circ \phi_0^{-1}$. The gradient of this mapping is written in terms of the co- and contravariant basis of the two configurations in the form $F := \nabla \Phi = \mathbf{g}_i \otimes \mathbf{G}^i$. As nonlinear strain measure the Green-Lagrange tensor $2E = F^T F - \mathbb{I}$ is chosen, which in the case of a geometrically exact shell takes the form

$$\begin{aligned} 2E &= (g_{ij} - G_{ij}) \mathbf{G}^i \otimes \mathbf{G}^j \\ &= (\mathbf{m}_{\alpha\beta} + \zeta \mathbf{b}_{\alpha\beta}) \mathbf{G}^\alpha \otimes \mathbf{G}^\beta + \mathfrak{s}_\alpha (\mathbf{G}^\alpha \otimes \mathbf{G}^3 + \mathbf{G}^3 \otimes \mathbf{G}^\alpha). \end{aligned} \quad (3)$$

This measure detects only differences in membrane $\mathbf{m}_{\alpha\beta} = a_{\alpha\beta} - A_{\alpha\beta}$, bending $\mathbf{b}_{\alpha\beta} = \kappa_{\alpha\beta} - \varkappa_{\alpha\beta}$ and shear forms $\mathfrak{s}_\alpha = \gamma_\alpha - \Gamma_\alpha$ as strains. Therefore, arbitrary rigid body motions cause no strain contribution. There is no strain in normal direction $E_{33} = 0$ in the undeformed reference surface, due to the unit length condition. This corresponds to a so called state of plain strain. The second Piola Kirchoff \mathbf{S} tensor is the corresponding work conjugate stress measure. In case of small local deformations, a linear connection between stresses and strains is assumed. According to Hookes law, the material law is written with a fourth order tensor \mathbb{C} as

$$\mathbf{S} = \mathbb{C} : \mathbf{E}. \quad (4)$$

In case of an inhomogeneous shell, (4) holds only pointwise. Therefore \mathbb{C} also depends on the position in the continuum. The components of the material tensor \mathbb{C} are needed in the basis $\mathbf{G}_i \otimes \mathbf{G}_j \otimes \mathbf{G}_k \otimes \mathbf{G}_l$, which corresponds to a relation $S^{kl} = \mathbb{C}^{kl ij} E_{ij}$ of the tensor components. For arbitrary linear materials, the components of the tensor \mathbb{C} must have the following symmetries: $\mathbb{C}^{ijkl} = \mathbb{C}^{klij}$ and $\mathbb{C}^{ijkl} = \mathbb{C}^{jikl} = \mathbb{C}^{ijlk}$. If isotropy is assumed, the material tensor simplifies to $\mathbb{C}^{ijkl} = L_1 G^{ij} G^{kl} + L_2 (G^{ik} G^{jl} + G^{il} G^{jk})$ with the two scalar Lamé parameters L_1 and L_2 . For a special kind of orthotropy, the material tensor will be discussed in detail in section 4.3. The following procedure applies to both cases. Because of $G^{\alpha 3} = 0$, the terms $\mathbb{C}^{\alpha 333} = \mathbb{C}^{\alpha\beta\pi 3} = 0$ vanish, see [5]. Therefore the components of the second Piola Kirchoff stress tensor read

$$S^{\alpha\beta} = \mathbb{C}^{\alpha\beta\iota\pi} E_{\iota\pi} + \mathbb{C}^{\alpha\beta 33} E_{33}, \quad S^{\alpha 3} = \mathbb{C}^{\alpha 3\iota 3} E_{\iota 3} + \mathbb{C}^{\alpha 33\iota} E_{3\iota}, \quad S^{33} = \mathbb{C}^{33\iota\pi} E_{\iota\pi} + \mathbb{C}^{3333} E_{33}. \quad (5)$$

Due to the unit length assumption, we have plain strain $E_{33} = 0$. In order to prevent the occurrence of reactive stresses along the normal direction of the mid surface, the assumption $S^{33} = 0$ (plain stress) is made. If this is applied in (5), a virtual strain in normal direction is calculated $E_{33} = -\mathbb{C}^{33\iota\pi} / \mathbb{C}^{3333} E_{\iota\pi}$. This approach yields two independent constitutive relations

$$\mathfrak{e}^{\alpha\beta\iota\pi} = \mathbb{C}^{\alpha\beta\iota\pi} - \frac{\mathbb{C}^{\alpha\beta 33} \mathbb{C}^{33\iota\pi}}{\mathbb{C}^{3333}}, \quad \mathfrak{S}^{\alpha\iota} = \mathbb{C}^{\alpha 3\iota 3} + \mathbb{C}^{\alpha 33\iota}. \quad (6)$$

Membrane and bending strains imply tangential stresses in the midsurface $S^{\alpha\beta} = \mathfrak{e}^{\alpha\beta\iota\pi} (\mathbf{m}_{\iota\pi} + \zeta \mathbf{b}_{\iota\pi})$ and shear strains affects transverse shear stresses $S^{\alpha 3} = \mathfrak{S}^{\alpha\iota} \mathfrak{s}_\iota$. In particular there is no coupling between these two cases.

3 The weak formulation of the underlying shell formulation

The weak solution theory and its discretization are the topics of this section. By integration over the thickness variable, a two dimensional shell formulation similar to [12] is achieved. The resulting equations are discretized in space and time by the approach presented in [2].

In FE formulations of three dimensional continuum mechanics test functions $\delta\Phi$ are required. In case of shell kinematics one for the midsurface $\delta\varphi : \omega \rightarrow \mathbb{R}^3$ and another one for the director $\delta\mathbf{d} : \omega \rightarrow T_{\mathbf{d}}S^2 := \{\delta\mathbf{d} \in \mathbb{R}^3 \mid \delta\mathbf{d} \cdot \mathbf{d} = 0\}$ are required. The test function of the shell is defined as $\delta\phi(\xi, \zeta) := \delta\varphi(\xi) + \zeta\delta\mathbf{d}(\xi)$ at the parameter domain. If this function is connected with the inverse mapping of the reference configuration, a suitable test function $\delta\Phi := \delta\phi \circ \phi_0^{-1}$ is achieved. The deformation Φ and the associated test function $\delta\Phi$ are mappings from reference configuration \mathcal{B}_0 into the three dimensional space. Conservation of linear momentum in relation to the second Piola Kirchoff tensor reads

$$G(\Phi, \delta\Phi) = \underbrace{\int_{\mathcal{B}_0} \mathbf{S} : \delta\mathbf{E} \, dV}_{G_{\text{int}}(\Phi, \delta\Phi) :=} + \underbrace{\int_{\mathcal{B}_0} \rho\ddot{\Phi} \cdot \delta\Phi \, dV}_{G_{\text{dyn}}(\Phi, \delta\Phi) :=} + \underbrace{\int_{\mathcal{B}_0} f \cdot \delta\Phi \, dV}_{G_{\text{ext}}(\delta\Phi) :=} = 0. \tag{7}$$

We eliminate the ζ dependence in the material law with the assessment $G^{\alpha\beta} \approx A^{\alpha\beta}$. The integration of the thickness variable is executed by substitution

$$\begin{aligned} G_{\text{int}}(\Phi, \delta\Phi) &= \int_{\omega} \int_{-\frac{h}{2}}^{\frac{h}{2}} \mathbf{E} : \mathbb{C} : \delta\mathbf{E} \, \det(A) \, d\zeta \, d\xi \\ &= h \int_{\omega} \mathbf{m} : \mathbb{C} : \delta\mathbf{m} \, \det(A) \, d\xi + \frac{h^3}{12} \int_{\omega} \mathbf{b} : \mathbb{C} : \delta\mathbf{b} \, \det(A) \, d\xi + h \int_{\omega} \mathbf{s} : \mathbb{S} : \delta\mathbf{s} \, \det(A) \, d\xi. \end{aligned} \tag{8}$$

The linear terms in ζ vanish $\int \zeta \dots d\zeta = 0$, through the assumption that the material is at least symmetric across the normal. Otherwise, coupling terms between bending and membrane strains arise, see for example [4]. The integration in G_{dyn} and G_{ext} is done in the same way.

3.1 Spatial discretization

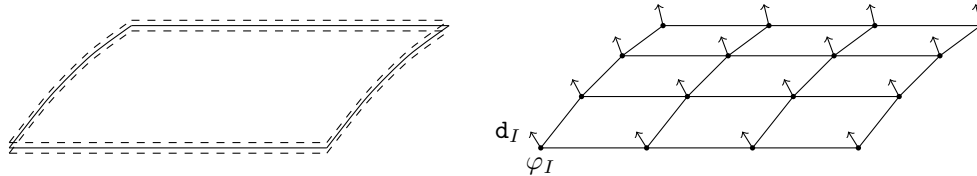


Figure 1: discretization with quadrilateral finite elements, with nodal DOFS

The solution of the problem $G(\Phi, \delta\Phi) = 0 \, \forall \delta\Phi$, requires a discretization of Φ and $\delta\Phi$. In space isoparametric interpolation with quadrilateral finite elements are used, see Figure 1. The midsurface and the director are discretized by the same piecewise linear Lagrangian shape function N^I with associated nodal values $\varphi_I, \mathbf{d}_I \in \mathbb{R}^3$

$$\varphi^h(\xi) = \sum_I^{n_{\text{node}}} \varphi_I N^I(\xi) \quad \mathbf{d}^h(\xi) = \sum_I^{n_{\text{node}}} \mathbf{d}_I N^I(\xi). \tag{9}$$

All other involved functions are discretized in the same way. Inserting the discretization into the weak form $G(\Phi^h, \delta\Phi^h)$ and neglecting the dynamical part G_{dyn} , we end up with a $6n_{\text{node}}$ dimensional nonlinear system of equation for the nodes $\mathbf{q}_I = (\varphi_I, \mathbf{d}_I)^T \in \mathbb{R}^6$:

$$R(\mathbf{q}) = F \in \mathbb{R}^{6n_{\text{node}}}, \quad \mathbf{q} := (\mathbf{q}_1 \ \dots \ \mathbf{q}_{n_{\text{node}}})^T. \tag{10}$$

To avoid shear locking, the approach from [6] is used. It is assumed that the director is fully three dimensional, the fact that $\mathbf{d} \in S^2$ has not been considered yet. This issue is resolved with Lagrangian multipliers λ_I , which ensures in every node, that the unit length condition $\|\mathbf{d}_I\| = 1$ is fulfilled. This results in additional equations $\Lambda_I(\mathbf{q}) := \frac{1}{2}(\mathbf{q}_I \cdot \mathbf{q}_I - 1) = 0$

and a constraint force $\mathbf{G}^T \lambda$ with $\mathbf{G} \in \mathbb{R}^{n_{\text{node}} \times 6n_{\text{node}}}$ and $\lambda = (\lambda_1, \dots, \lambda_{n_{\text{node}}})^T$. For the quasi statical problem a nonlinear system of e equation is obtained

$$\begin{aligned} R(\mathbf{q}) - \mathbf{G}^T \lambda &= F \\ \Lambda(\mathbf{q}) &= 0 \end{aligned} \quad (11)$$

which is solved with Newton's Method. Like in [12, 15], the stiffness matrix $K \in \mathbb{R}^{6n_{\text{node}} \times 6n_{\text{node}}}$ of $R(\cdot)$ is calculated by taking the Frechét derivative of $G_{\text{int}}(\Phi, \delta\Phi)$ and discretize the linearization.

3.2 Time discretization

If a transient simulation has to be done, the term G_{dyn} in (7) must by considered, too. Hence, the spatially discrete function has to depend on the time variable t . This is realized by time dependent nodal values

$$\varphi^h(\xi, t) = \sum_I^{n_{\text{node}}} \varphi_I(t) N^I(\xi), \quad \mathbf{d}^h(\xi, t) = \sum_I^{n_{\text{node}}} \mathbf{d}_I(t) N^I(\xi). \quad (12)$$

By substituting $\mathbf{v}(t) := \dot{\mathbf{q}}(t)$ a differential algebraic equation (DAE) arises

$$\begin{aligned} \dot{\mathbf{q}}(t) &= \mathbf{v}(t), \\ M\dot{\mathbf{v}}(t) &= -R(\mathbf{q}(t)) + \mathbf{G}^T \lambda(t) - F(t), \\ 0 &= \Lambda(\mathbf{q}), \end{aligned} \quad (13)$$

where M is the mass matrix resulting from the discretization of G_{dyn} . The DAE system (13) is integrated by the midpoint rule, which on the representative time intervall $[t_n, t_{n+1}]$ is defined in the following way:

$$\begin{aligned} \mathbf{q}_{n+1} - \mathbf{q}_n &= \frac{\Delta t}{2} (\mathbf{v}_{n+1} + \mathbf{v}_n), \\ M(\mathbf{v}_{n+1} - \mathbf{v}_n) &= -\Delta t R(\mathbf{q}_{n+\frac{1}{2}}) + \Delta t \mathbf{G}(\mathbf{q}_{n+\frac{1}{2}})^T \lambda_{n+1}, \\ \Lambda(\mathbf{q}_{n+1}) &= 0. \end{aligned} \quad (14)$$

All quantities $(\mathbf{q}_n, \mathbf{v}_n, \lambda_n)$ of the discrete shell are known at time t_n . With the set of equations (14) the states at t_{n+1} are calculated. This approach yields conservations of linear and angular momentum even in the discretized case, see [2]. The dependence between the discrete velocities and positions is linear, therefore \mathbf{v}_{n+1} is substituted and recalculated after the nonlinear system is solved. We end up with a system involving seven degrees of freedom φ_I , \mathbf{d}_I and λ_I per node. This over determination is resolved with the help of a mapping $\mathcal{F}(u, \mathbf{q}_n) = \mathbf{q}_{n+1}$, with the local parametrization $u \in \mathbb{R}^{5n_{\text{node}}}$. In the position variable a linear displacement is used. For the director a rotation is prescribed by two angles. This mapping ensures that the vector \mathbf{d}_I has unit length. With a discrete null space matrix $P(\mathbf{q}_n, \mathbf{q}_{n+1})$, the constraint forces in $\mathbf{G}^T \lambda$ are eliminated. Instead of seven DOF, only five are left per node. For more details of the parametrization and the discrete null space method see [2, 9].

4 Additional extensions

The discrete shell element is extended, to capture the main features of a tire in a MBS simulation. Normal contact with a rigid road surface is integrated with a penalty method. The inflation of the tire is handled with a configuration depended force. A three dimensional orthotropic material law is transferred onto the shell. The incorporation into the MBS is briefly summarized.

4.1 One sided normal contact

The tire has to interact with a rigid road, which is given via a height profile $X = (x, y, h(x, y))^T$. Also its first two derivatives are analytically given. The rigidity of the road and its explicit description substantially simplifies the problem, compared to contact problems of two elastic discrete bodies. The second contact partner is the outer surface of the shell continuum, which is given by $\chi(\xi) := \varphi(\xi) + \frac{h}{2} \mathbf{d}(\xi)$. For every point in this surface χ a associated one in the road with

minimal distance is calculated by $\hat{X} = \operatorname{argmin} \|X - \chi\|$. This is achieved by Newton’s method, because even the second order derivatives of $h(x, y)$ are given. Having the minimal distance point \hat{X} , a penetration function is defined

$$g(\xi) = \begin{cases} 0 & (\chi(\xi) - \hat{X}) \cdot \hat{\mathbf{n}} > 0 \\ (\chi(\xi) - \hat{X}) \cdot \hat{\mathbf{n}} & (\chi(\xi) - \hat{X}) \cdot \hat{\mathbf{n}} \leq 0 \end{cases}, \tag{15}$$

where $\hat{\mathbf{n}}$ is the normal of the road surface in \hat{X} . Its variation is calculated as

$$\delta g = \delta \chi \cdot \mathbf{n} = \left(\delta \varphi + \frac{h}{2} \delta \mathbf{d} \right) \cdot \mathbf{n} = \left(\delta \varphi \quad \delta \mathbf{d} \right) \begin{pmatrix} \mathbf{n} \\ \frac{h}{2} \mathbf{n} \end{pmatrix}. \tag{16}$$

With a positive scalar value $\epsilon > 0$, a penalty term is added to the balance of linear momentum (7)

$$G(\phi, \delta \varphi) + \epsilon \int_{\omega} g(\xi) \delta g(\xi) d\xi = 0. \tag{17}$$

A force proportional to penetration depth and in direction of the normal is acting on the outer shell surface in case of contact. In the discrete problem the integral in (17) is evaluated in every node \mathbf{q}_I

$$\epsilon \int_{\omega} g(\xi) \delta g(\xi) d\xi \approx \epsilon \sum_I^{n_{\text{node}}} g_I \left(\delta \varphi_I \quad \delta \mathbf{d}_I \right) \begin{pmatrix} \mathbf{n}_I \\ \frac{h}{2} \mathbf{n}_I \end{pmatrix}, \tag{18}$$

with $g_I = g(\mathbf{q}_i)$. Due to the nonlinearity of the problem, the derivative of the contact term must be evaluated to perform a Newton step. The contribution to the tangential matrix at a the node \mathbf{q}_I is given by

$$K_{II}^c = \epsilon \begin{pmatrix} \mathbf{n}_I \\ \mathbf{n}_I \end{pmatrix} \begin{pmatrix} \mathbf{n}_I & \mathbf{n}_I \end{pmatrix} = \epsilon \begin{pmatrix} \mathbf{n}_I \otimes \mathbf{n}_i & \frac{h}{2} \mathbf{n}_I \otimes \mathbf{n}_i \\ \frac{h}{2} \mathbf{n}_I \otimes \mathbf{n}_i & \frac{h^2}{4} \mathbf{n}_I \otimes \mathbf{n}_i \end{pmatrix}. \tag{19}$$

The presented method only detects contact at the nodes of the finite element mesh. The number of contact points could be increased by using another integration scheme for (17). The evaluation inside the elements is one possibility. This would increase the number of possible contact points depending on the used quadrature rule.

4.2 Pressure load

A tire is inflated with a certain pressure, which is assumed spatially constant. For this reason, a additional force arises at the surface pointing into normal direction. The incorporation of a pressure load into a 3D continuum based FE concept is presented in [13]. This approach is adopted for the midsurface, which yields a contribution to the weak form

$$G_p(\Phi, \delta \Phi) = \int_{\varphi(\omega)} p \mathbf{a}_3 \cdot \delta \varphi d\varphi = \int_{\omega} p (\mathbf{a}_1 \times \mathbf{a}_2) \cdot \delta \varphi d\xi. \tag{20}$$

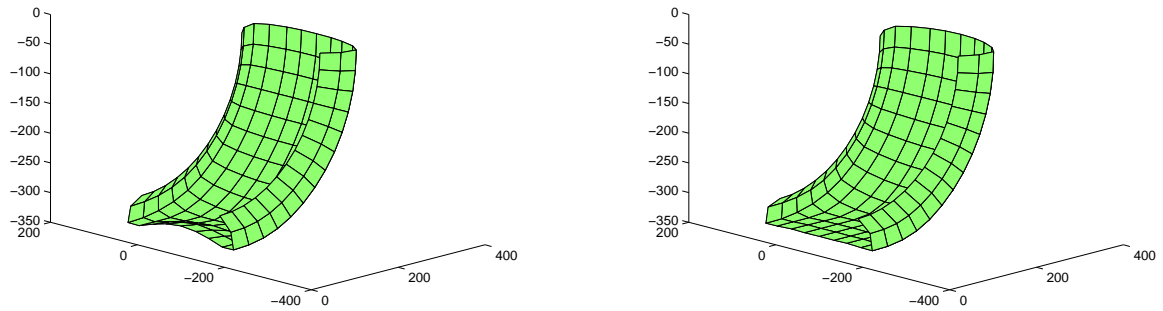
The integral is taken over the deformed configuration, to create the correct force. The discretization $\varphi^h(\xi) = \sum_I \varphi_I N^I(\xi)$ is inserted in (20). After some algebraic manipulations the discretized version of the pressure term reads

$$G_p(\varphi^h, \delta \varphi^h) = \sum_I \sum_J \sum_K \delta \varphi_K \cdot (\varphi_I \times \varphi_J) \int_{\omega} N_{,1}^I N_{,2}^J N^K d\xi. \tag{21}$$

In contrast to F in (11), the force depends on the current discrete configuration φ_I . As a consequence, for the solution procedure the contribution to the tangential matrix has to be computed

$$K_{IJ}^p = \begin{pmatrix} \sum_K \hat{\varphi}_K \int_{\omega} (N_{,1}^I N_{,2}^J - N_{,2}^I N_{,1}^J) d\xi & 0_{3 \times 3} \\ 0_{3 \times 3} & 0_{3 \times 3} \end{pmatrix}, \tag{22}$$

where $\hat{\varphi}_K \in \mathbb{R}^{3 \times 3}$ is defined, such that for all $\mathbf{x} \in \mathbb{R}^3$ the equality $\hat{\varphi}_K \mathbf{x} = \varphi_K \times \mathbf{x}$ holds.



(a) Deflection of 35mm relative to the first contact, no inflation pressure

(b) Deflection of 35mm relative to the first contact, 2 bar inflation pressure

Figure 2: Midsurface of a tire in contact with a flat rigid surface

Together with normal contact formulation from section 4.1, a first static simulation is performed, see Figure 2. The discrete model is flattened out against a flat surface. In Figure 2a no pressure is present inside the wheel, which induces bending in the tread. The contact region is a small banded ellipse around the ideal contact patch. This phenomenon is also known in practice in case of under-inflation. In Figure 2b, the same simulation is shown with 2 bar inflation pressure. Hence, the bending vanishes and the tread is completely in contact with the road around the ideal contact patch.

4.3 Orthotropic material

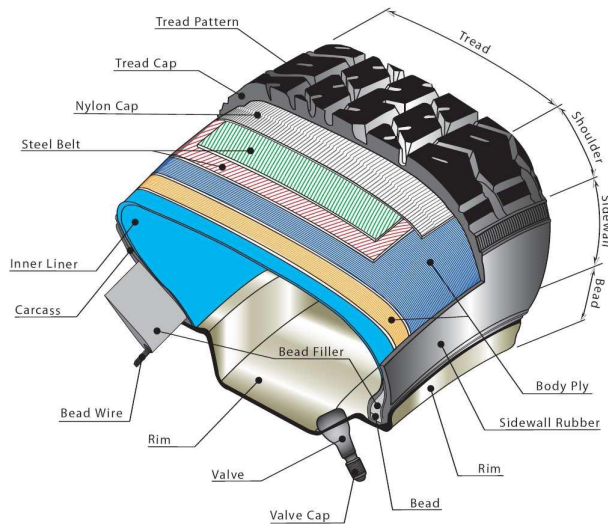


Figure 3: Structure of a passenger car tire

In the previous static simulation shown in Figure 2, the material of the shell was assumed to be homogeneous and isotropic. In contrast, an automotive tire is highly anisotropic, due to steel cords embedded into the rubber in different directions. Additionally across the thickness dimension there are many different layers, see Figure 3. We assume that the effective stiffness properties of this rather complex composite structure is represented in a condensed manner by an anisotropic constitutive law related to the midsurface. Otherwise coupling terms between bending and membrane strains arise, see [4]. An orthotropic material law in three dimensional space is assumed. There are three planes of symmetry orthogonal to each other. As a basis, an orthonormal reference frame $(\mathbf{N}_1, \mathbf{N}_2, \mathbf{N}_3)$ is defined, whose vectors are each perpendicular to another symmetrical plane. Correspondingly there are nine independent material parameters, which lead to a compliance

matrix in Voigt notation of the following form

$$\mathbb{S} = \begin{pmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & \frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{13}} \end{pmatrix}, \quad (23)$$

see [8] for example. To prescribe the material tensor \mathbb{C}_{orth} , two symmetric matrices $L_1, L_2 \in \mathbb{R}^{3 \times 3}$ are introduced, with zeros in the diagonal elements of L_2 . The entries of L_1 are functions of the three elastic moduli E_i and the three independent Poisson's ratios ν_{ij} . The second matrix is written in terms of the three shear modulus as $L_2^{ij} = L_2^{ji} = (1 - \delta^{ij})G^{ij}$, see [7]. The fourth order material tensor with respect to the basis \mathbf{N}_i is then given by

$$\mathbb{C}_{\text{ort}} := L_1^{ik} (\mathbf{N}_i \otimes \mathbf{N}_i \otimes \mathbf{N}_k \otimes \mathbf{N}_k) + L_2^{ik} (\mathbf{N}_i \otimes \mathbf{N}_k \otimes \mathbf{N}_i \otimes \mathbf{N}_k + \mathbf{N}_i \otimes \mathbf{N}_k \otimes \mathbf{N}_k \otimes \mathbf{N}_i).$$

The components of this material tensor are required w.r.t. to the the covariant Basis \mathbf{G}_j . These entries are calculated by $\mathbb{C}_{\text{ort}}^{ijkl} := (\mathbf{G}^i \otimes \mathbf{G}^j) : \mathbb{C} : (\mathbf{G}^k \otimes \mathbf{G}^l)$. Before the evaluation is done, an additional assumption on the material is made. One plane of symmetry is assumed to be equal to the tangential plain of the midsurface. As a consequence, without loss of generality $\mathbf{N}_3 = \mathbf{G}_3 = \mathbf{G}^3 = \mathbf{d}_0$ holds. It can be shown, that the same entries of the fourth order tensor vanish as in the isotropic case: $\mathbb{C}_{\text{ort}}^{\alpha\beta i3} = \mathbb{C}_{\text{ort}}^{\alpha333} = 0$. The plain stress assumption ($S^{33} = 0$) implies the use of the two independent material tensors \mathbb{C}_{ort} and \mathbb{S}_{ort} , as in the isotropic case. To compute the entries of \mathbb{C}_{ort} , it is sufficient to evaluate the four quantities

$$B_\alpha^\beta := \mathbf{N}_\alpha \cdot \mathbf{G}^\beta. \quad (24)$$

It is easy to see that the vectors \mathbf{G}_α and \mathbf{N}_α span the same plain. If the angle \aleph between \mathbf{G}_1 and \mathbf{N}_1 is known, it holds:

$$\mathbf{N}_1 = \cos(\aleph) \frac{1}{\sqrt{G_{11}}} \mathbf{G}_1 + \sin(\aleph) \frac{1}{\sqrt{G^{22}}} \mathbf{G}^2, \quad \mathbf{N}_2 = \sin(\aleph) \frac{1}{\sqrt{G_{11}}} \mathbf{G}_1 - \cos(\aleph) \frac{1}{\sqrt{G^{22}}} \mathbf{G}^2. \quad (25)$$

Hence, B_α^β can be computed, if in every point of the shell the angle \aleph is known. The entries in (24) are explicitly given by

$$\begin{aligned} B_1^1 &= \cos(\aleph) \frac{1}{\sqrt{G_{11}}} + \sin(\aleph) \frac{G^{12}}{\sqrt{G^{22}}}, & B_1^2 &= \sin(\aleph) \sqrt{G^{22}}, \\ B_2^1 &= \sin(\aleph) \frac{1}{\sqrt{G_{11}}} - \cos(\aleph) \frac{G^{12}}{\sqrt{G^{22}}}, & B_2^2 &= -\cos(\aleph) \sqrt{G^{22}}. \end{aligned} \quad (26)$$

Again the approximation $G^{\alpha\beta} \approx A^{\alpha\beta}$ is made, to eliminate the dependence of the thickness variable ζ . To transfer this results to the discrete shell, a restriction on the finite element mesh is made. It is assumed that two edges of the quadrilateral element, which describes the reference configuration, are parallel. This yields a constant angle \aleph inside the element. With that assumptions, nine material parameters and one angle \aleph prescribe the material law at the element level.

4.4 Connection to MBS

To incorporate a discrete shell into a multi body system, there are at least two possibilities. The first one is to build up a MBS and attach the shell with the help of joints. Coupled equations of motions are obtained, which calculate the quantities of the rigid bodies as well as each node of the discrete shell. In simulations with MBS car models for industrial applications, the tire is seen as complex force element, which delivers forces and torques in dependence of the kinematical state of the rim. Since the discrete shell is a dynamical system itself, a co-simulation is performed. The first approach is shown in [2]. Therefore the boundary nodes of the discrete mesh are rigidly linked to the rigid body defining the rim. This is done with the help of Lagrangian multipliers. Assume the node $\mathbf{q}_0 = (\varphi_0, \mathbf{d}_0)$ in the reference configuration should be connected to the rigid body with displacement $\mathbf{X}(t)$ and transformation matrix $R(t)$. The coupling constraints equation for the deformed node $\mathbf{q}(t)$ are

$$\varphi(t) - \mathbf{X}(t) - R(t)\varphi_0 = 0, \quad \mathbf{d}(t) \cdot (R(t)\hat{\mathbf{N}}_1) = 0, \quad \mathbf{d}(t) \cdot (R(t)\hat{\mathbf{N}}_2) = 0, \quad (27)$$

with $\hat{\mathbf{N}}_1$ and $\hat{\mathbf{N}}_2$, such that they built a orthonormal basis together with \mathbf{d}_0 . These five equations together with the corresponding Lagrangian multipliers, imply additional constraint forces to the discrete shell nodes as well as to the rigid

body. Due to that, the number of DOF increases. The over determination could be resolved similar to section 3.2, for more details see [2, 3, 9]. Nevertheless, the time integration must be done for the whole system.

If to the contrary the tire is requested as pure force element, the kinematical state of the rim is chosen as interface condition. With that input the discrete shell tire produces corresponding forces and torques as output. The interface in the tire model are the boundary points of the shell, which have to perform the rigid body motion prescribed from the rim. The resulting forces and torques are calculated by summing up all forces at the boundary nodes w.r.t. the center of the rim. The benefit of this strategy is that the MBS and the shell model could be integrated in time independently. Because they have a common interface, the communication of the two models has to be managed.

5 Numerical examples

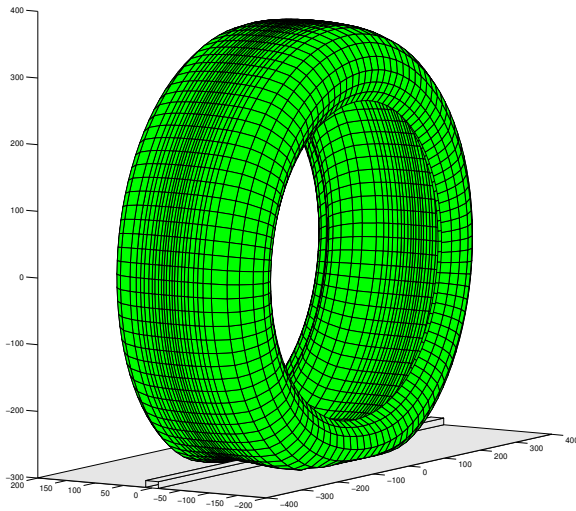


Figure 4: Tire modeled by shell elements, inflated with 2.5 bar air pressure and pressed against a cleat with height 10mm and width 20 mm

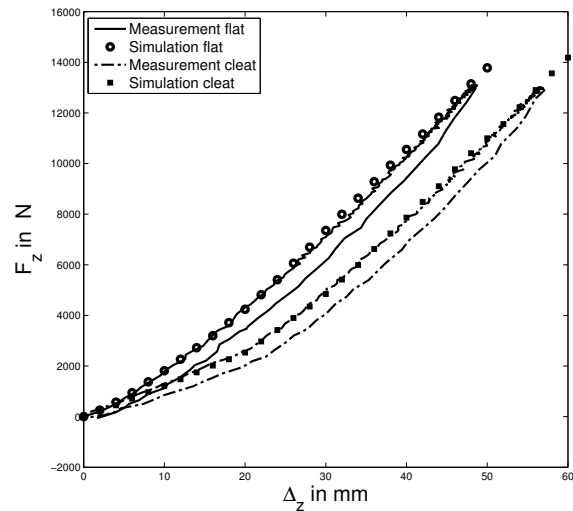


Figure 5: Results of the simulation plotted against measurements

Pressing the inflated tire against a flat rigid ground is the most simple experiment realized in a real physical test rig. Hereby, the stiffness of the tire is measured, which relates vertical deflection against the resulting force. The same test is done, with a cleat mounted on the flat surface, see Figure 4. Because the tire is not rolling, only normal contact is needed in this case. This two tests are simulated with the discrete shell model described above. As comparison a radial passenger car tire with 17 inches¹ rim diameter and 225 mm width is chosen. The inflation pressure is 2.5 bar for both tests. To built up the FE mesh, a cross section is discretized with a number of points representing the midsurface. By revolving this nodes around the center line of the rim, a 2D quadrilateral mesh is constructed representing the undeformed mid surface of the tire. The condition of two parallel edges, made in Section 4.3 to enable a simple representation (by a single angle quantity) of orthotropic materials at the discrete level, is fulfilled. In every node of the mesh a unit vector is needed, representing the discrete director. These are generated heuristically, in a way that they are approximately normal to the midsurface. In Figure 5, a comparison between simulation results and measurements is shown. The deflection is plotted against the resulting force acting in the rim center. As mentioned above, two different simulations are performed. In both cases the orthotropic material parameters from Table 1 are used.

	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
Tread	150MPa	10MPa	30MPa	0.1	0.4	0.4	36.36MPa	32.14MPa	7.14MPa
Sidewall	17MPa	19MPa	17MPa	0.2	0.4	0.4	7.5MPa	6.07MPa	6.43MPa

Table 1: Material data for the simulation. N_1 points into circumferential, N_2 in lateral direction.

The inhomogeneities are approximated by taking different parameters per element in the tread and the sidewall. The

¹The units do not match because of the usual standardization.

material data from Table 1 is adjusted, such that the simulation results match with the measurements in Figure 5. In the experimental data hysteresis effects are visible. This could not be reproduced in simulation, because in the present discrete shell model no damping or plastic effects are included. In our modeling approach the normal contact only detects the position of the nodes. Therefore a very detailed resolution of the tread must be used to detect contact with the cleat, see Figure 4. In the first simulation with a completely flat ground, the mesh could be much coarser with the same results.

6 Conclusion and outlook

In this work a finite element tire model based on geometrically exact shells has been introduced. To represent the essential features of a tire, the model is able to handle inflation pressure, orthotropic materials and one sided normal contact. Also the incorporation into a multi body system is possible directly or via co-simulation. The shell model is applied by simulating the flattening of a tire against two different road profiles. A short review of the time integration for the corresponding DAE is given.

In the current (not yet completed) version of our shell tire model, only normal contact is considered. Dynamic tangential contact modeling for frictional interaction between tire and road surface has not yet been incorporated into the model. As seen in section 5, the normal contact is only detected in the FE nodes. If a more detailed resolution is favored, the number of nodes must be increased in the contact patch. This raises the quantity of DOF and as a consequence the computational time. To parametrize the orthotropic material law of the shell, the simulation results are compared with real measurements. Hence, a suitable model which connects the structure of the material to the parameters would be highly desirable. To tackle this problems, will be the subject of the further work.

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