FINITE ELEMENT MODELLING OF OFF-ROAD TYRES

Johan Conradie
OBJECTIVES

- Explore the most recent developments in tyre modelling.
- Parameterize the properties of an “off-road” tyre through a range of simple experiments.
- Develop a tyre model that can solve fast enough to be used in multibody dynamic vehicle simulations. (The use of elements with equivalent homogeneous properties is investigated)
- Ensure that the tyre model can accurately simulate tyre behaviour. The tyre model will be validated and updated through the use of deformation profiles of the sidewall and radial load-vs.-displacement curves obtained from experiments.
Geometry of the tyre
(Measured using laser, stereovision,)

Material Properties
(Experimental testing of rubber, belts, bead wire)

Build a 2D FE model (MSC.Marc) based on the updated results

Structural static analysis of tyre mounting and inflation using axisymmetric model

Check correlation of tyre shape and stress distribution on carcass

Yes

3D model to perform radial static load tests (MSC.Marc)

Check tyre, load deflection curve, cleat tests (effective stiffnesses)

No

Modify/update model parameters

Yes

Acceptable Design
- Fairly good results
- Most deviations between laser profile and photogrammetry points are smaller than 4mm
- Larger deviations are found at the shoulder, tread blocks.
TYRE GEOMETRY

Solid Works Model

Section view of the tyre with some imported profiles shown.
Tyre segmenting
Shore hardness tests
Hyper elastic constitutive models

The Neo-Hookean model:

\[ W = C_{10}(I_1 - 3) \]

which is a special case of the Mooney-Rivlin form, with \( C_{01} = 0 \)

The Ogden Model:

\[ W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n} (\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3) \]
Orthotropic material properties

$$\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{23} \\
\gamma_{13} \\
\gamma_{12}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{23} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G_{12}
\end{bmatrix} \begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{23} \\
\tau_{13} \\
\tau_{12}
\end{bmatrix}$$

The following equations relate the material constants:

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}$$
$$\frac{\nu_{13}}{E_1} = \frac{\nu_{31}}{E_3}$$
$$\frac{\nu_{23}}{E_2} = \frac{\nu_{32}}{E_3}$$
TYRE STUDIED – MATERIAL PROPERTIES

- Experimental tests for material properties
- Tensile tests on each orthogonal direction
- Digital image correlation
TYRE STUDIED – MATERIAL PROPERTIES

Ogden fit for tangential sidewall stiffness

Orthotropic stiffness component in sidewall

σ (Sidewall-Tangent - Experiment)

σ (Sidewall-Tangent - Ogden fit)

σ (Young's modulus = 320 MPa)
TYRE STUDIED – MATERIAL PROPERTIES

Sidewall material properties in radial direction

\[ \sigma_{\text{sidewall,radial}} \approx \sigma_{\text{sidewall,tangential}} + \sigma \]

Orthotropic Young's Modulus = 320 MPa

\[ \sigma_{\text{sidewall,radial}} = \sigma_{\text{sidewall,radial - approximation}} \]

\[ \sigma_{\text{sidewall,radial - experiment}} \approx \sigma_{\text{sidewall,radial - experiment}} \]

\[ \sigma_{\text{Sidewall-Radial - Experiment}} \]

\[ \sigma_{\text{Sidewall-Tangent Experiment}} \]

\[ \sigma_{\text{(Sum R)}} = \sigma_{\text{Tangent}} + (320 \text{ Mpa})*\epsilon \]

\[ \sigma_{\text{FE Model}} \]
FE MODEL (2-D INFLATION)
The displacement and output from the actuator was measured and recorded during tests. The equipment used in the experimental measurements was as follow:

- Schenck PL100 Actuator
- 100 kN load cell
- Laser displacement sensor (Acuity AR700)
- eDaq data acquisitioning system
- K7500 Servo controller
- Solid frame for mounting of tyre
- Flatbed for mounting the lasers
- Cleats
FE MODEL (MARC)
The validity of the material properties in the three-dimensional tyre model was first checked by analysing the model with no internal pressure (simulating the deflated tyre).
GLOBAL STIFFNESS AND CLEAT TESTS

Load vs. Displacement (lateral cleats)

Load vs. Displacement (longitudinal cleats)
LOAD CASES ANALYSED

Effects of changing stiffnesses investigated

Vertical Tyre Stiffness for Longitudinal Cleats

- Applied Load [N]
- Displacement [m]

Graph showing the relationship between applied load and displacement for different stiffness values.
Using the same experimental setup, with the same cleats, the tyre profile was measured at the centre of indentation at different loading conditions, using two Acuity AR700 lasers.
LOAD VS. DISPLACEMENT & SIDEWALL PROFILES

25mm x 25mm Lateral cleat
25mm x 25mm Longitudinal cleat
CONCLUSIONS & ACHIEVEMENTS

• Established experimental methods for testing.
• Used accurately measured deformation profiles of the tyre to verify the tyre models' behaviour.
• A simple FE model was developed using the global material properties of sidewall, tread.
• Developed a finite element tyre model that can solve fairly fast.
• Investigate the use of two subsets of elements were superimposed onto each other to compensate for different stiffnesses caused by the steel wires, polyester and nylon threads.

The final FE model can successfully predict the vertical force vs. displacement, as well as side wall deformation of the tyre under static loading conditions on both a flat surface and various different cleats.