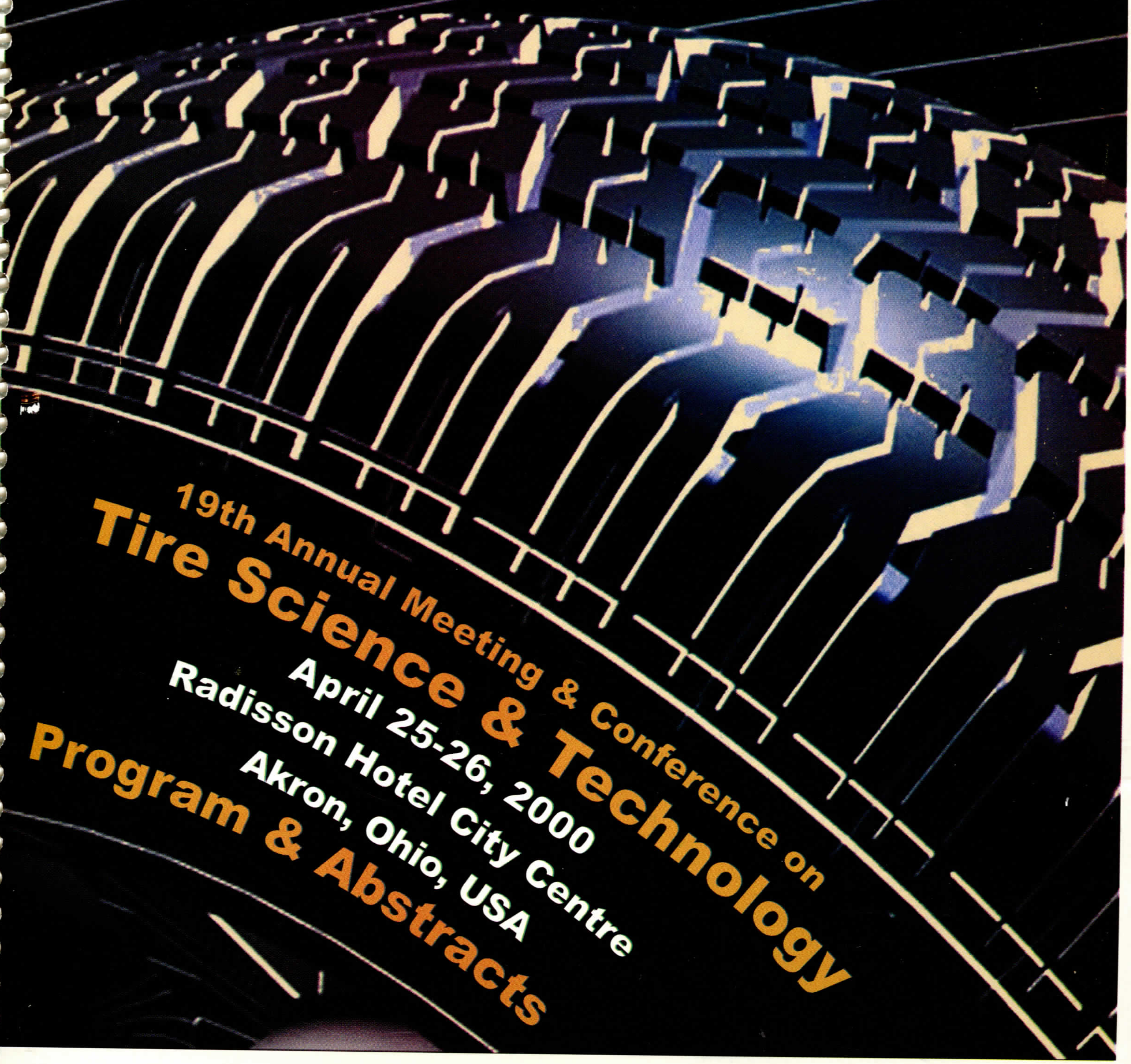
# Tire Society 2000



## 19th Annual Meeting & Conference on Tire Science & Technology

April 25-26, 2000
Radisson Hotel City Centre
Akron, Ohio, USA

## Program & Abstracts

# The Tire Society, Inc.

## The 19th Annual Meeting and Conference on Tire Science and Technology
## April 25-26, 2000
## Radisson Hotel City Centre, Akron, Ohio

## Conference Schedule Summary

### *Day 1* - Tuesday, April 25

| *Time* | *Description* |
|---|---|
| (7:30 | **Speaker's Breakfast** - day 1 speakers & chairs only) |
| 8:00 | **Registration** |
| 9:00 | **Opening:** *Bob Pelle*, Pres., Tire Society |
| 9:05 | **Welcome** |
| 9:15 | **Keynote Address:** *Pat Rooney,* CEO & Chairman, Cooper Tire |
| 9:55 | **Break** (10 minutes) |
| 10:05 | **Technical Program Begins:** *Bob Wheeler, Denny Dubs, Co-Chairs* |
| 10:05 | **Technical Session #1:** **Rolling Resistance/Traction/Wear** 4 presentations |
| 11:50 | **Lunch** |
| 1:05 | **Technical Session #2:** **Tire Mechanics** 4 presentations |
| 2:50 | **Break** (10 minutes) |
| 3:00 | **Technical Session #3:** **NVH - Low Frequency** 5 presentations |
| 5:10 | **End of Day 1 Technical Presentations** |
| 5:15 | **Business Meeting** |
| 5:30 | **Social Hour:** Radisson Hotel City Centre |
| 6:30 | **Dinner Banquet:** Radisson Hotel City Centre, Speaker: *David Davenport,* Davenport-Mammoet LLC, "Where the Rubber Meets the Road" |

### *Day 2* - Wednesday, April 26

| *Time* | *Description* |
|---|---|
| (7:30 | **Speaker's Breakfast** - day 2 speakers & chairs only) |
| 8:00 | **Technical Session #4:** **Handling/Vehicle Dynamics** 3 presentations |
| 9:20 | **Break** (10 minutes) |
| 9:30 | **Technical Session #5:** **NVH - Mid/High Frequency** 3 presentations |
| 10:50 | **Break** (10 minutes) |
| 11:00 | **Plenary Lecture***:* *Nissim Calderon,* Vice President Research (Ret.), Goodyear Tire & Rubber Co., "A Changing Tire Business Model" |
| 11:50 | **Lunch** |
| 1:05 | **Technical Session #6:** **Special Topics** 4 presentations |
| 2:50 | **Break** (10 minutes) |
| 3:00 | **Technical Session #7:** **Materials/Components/Fracture** 4 presentations |
| 4:45 | **Closing Remarks** |
| 4:50 | **End of Conference** |

## 2000 Tire Society: Officers & Committee Members

| | |
|---|---|
| **President:** | Robert Pelle |
| **Vice President:** | John R. Luchini |
| **Secretary:** | Marion Pottinger |
| **Treasurer-elect:** | Jozef DeEskinazi |
| **Past President:** | Michael Berzins |
| **Senior Journal Editor:** | Farhad Tabaddor |
| **Members at Large:** | Eddie Morant, Mike Hamaya, William Hopkins, Raymond Labuda |
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| **Conference Arrangements:** | Mechelle Miller |
| **Business Office Manager:** | Howard Snyder |
| **2000 Conference Program Co-Chairs:** | Robert Wheeler, Dennis Dubs |

Visit the Tire Society's website at: http://www.tiresociety.org

## *Day 1* - Tuesday, April 25

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| **8:00** | **Registration** |
| **9:00** | **Opening:** *Bob Pelle*, Pres., The Tire Society |
| **9:05** | **Welcome:** *Don Plusquellic*, Mayor of Akron |
| **9:15** | **Keynote Address:** *Pat Rooney,* CEO & Chairman, Cooper Tire |
| **9:55** | **Break** (10 minutes) |
| **10:05** | **Session 1. Rolling Resistance/Traction/Wear**<br>*Chairman: Rolf Gall*, Shanghai Tyre & Rubber |
| **10:10** | **1.1.** "A New Computational Procedure to Predict Transient Hydroplaning Performance of a Tire," *Toshihiko Okano, Masataka Koishi,* Yokohama Rubber Co. |
| **10:35** | **1.2.** "Tread Depth Effects on Tire Rolling Resistance," *John R. Luchini, Matthew M. Motil, William V. Mars,* Cooper Tire & Rubber |
| **11:00** | **1.3.** "FEM Simulation of Steady State Rolling Along a Circular Path," *Dong Zheng,* Continental General Tire, Inc. |
| **11:25** | **1.4.** "Analysis of Contact Stresses on the Tread Rubber Blocks with Slip," *DooMan Kim, Injeong Park,* Hankuk Aviation University |
| **11:50** | **Lunch** |
| **1:05** | **Session 2. Tire Mechanics**<br>*Chairman: Hamid Aboutorabi,* Kumho Tire |
| **1:10** | **2.1.** "A Finite Element Analysis for Bias Ply Tires by Laminated Theory," *Dr. Tan Hui-Feng, Miao Chang-Qing, Du Xing-Wen,* Harbin Institute of Technology, *Yang Jun, Zhang Guoxiang, Luo Guoqiang,* Guizhou Tyre Co. |
| **1:35** | **2.2.** "A Generalized Refined Shell Theory for Nonlinear Analysis of Tires," *YuanKan Dai, YongPing Shu,* Shanghai Tyre and Rubber Co. |
| **2:00** | **2.3.** "Application of the Lateral Stress Theory for Groove Wander Prediction Using Finite Element Analysis," *James Peters,* Cooper Tire & Rubber |
| **2:25** | **2.4.** "Finite Element Modelling of Rotating Tyres in the Time Domain," *Dr. Oluremi Olatunbosun, A. M. Burke,* University of Birmingham |
| **2:50** | **Break** (10 minutes) |
| **3:00** | **Session 3. NVH - Low Frequency**<br>*Chairman: Farhad Tabaddor,* Michelin |
| **3:05** | **3.1.** "Comparison of Substructuring Techniques for the Dynamic Behavior of Tires," *Dimitri Tsihlas, Thierry Lacroix, Bill Clayton,* Michelin |
| **3:30** | **3.2.** "SWIFT-Tyre Application for Ride Analysis," *Sven T.H. Jansen,* TNO Automotive, *Krystof P. Jankowski,* GM, *Antonius J.C. Schmeitz,* Delft University |
| **3:55** | **3.3.** "Tire Modal Analysis by Finite Element Method," *Xiurong Bai, Rolf Gall,* Shanghai Tyre & Rubber Co.Ltd. |
| **4:20** | **3.4.** "Dynamic Damping & Stiffness Characteristics of the Rolling Tire," *Jianmin Ge,* Shanghai Tyre & Rubber Company., *LianZhu Zheng,* Jilin University of Technology |
| **4:45** | **3.5.** "Dynamics of Tire & Rim & Suspension," *Han J. Yu, Hamid Aboutorabi,* Kumho Tire |
| **5:10** | **End of Day 1 Technical Presentations** |
| **5:15** | **Business Meeting** |
| **5:30** | **Social Hour:** Radisson Hotel City Centre |
| **6:30** | **Dinner Banquet:** Radisson Hotel City Centre, Speaker: *David Davenport,* Davenport-Mammoet LLC, "Where the Rubber Meets the Road" |

# *Day 2* – Wednesday, April 26

| *Time* | *Description* |
|---|---|
| (7:30 | **Speaker's Breakfast** - day 2 speakers & chairs only) |
| 8:00 | **Session 4. Handling/Vehicle Dynamics**<br>Chairman: Keith Sansalone, *Cooper Tire* |
| 8:05 | **4.1.** "A New Standard for Steady State Cornering Tyre Testing," *Jan van Oosten,* TNO Automotive, *C. Savi,* Pirelli, *H.J. Unrau,* University of Karlsruhe, *O. Bouhet,* Michelin, *J. Sommer,* Continental, *J.P. Colinot,* Peugeot SA. |
| 8:30 | **4.2.** "Optimization for Motorcycle Tire Using Explicit FEM," *Masafumi Koide, Hisashi Heguri, Tatsuhiko Kamegawa, Yukio Nakajima, Hiroshi Ogawa,* Bridgestone Corporation |
| 8:55 | **4.3.** "Effects in The Simulation of Steady State Tire Characteristics (F&M)," *Axel Becker, Kathrin Thiele, Burkhard Pollak, Dong Zheng,* Continental AG |
| 9:20 | **Break** (10 minutes) |
| 9:30 | **Session 5. NVH - Mid/High Frequency**<br>*Chairman: Tom Williams*, Hankook Tire |
| 9:35 | **5.1.** "High Frequency Validation of a Tire Modal Model," *Dave Johansen, E.D. Pan,* The Goodyear Tire & Rubber Company, *Randy Mayes,* Sandia National Laboratories |
| 10:00 | **5.2.** "New Predictive Model for the Study of Vertical Forces (up to 250 Hz) Induced on the Tyre by Road Irregularities," *Damiano Belluzzo, Federico Mancosu, Federico Cheli,* Politecnico di Milano, *Roberto Sangalli,* Pirelli Pneumatici |
| 10:25 | **5.3.** "Quantification of Tire and Wheel Model Quality," *James Lee, Hao Pham, Archie Ni,* Ford |
| 10:50 | **Break** (10 minutes) |
| 11:00 | **Plenary Lecture***:* *Nissim Calderon,* Vice President Research (Ret.), The Goodyear Tire & Rubber Co., "A Changing Tire Business Model" |
| 11:50 | **Lunch** |
| 1:05 | **Session 6. Special Topics**<br>*Chairman: Frank Matyja,* Continental/General |
| 1:10 | **6.1.** "Study on Rubber Composite Heat Conductivity," *Youshan Wang, Yanlin Wang,* Hualin Group Co. |
| 1:35 | **6.2.** "Inverse Design Methodology of a Tire," *Dr. Masataka Koishi,* Yokohama Rubber Co., *S. Govindjee,* University of California, Berkeley |
| 2:00 | **6.3.** "Prediction of Tire Shape Change During Post Cure Inflation," *Ron Kennedy*, Hankook Tire. |
| 2:25 | **6.4.** "Temperature Gradients Around a Rubber Fatigue Crack Tip," *Cheng Shaw, Vladimir Kerchman, Perry Marteny,* Goodyear |
| 2:50 | **Break** (10 minutes) |
| 3:00 | **Session 7. Materials/Components/Fracture**<br>*Chairman: Vladimir Roth,* Bridgestone/Firestone |
| 3:05 | **7.1.** "Multiaxial Fatigue Crack Initiation in Rubber," *Will Mars,* Cooper Tire & Rubber Company |
| 3:30 | **7.2.** "Truck Tire Zipper Break: A Testing Method for the Reproduction of the Failure in Lab," *Fabrizio Crema, Carlo Di Bernardo,* Pirelli Pneumatici |
| 3:55 | **7.3.** "Torsional Crack Growth Test to Simulate Belt Edge Deformation," *Thomas Fleischman, Vladimir Kerchman, Thomas Ebbott,* Goodyear Tire & Rubber Company |
| 4:20 | **7.4.** "Prediction of Mixed-Mode Fracture in Particulate Composite Using Damage Criterion," *C.L. Chow, W.H. Tai,* University of Michigan, *C.T. Liu,* Philips Laboratory, Edward AFB |
| 4:45 | **End of Day 2 Technical Presentations** |

**Additional Papers Submitted for Journal Publication**

**S.1.** A Study on the Severity of Cracks in Radial Tires Using Finite Elements," *F. Niknam Moghadam, G. Karami, M. Kamran,* Rubber Industries Engineering & Research Co. Ltd., Iran

**Paper Number 1.1**

# A New Computational Procedure to Predict Transient Hydroplaning Performance of a Tire

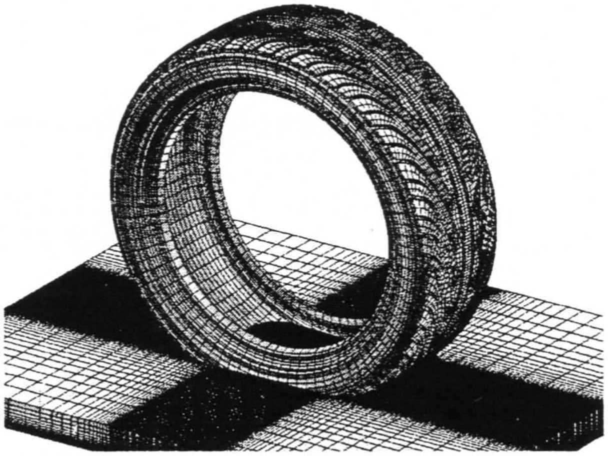
*Toshihiko Okano, Masataka Koishi,*
The Yokohama Rubber Co., Ltd

Hydroplaning performance is one of the vital functions for safety driving on wet road. Since hydroplaning performance depends on the velocity of a car, as well as the tire construction and tread patterns, effective simulation tools dealing with all these effects were badly needed.

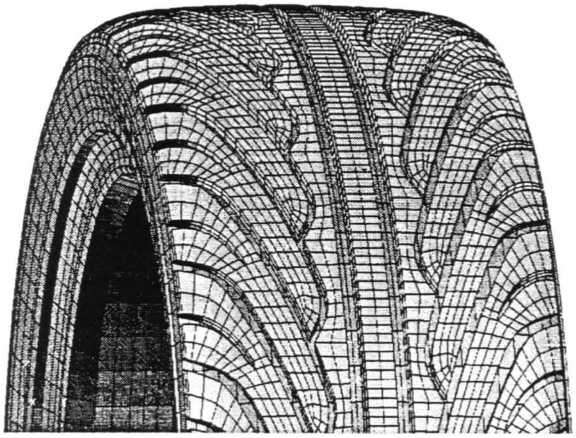
The numerical analysis procedure to predict the onset of hydroplaning of a tire is proposed here, considering the vehicle velocity dependency. A commercial explicit FEM/FVM package is used to solve coupled problems between tire deformations and surrounding fluid. Tire deformations and fluid behaviors are computed, using FEM and FVM, respectively. A reference frame fixed on a moving car is used to simulate transient phenomena effectively. Complex geometry of tread pattern and rotational effect of a tire, which are important functions of hydroplaning simulation, and also dependency on vehicle velocity are included in the proposed procedure.

To verify the effectiveness of the procedure, predicted hydroplaning velocities for five different simplified tread patterns are compared with experiments measured at proving ground. Visual images of water flows around contact patch are captured, using high-speed video camera. A comparison supports the effectiveness of the numerical simulation of hydroplaning. Lastly, numerical examples for the newly developed tires are also presented.

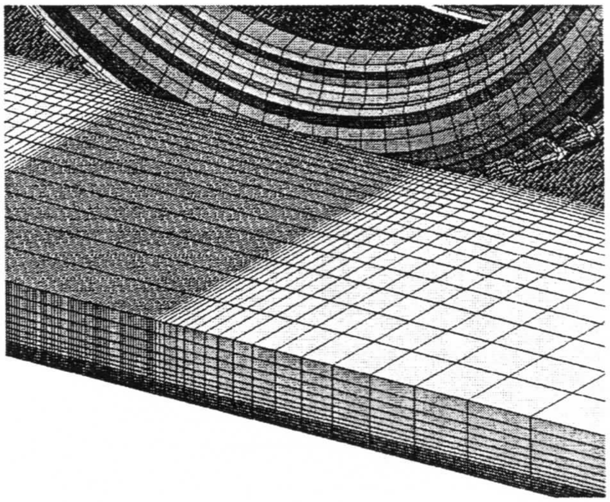
View of hydroplaning test in proving ground



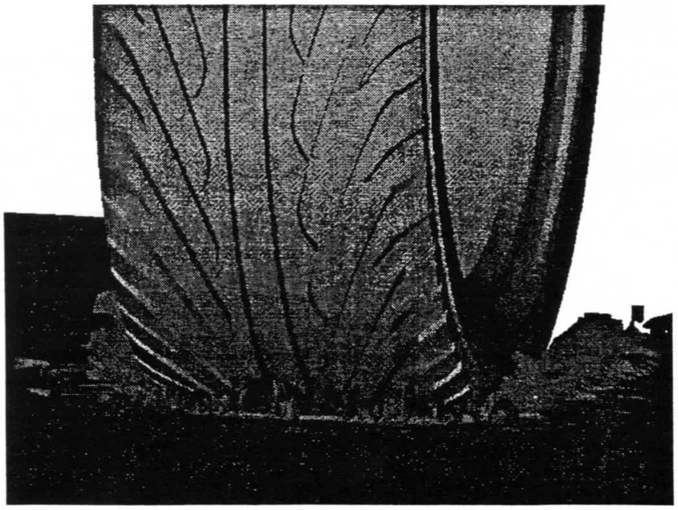
Hydroplaning simulation model of the newly developed prototype tire



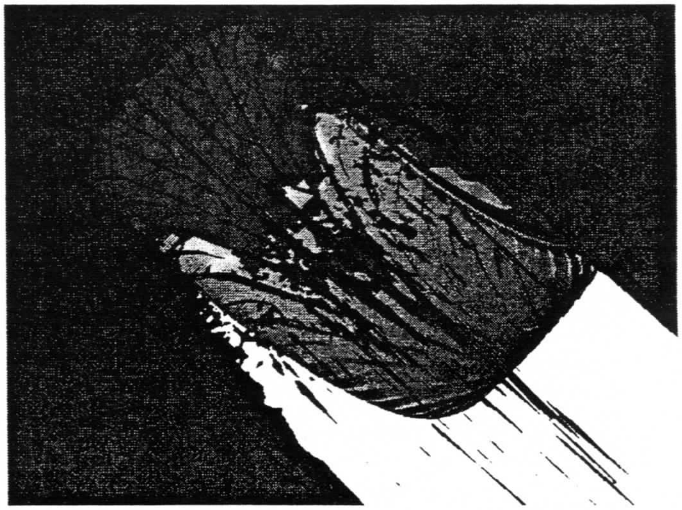
Finite element model of a tire with tread pattern



Finite volume model of water film



Front view of computational results (80 km/h)



Bottom view of computational results (80 km/h)

**Paper Number 1.2**

## Tread Depth Effects on Tire Rolling Resistance

*John R. Luchini, Matthew M. Motil, William V. Mars,*
Cooper Tire and Rubber Company

This paper discusses the measurement and modeling of tire rolling resistance for a group of radial medium truck tires. These tires were subjected to tread depth modifications by "buffing" the tread surface. The experimental work used the equilibrium test method of SAE J-1269. The FEA tire model for tire rolling resistance has been previously presented. The results of the testing showed changes in rolling resistance as a function of tread depth that were inconsistent between tires. The observations were also inconsistent with published information and common knowledge. Several mechanisms were proposed to explain the results. Additional experiments and models were used to help evaluate the mechanisms.

Mechanisms that were examined included tire age, surface texture, and tire shape. An explanation based on buffed tread radius, and the resulting changes in footprint stresses, is proposed that explains the observed experimental changes in rolling resistance with tread depth.

Key words:

tire rolling resistance, tire rolling loss, tire heat build up, tire testing, pneumatic tire modeling, finite element modeling, material hysteresis

- By buffing all tires to same profile, contact pressure distribution changed, in some cases increasing RR
- RR does decrease with decreasing tread depth
- To know worn profile, must wear tire
- No age effects considered

| Tire ID | Brand | Type | Use | Other Features |
|---|---|---|---|---|
| 1 | C | Rib | New | *Modeled* |
| 2 | C | Rib | New | Replicate |
| 3 | C | Rib | New | Replicate |
| 4 | G | Rib | New | Match to #19 |
| 5 | B | Rib | New | Older line, Match to #20 |
| 6 | E | Rib | New | Match to #21 |
| 7 | A | Rib | New | Match to #22 |
| 8 | A | Lug | New | |
| 9 | F | Rib | New | Match to #24 |
| 10 | B | Rib | New | Newer line, Match to #25 |
| 11 | G | Lug | New | |
| 12 | B | Lug | New | Match to #26 |
| 13 | E | Lug | New | Match to #27 |
| 14 | D | Lug | New | Match to #28 |
| 15 | C | Lug | New | *Modeled* |
| 16 | C | Lug | New | Replicate |
| 17 | C | Lug | New | Replicate |
| 18 | C | Lug | New | Replicate |
| 19 | G | Rib | Road | Match to #4 |
| 20 | B | Rib | Road | Older line, Match to #5 |
| 21 | E | Rib | Road | Match to #6 |
| 22 | A | Rib | Road | Match to #7 |
| 23 | F | Rib | Road | Match to #9 |
| 24 | B | Rib | Road | Newer line, Match to #10 |
| 25 | B | Rib | Road | |
| 26 | G | Lug | Road | Match to #12 |
| 27 | B | Lug | Road | Match to #13 |
| 28 | E | Lug | Road | Match to #14 |

Table 1. Test Tire Layout

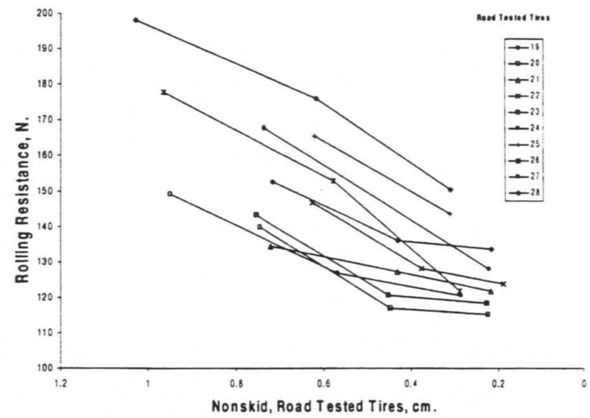



Figure 1. Tread depth effect on rolling resistance for road tested tires. The tread was removed from tested tires by buffing to match the profile of the "new" buffed tires.

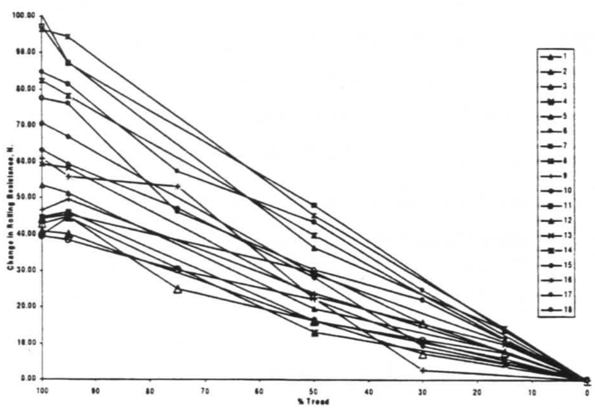


Figure 2. Tread depth effect on rolling resistance for "new" tires. The tread was removed from tested tires by buffing.

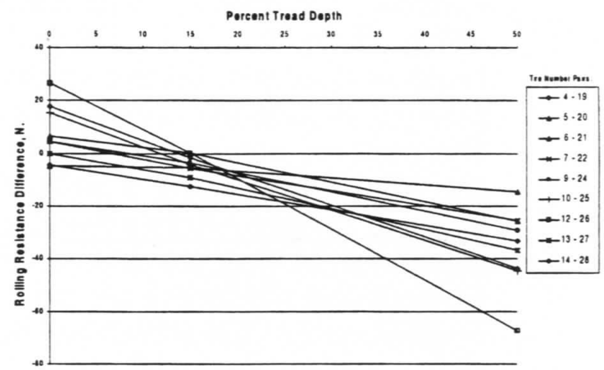



Figure 3. Difference in rolling resistance between a "new" buffed tire and a matched road tested and buffed tire. Negative difference indicates the road tested tire has lower rolling resistance at the same buffed tread depth.

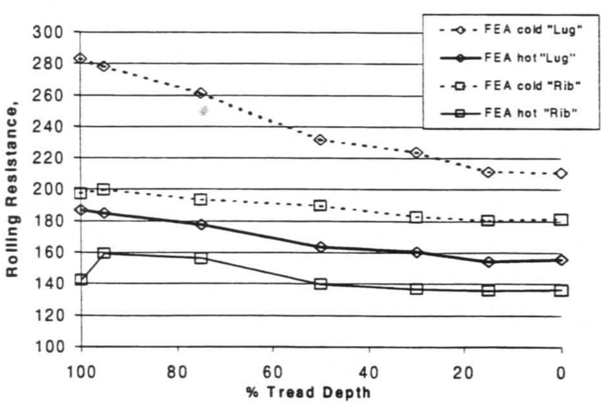



Figure 4. Computational model results for tire 1 and tire 15. "Rib" and "Lug" indicate the tread thickness for the models. The models have no tread pattern. "Cold" results are from a stress-strain model at SAE ambient conditions, and "Hot" results are from the thermodynamic model using the stress-strain inputs.

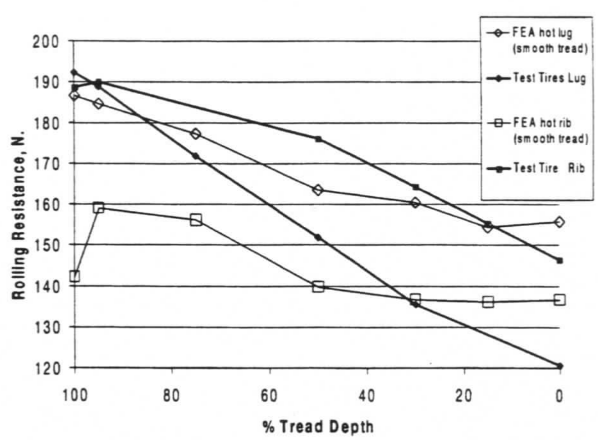



Figure 5. Experimental and computational ("hot") results for tire 1 and tire 15.

**Paper Number 1.3**

## FEM Simulation of Steady State Rolling along a Circular Path

*Dong Zheng,*
Continental General Tire, Inc

The FEM simulation of the steady state rolling tire has been studied and used by the tire industry for a number of years. However, most of the studies simulate a tire rolling along a straight line. In reality, the tire travels along a circular path while it is cornering. Similarly, in a laboratory test such as the Goodyear/Grosch Abrader test, a rubber disk specimen travels along a circular path. Therefore, it should be beneficiary to study the differences between rolling along a straight line and rolling along a circular path.

In this study, an FEM algorithm has been developed to simulate steady state rolling along a circular path. This algorithm is then used to simulate the Goodyear/Grosch Abrader test. The results show that there are noticeable differences between rolling along a straight line and rolling along a circular path. The frictional energy from rolling along a circular path is always higher than the one from rolling along a straight line. When rolling along a circular path, the frictional energy reaches the minimum value at a non-zero slip angle. There is also a shift in the force and moment curves. The shift is in the opposite direction for the force and for the moment. Finally, the results of a tire rolling along circles of different radii are shown and discussed.

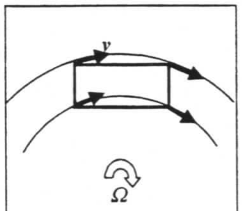
path-curvature effects

**FEM Simulation of Steady State Rolling Along a Circular Path**

## Frictional Rolling Contact --- Straight line vs. circular path

When rolling along a straight line, the tire corning angular velocity is zero. The sliding velocity of a point becomes

$$v = \left( S_\omega X + \frac{\partial u}{\partial X} S_\omega X \right) \cdot E + V_0$$




Ground velocity related to tire system with rolling along a circular path

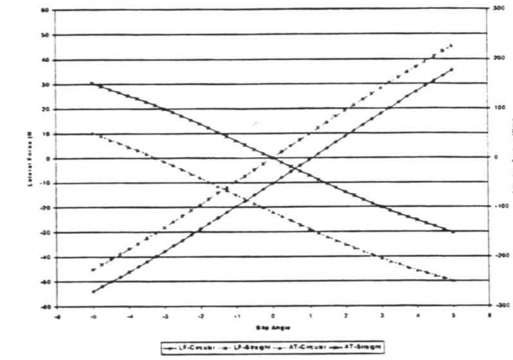
When rolling along a circular path, the sliding velocity remain as

$$v = \left( S_\omega X + \frac{\partial u}{\partial X} S_\omega X + (X + u) S_\Omega \right) \cdot E + V_0$$



**FEM Simulation of Steady State Rolling Along a Circular Path**

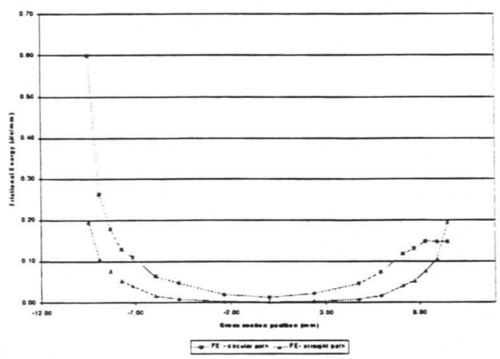
## Rubber ring: F&M curve shift toward opposite direction





**FEM Simulation of Steady State Rolling Along a Circular Path**

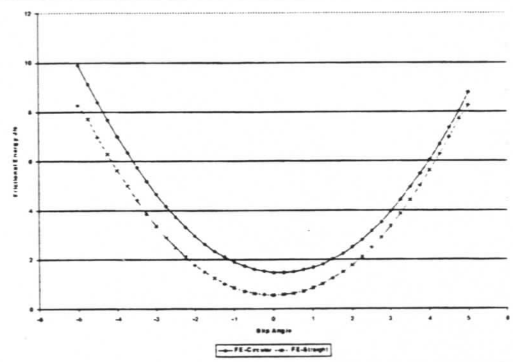
## Rubber ring: FE cross section distribution at 0 slip angle





**FEM Simulation of Steady State Rolling Along a Circular Path**

## Rubber ring: Total frictional energy vs. slip angle



**Paper Number 1.4**

## Analysis of Contact Stresses on the Tread Rubber Blocks with Slip

*D. M. Kim, I. J. Park,* Hankuk Aviation Univeristy

The tread rubber block of tire in contact with the roadway plays an important role of holding the frictional forces between the tire and the road, which applied to compressive and shearing forces with slip in contact patch for automobiles of driving and braking. In this paper, a theoretical study based on the energy method is presented on the contact pressure of the tread block under the compressive and shearing forces with the slip between tread block and contact surfaces, by using the 2-D model of tread rubber block. The experimental studies are conducted to verify the predicted results. Good agreement is obtained between these theoretical and experimental results for contact surface stresses of the tread rubber block.

Key Words: tread rubber block, contact, slip, energy method

**Paper Number 2.1**

# A Finite Element Analysis for Bias Ply Tires with Laminated Theory

*Tan Hui-Feng, Miao Chang-Qing, Du Xing-Wen,*
Harbin Institute of Technology, P.R. China

*Yang Jun, Zhang Guoxiang, Luo Guoqiang,*
Guizhou Tyre Co., Ltd., P.R.China

With the development of tire mechanics and computer technology, Bias ply tire mechanical properties may be predicted accurately through Finite Element Analysis (FEA). During the past years, an in-house finite element program has been developed in our research laboratory, which processed the capabilities to analyze the tire deformation, stress and strain under static inflation and footprint load conditions.

In this paper, the bias ply tire structure in contact with a flat foundation and mounted on a rigid rim is analyzed with our three-dimensional finite element program. A Laminated theory, which can predict material properties of laminated ply from that of reinforced cord and rubber, is introduced to deal with multi-ply structure of bias ply tire in order to avoid great computing expense and to obtain good element properties. The concept of variable constraint and constraint increment is also introduced to the three-dimensional finite element analysis for bias ply tires.

A satisfying precision of the calculation is obtained comparing with experiments.

**Paper Number 2.2**

## A General Refined Shell Theory for Nonlinear Analysis of Tires

*YuanKan Dai* and *YongPing Shu*,
Shanghai Tire and Rubber (Group) Co. Ltd.

Typical tire design theories of tire industry are reviewed and various prevalent structural models of tires in different time periods are discussed in this paper. In general, 3D finite element model and laminated shell model are recognized for their performance. However, the computational effort for FEM is high and convergence of the FEM solutions is very sensitive to some variation of tire material properties. In the existing laminated shell models, the tires are usually simplified to a laminated toroidal shell. This simplification means that geometry and deformations of tires can not be described precisely and further large deflections and transverse shear deformations of tires are not taken into account sufficiently.

Based on a general refined shell theory, a semi-analytical procedure for nonlinear analysis of tires is proposed. In the presented shell model, the tire structure is conceived as a general thickness-variable shell of composite construction counting for higher-order shear deformations that consists mainly of two structural parts, belt and carcass. The interior contour surface of the tire is taken as the surface of reference and the system of orthogonal curvilinear coordinates is used for modeling the shell geometry and deformations. Generalized displacements at any point of the shell are expressed by means of higher-order shear deformation theory of the Reddy type. A piece-wise Rayleigh-Ritz procedure is applied to approximate the solution. This may be regarded as a semi-analytical method, since a number of surface patches mesh-idealized on the surface of reference and components of generalized displacement vectors defined on each of the patches are presented by Bezier polynomials.

In comparison with FEM numerical models in Cartesian coordinates, the semi-analytical model of piecewise surface patches defined in curvilinear coordinates can simulate geometry and deformed shape of the tire with better accuracy. Also, the laminated shell model can be used to model tires of different composite construction to investigate effects of belt geometry on the static and dynamic performance of the tire.

To demonstrate effectiveness of the presented model, deformations and stress distribution of a multi-layered P215/70R15 tire subjected to inflation pressure are analyzed and compared to the results of 3D finite element analysis. Both solutions are in good agreement.

## Contour Theories for Radial Tires

- Rolling Contour Optimization Theory (RCOT)
  Bridgestone - 1985
- Tension Contour Optimization Theory (TCOT)
  Bridgestone - 1988
- Prestress Profile Theory (PSP)
  Sumotomo 1987
- Strain Energy Minimization Theory (SEMT)
  Yokohama - 1988
- Dynamic Simulation Optimized Contour (DSOC)
  Toyo - 1988

## Contour Theories for Radial Tires (cont.)

- Prestress Profile - Fourth (PSP-F)
  Sumotomo - 1989
- Dynamic Stability Optimized Contact Theory (DSOCT)
  Toyo - 1989
- Tire Design Theory Based on Optimization of Stress-Strain Cycles of its Elements (CSSOT)
  USSR 1989
- Integrated Tire Technical Concept (ITTC)
  Okazu - 1989
- Grand Unified Tire Technology (GUTT)
  Bridgestone - 1995

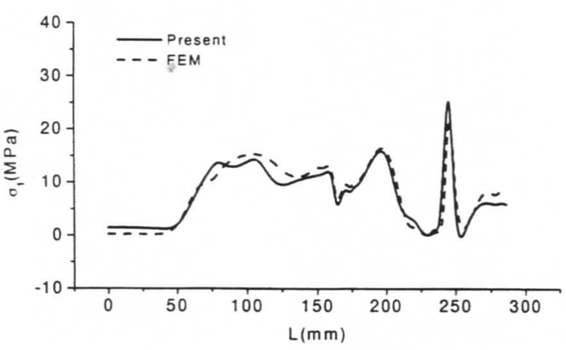
## Method

- It is assumed that the belt and carcass are the major force-carrying parts of a tire. An an-isotropic shell with varying thickness is used to simulate the composite structure.
- The interior contour curve of the tire is described as Bezier curve.
- The interior contour surface of the tire is the reference surface.
- Displacements at any point of the shell are expressed by a higher-order shear deformation theory of a Reddy type.

## Method (cont.)

- The reference surface is divided into several surface patches,the displacement and rotation of each patch are expressed by Bezier function.
- The displacements and rotations of adjacent Bezier surface patches must be geometrical constraints of $C^1$ continuity.
- A Rayleigh-Ritz procedure is used to solve the problem.

## Comparison of Stress in the Carcass




## Summary

The proposed Method was developed with MATHEMATICA and can be used to support the tire design and development.

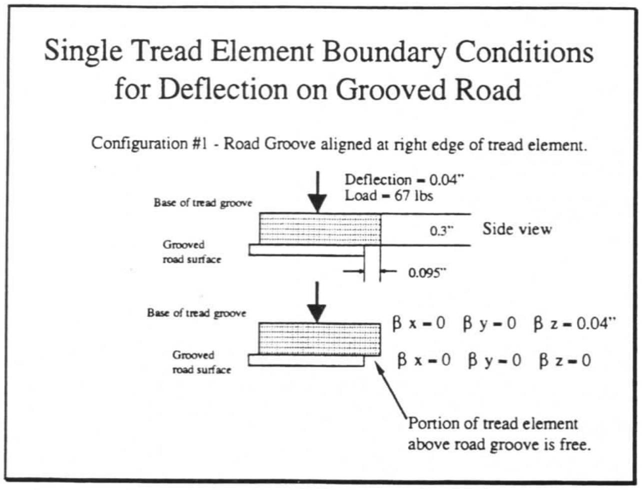
**Paper Number 2.3**

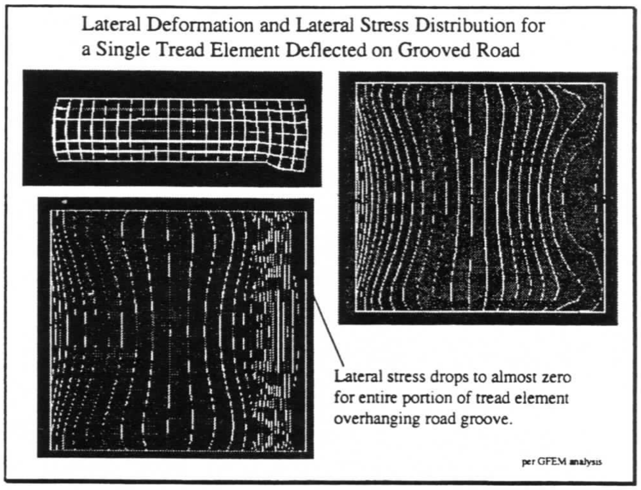
## Application of the Lateral Stress Theory for Groove Wander Prediction Using Finite Element Analysis

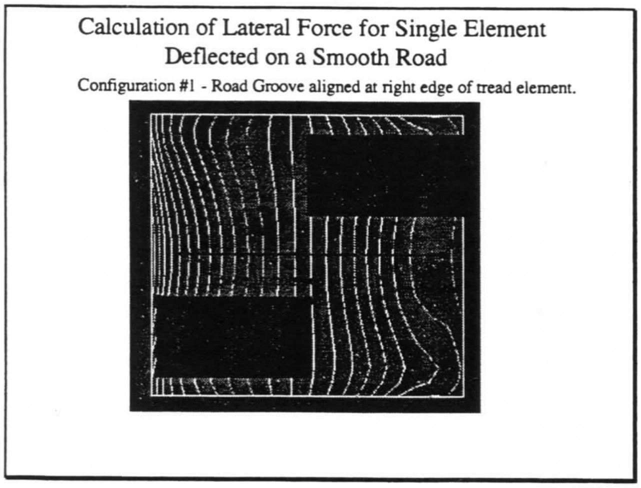
*James M. Peters,*
Cooper Tire and Rubber Company

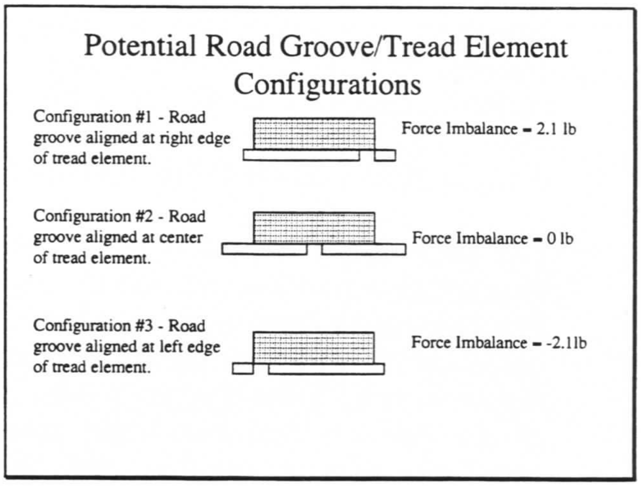
Ride is a critical component for driver and passenger satisfaction. Groove wander is a ride disturbance experienced on grooved highways. Screening new tire designs for groove wander requires accurate measurement or accurate prediction tools.

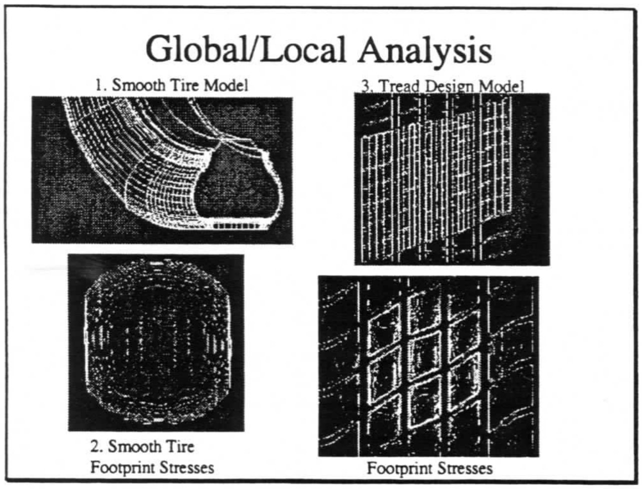
This paper presents a review of published theories for groove wander. A new theory for groove wander is presented and validated using an indoor test developed at Smithers. In addition, the development and validation of an FEA based groove wander model by application of the lateral stress theory will be presented.

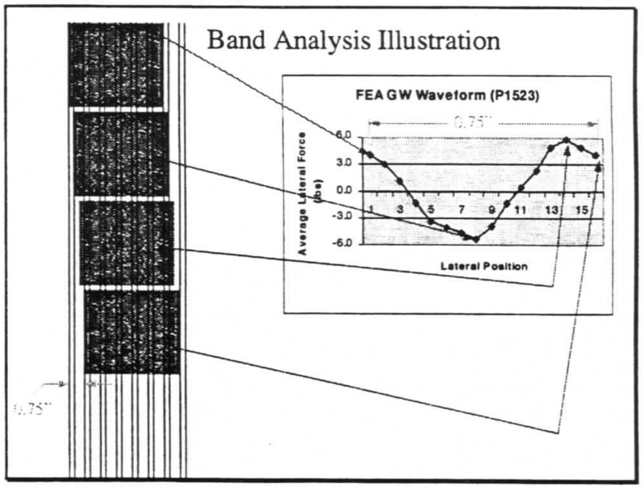

Single Tread Element Boundary Conditions for Deflection on Grooved Road
Configuration #1 - Road Groove aligned at right edge of tread element.
Deflection = 0.04"
Load = 67 lbs
Base of tread groove
Grooved road surface
0.3"
Side view
0.095"
Base of tread groove
Grooved road surface
β x = 0 β y = 0 β z = 0.04"
β x = 0 β y = 0 β z = 0
Portion of tread element above road groove is free.


Lateral Deformation and Lateral Stress Distribution for a Single Tread Element Deflected on Grooved Road
Lateral stress drops to almost zero for entire portion of tread element overhanging road groove.
per GFEM analysis


Calculation of Lateral Force for Single Element Deflected on a Smooth Road
Configuration #1 - Road Groove aligned at right edge of tread element.


Potential Road Groove/Tread Element Configurations
Configuration #1 - Road groove aligned at right edge of tread element.
Force Imbalance = 2.1 lb
Configuration #2 - Road groove aligned at center of tread element.
Force Imbalance = 0 lb
Configuration #3 - Road groove aligned at left edge of tread element.
Force Imbalance = -2.1lb


Global/Local Analysis
1. Smooth Tire Model
3. Tread Design Model
2. Smooth Tire Footprint Stresses
Footprint Stresses


Band Analysis Illustration
FEA GW Waveform (P1523)
0.75"
Average Lateral Force (lbs)
6.0
3.0
0.0
-3.0
-6.0
1 3 5 7 9 11 13 15
Lateral Position
0.75"

**Paper Number 2.4**

## Finite Element Modelling of Rotating Tyres in the Time Domain

*O A Olatunbosun, A M Burke,*
University of Birmingham, UK

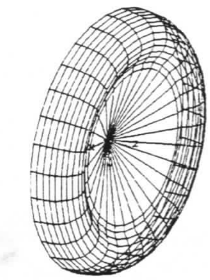
The dynamic behaviour of the rotating tyre is of great interest because of its influence on vehicle ride and handling, passenger compartment noise, and pass-by noise. Because the tyre is an extremely complex engineering system, the Finite Element method has seen increasing use in order to represent the complexities of tyre material construction and behaviour in detail. While many models now exist which can accurately predict tyre inflation, hub load and the dynamic behaviour of the non-rotating tyre, these can only go part of the way in describing the behaviour of the tyre under real operating conditions which involves rotation of the tyre. Hence a model of the rotating tyre is essential for understanding the behaviour of the tyre under real operating conditions. In this paper, techniques and strategies for tyre rotation modelling are presented and discussed as a guide to the creation of a successful model.

The large deflection that occurs from inflation of the tyre and hub loading results in geometric non-linearity which has to be handled within the FE code chosen. The tyre-road interface is modelled using an adaptive gap element formulation to get over the previous method of using empirical data to relate hub force and displacement. Time domain solution is used in examining the dynamic behaviour of the tyre so that non-linear effects, which are impossible to model in a frequency domain solution, can be included in the analysis. Since the gap element formulation is limited for rotation modelling, slide line analysis is used in the simulation of tyre rotation. MSC/NASTRAN FE code has been used in the simulation of the model because of the versatility of the code and its ability to cope with the modelling requirements. Some results from simulation of the model are presented and compared to experimental results obtained from rig testing to show how well the model represents real life dynamic behaviour of the tyre.

## Tyre FE Model Characteristics

- Tyre carcass - laminated anisotropic shell elements
- Tyre rim – rigid links between hub and bead using CBEAM elements.
- Slide line analysis for tyre/ground plane contact
- Hysteretic damping using critical damping ratio determined from modal tyre test

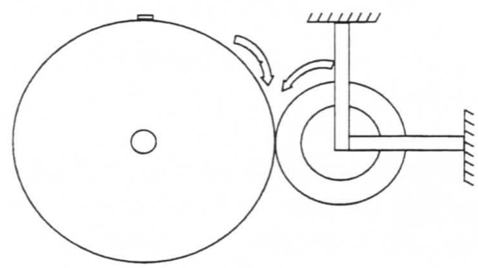
## Half Tyre Model for Rotational Response



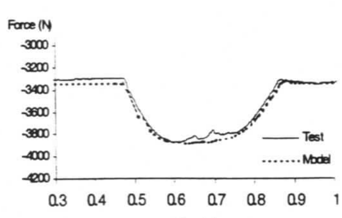
## Solution Procedure

- SOL 106 – Application of inflation pressure
- Application of hub load: force slide line ground plane up against the fixed tyre
- SOL 129 restart – modify tyre and ground plane constraints
- Acceleration of ground plane by gradual application of enforced velocity
- Maintain uniform ground plane velocity

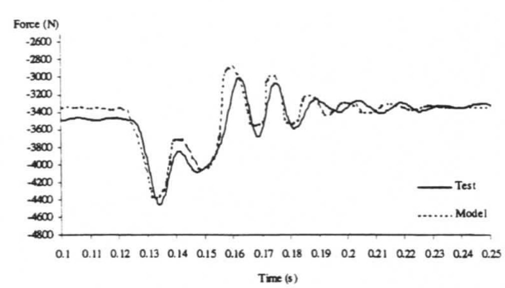
## Cleat Test Set-up



## Slow speed radial force response (1 km/hr)




## Higher speed radial force response (20 km/hr)



**Paper Number 3.1**

## Comparison Of Sub-Structuring Techniques For the Dynamic Behavior Of Tires

*Dimitri Tsihlas, Thierry Lacroix, and Bill Clayton,*
The Michelin Tire Company

Different numerical sub-structuring techniques for the tire dynamic behavior have been developed in the past 20 years. By using these numerical techniques reduced dynamic models are obtained which can be used for internal studies but are also provided to automobile industry and linked to reduced dynamic vehicle model in order to optimize the coupled vehicle-tire response for Noise Vibration and Harshness purposes.

Two techniques that have been developed in a custom made Finite Element code are presented:

1. The Mac Neal type models for which the wheel center interface is free and,
2. The Craig and Bampton type models for which the wheel center interface is fixed.

For both techniques the interface between the tire and the ground are fixed. The choice of fixed or free wheel center boundary condition is arbitrary. In this paper we will compare the formulation of these two numerical methods and we will show the equivalency of both methods by showing the results obtained in terms of frequency and transfer functions. We will show that the two methods are equivalent in principle and the reduced dynamic models can be converted from one to the other. The advantages-disadvantages of each method will be discussed along with a comparison with experimentally obtained results.

Modern FEM Models 200,000 DOF
To develop Dynamic Tire models to be given to auto OEMs to be coupled with their models

Paper Number 3.2

# SWIFT-Tyre Application For Ride Analysis

*Sven T.H. Jansen,* TNO Automotive,
*Krystof P. Jankowski,* GM Truck Group,
*Antonius J.C. Schmeitz,* Delft University of Technology

As is well known, Magic Formula tyre modelling allows an accurate and efficient description of tyre-road interaction forces required for any usual vehicle handling simulation. When it comes to modelling of tyre behavior at higher frequencies, which are important for vehicle ride assessment, advanced chassis control systems and chassis system vibrations, a more sophisticated approach is required.

In close co-operation with the Delft University of Technology and with involvement of nine automotive companies, TNO has developed the SWIFT (Short Wavelength Intermediate Frequency Tyre) model, which is based upon a rigid ring type of tyre model. The SWIFT model is able to describe dynamic tyre behavior for in-plane (longitudinal and vertical) and out-of-plane (lateral, camber and steering) motions up to 50-100 Hz, and for short wavelengths. For reasons of accuracy and calculation speed the SWIFT model has been programmed as a semi-empirical model which is derived with advanced physical models and dedicated high frequency tyre measurements to assess speed effects in tyre behavior.

Next to the dynamic response of the tyre, the interaction between road and tyre is important for Ride evaluation. In general the effect of road irregularities of wavelengths as short as 0.2 meter can be analyzed; in particular cases even the high non-linear enveloping effects are modelled using an effective inputs approach with basic functions.

This paper focuses on the method of Basic Functions for effective input calculation as it is applied in the SWIFT model. The method is discussed extensively and results are presented that concern experiments for identification and verification of the basic function properties. The SWIFT model is used in a Ride Evaluation Programme of GM's Light Truck Division, and simulation results of the tyre model in combination with an ADAMS vehicle model are presented to demonstrate the implication of basic functions and tyre belt dynamics.

Similar to other tyre models in the DELFT-Tyre product line, SWIFT-Tyre is available as a separate routine which complies to the Standard Tyre Interface. Dedicated implementations of the model have been carried out to offer the model also for use in combination with common simulation tools for vehicle analysis such as ADAMS, Simpack, DADS, MADYMO, Matlab/Simulink and MatrixX. vehicle simulations and tire design.

**Paper Number 3.3**

# Tire Modal Analysis by Finite Element Method

*Xiurong Bai*, *Rolf Gall,* Shanghai Tire and Rubber (Group) Co. Ltd.

This paper starts with a brief introduction of some basics of modal analysis and points out the importance of natural frequencies.

A three-dimensional finite element model was used for the dynamic analysis of tires. Dynamic characteristics such as three-dimensional vibration modes and natural frequencies were computed for different boundary conditions, using the Finite Element program MARC. It is shown that the natural frequencies are strongly dependent upon the boundary and loading conditions.

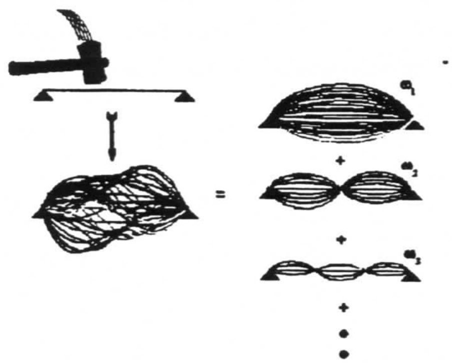
Tire-vehicle models, e.g. the Tire Modal Model according to SAE 870424 rely on computed or experimentally obtained natural frequencies and mode shapes of the tire as input. Usually this input is provided for well-defined loading conditions, e.g. vertical load, internal pressure etc. Nevertheless, during the vehicle's maneuvers these conditions and with it the natural frequencies will change. The authors of this paper believe that this change in natural frequencies is significant enough to modify the vehicle's response.

With the ever-increasing speed and power of computers it is suggested to include complete finite element models of the tires in the vehicle analysis instead of using modal properties of the tire.

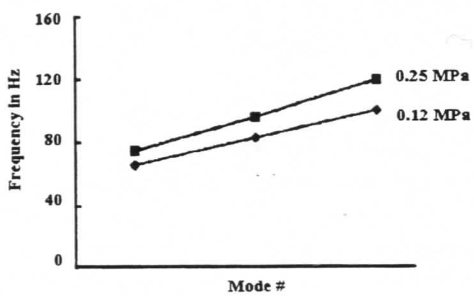
## Contents

- Introduction
- Inflated Tire - Deflected Tire
- Influence of Pressure and Deflection
- Influence of Suspension
- Effect of Rolling
- Summary and Conclusions

## Response to Dynamic Loading

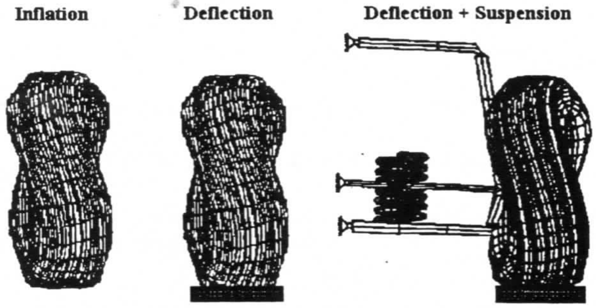


## Natural Frequencies vs. Pressure (Inflated Tire)

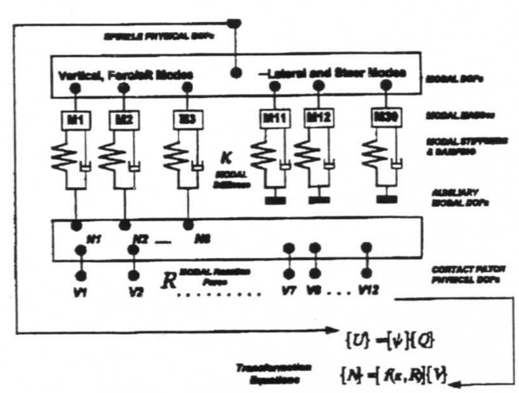



## Mode Shape of a Tire with different Boundary Conditions

Inflation | Deflection | Deflection + Suspension



## Tire Modal Model (SAE 870424)



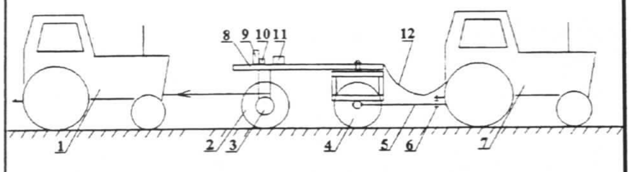
**Paper Number 3.4**

# Dynamic Damping and Stiffness Characteristics of the Rolling Tire

*Jianmin Ge*, Shanghai Tire and Rubber (Group) Co. Ltd.,
*LianZhu Zheng*, Department of Automotive Engineering, Jilin University of Technology

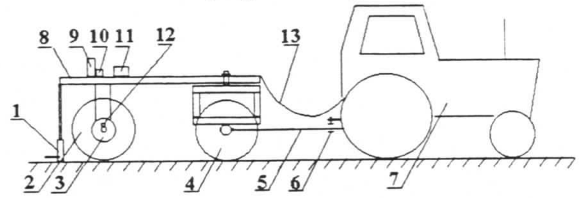
A variable parameter tire model to study the tire responses is presented. The longitudinal stiffness and damping of rolling tire are measured with a modified device to measure the terrain roughness. The vertical stiffness and damping are also measured with this device. The regression formulas of the non-linear experimental damping and stiffness are obtained. The results indicate that the damping and stiffness in the model decrease with velocity. The test stand is used to examine the dynamic damping behavior of the tire in the speed range from 0 to 10 km/h. The inflation pressure varied from 160 to 320 kPa, and the load varied from 5.2 to 7.2 kN. The calculation formulas of rotational stiffness and damping are derived. This paper deals with the research associated to the vehicle's driving and comfort performance in the medium-low frequency range (0-100Hz). The tire model can be useful for vehicle simulations and tire design.

## Principle to Measure the Longitudinal Stiffness and Damping of Rolling Tire




1. Draft load tractor
2. Test tyre
3. Hydraulic motor drive
4. Steering wheel
5. Guide rod
6. Slip ring (sliding bush)
7. Tractor
8. Frame assembly
9. Oil filter
10. Release valve
11. Speed regulator
12. Oil pipe

## Principle to Measure the vertical Stiffness and Damping of Rolling Tire




1. Jack
2. Test tyre
3. Hydraulic motor drive
4. Steering wheel
5. Guide rod
6. Slip ring
7. Tractor
8. Frame assembly
9. Oil filter
10. Release valve
11. Speed regulator
12. Acceleration cell
13. Oil pipe

**The mathematical modal of the vertical vibration tire can be written as**

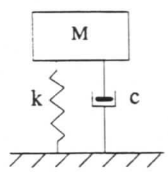
$$M\ddot{Z}+c\dot{Z}+kZ=0$$

**Vertical stiffness of the rolling tire is**

$$k_{zi}=\left(\frac{2\pi}{T_i}\right)^2 M/\left(1-\xi^2\right)$$

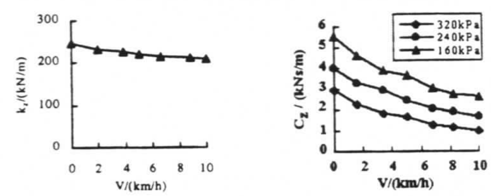
**Vertical damping of rolling tire is**

$$c_{zi}=2\xi_i\sqrt{k_iM}=\frac{2}{T_i}\ln\left(\frac{\ddot{Z}_i}{\ddot{Z}_{i+1}}\right)M$$




**Model to measure variable damping and stiffness of the tire**

## Results Analysis of the Longitudinal Damping and Stiffness of the Rolling Tire




**Tangential stiffness of tire is**

$$k_x=k_{sx}\cdot\exp(-\varsigma_k\cdot V)$$

$k_{sx}$ ~ static stiffness of the tire

$\varsigma_k$ ~ regressive coefficient of the tangential stiffness.

**Tangential damping of tire is**

$$c_x=c_{sx}\cdot\exp(-\varsigma_c\cdot V)$$

$C_{sx}$ ~ static damping of the tire

$\varsigma_c$ ~ regressive coefficient of the tangential damping

## Conclusions

- Longitudinal stiffness and damping of the rolling tire are measured with a modified device at first.
- Vertical stiffness and damping are measured with the device.
- Results indicated that the damping and stiffness decrease with velocity.
- Equations for the non-linear damping and stiffness of the rolling tires are obtained by curve-fitting.
- Calculation formulas of rotational stiffness and damping are derived.
- Results have been used for the analysis of the self-excited vibration and vehicle simulation.

**Paper Number 3.5**

## Dynamics of Tire & Rim & Suspension

*Han J. Yu, Hamid Aboutorabi,*
Kumho Tire

A FE model of a tire and rim and suspension system is made. The system simulates the tire mounted on the vehicle. The natural frequencies are calculated for this highly "non-linear" system where the tire is in the inflated and loaded condition. The random vibration response of the tire and rim and suspension to the road roughness is calculated. It is discovered that:

a) A stiffer steering system is needed in order to compensate for the instability caused by the tire.

b) The axle vibration amplitude is high at the vehicle-bouncing mode, wheel-hopping mode, and at the tire's first radial mode.

Paper Number 4.1

## A New Standard For Steady State Cornering Tyre Testing

*J.J.M. van Oosten*, TNO Automotive, *C. Savi*, Pirelli,
*R. Gnadler*, Univeristy of Karlsruhe, *O. Bouhet*, Michelin,
*J. Sommer*, Continental, *J.P. Colinot,* Peugeot SA

In order to develop vehicles, which have maximum active safety, car manufacturers need information about the so-called force and moment properties of tyres. Vehicle manufacturers, tyre suppliers and automotive research organisations have advanced test equipment to measure the forces between a tyre and a road surface under a variety of loading conditions. However, because of the large differences in the test equipment and the measurement procedures used, the consistency of the force and moment properties determined with the different test devices is a major problem. A comparison by a group of German car manufacturers showed differences in cornering stiffness, measured at 7 different tyre test devices, up to 40%.

In the scope of the EC 'Standards, Measurements and Testing' Research programme 13 automotive partners, under which the six main European tyre manufacturers and three European car manufacturers, started the project TIME. The project aimed at the development of a common tyre measurement procedure that will be reliable and consistent with realistic driving conditions.

In this presentation an overview will be given about the results of the project including the new common tyre testing procedure focused on steady state cornering conditions and passenger car tyres.

First, the differences between results obtained with the 11 different tyre test devices have been investigated, followed by a parameter sensitivity study in order to explain the differences between the results obtained with the different devices. Next step was the determination of the force and moment properties of different types of tyres under realistic vehicle driving conditions in order to establish reference measurements. The reference measurements have been used as a basis for developing the new tyre measurement procedure. Correlation of tyre test results of the 11 different tyre test devices with the reference measurements was the first part of the validation of the new measurement procedure. In addition, tyre test results coming from the new test procedure have been used in tyre models as a part of full vehicle dynamic simulation models in order to judge the procedure's validity and usefulness.

The wide support within the project consortium by the automotive industry already indicates that the result of this project, the common test procedure for steady state tyre testing, can be seen as a basis for a next generation of tyre test procedures.

Iso constant circle - assymmetric loading, very high tire temps ~120°C
assymmetric tire temps
Believes a Round - Flat correlation possible

## TIME objectives

A common tyre measurement procedure, which is reliable and consistent with realistic driving conditions

- Correlation test devices
- Identification of realistic tyre driving conditions
- Validity range of the procedure
- Requirements for testing devices
- Steady state cornering
- Passenger car tyres



## Vehicle Reference testing

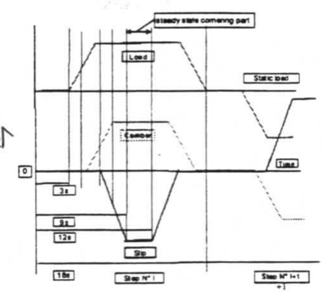

## New tyre test procedure

- simultaneous change of load, slip and camber
- excitation based on 4 general 'axle configurations'
- input level based on tyre ETRTO load
- three parts:
  - warming-up
  - linear sequence
  - non-linear sequence
- additional points for tyre modelling requirements
- repetition of certain measurement points allows quality checks



## New tyre test procedure

Time history of one step in the procedure

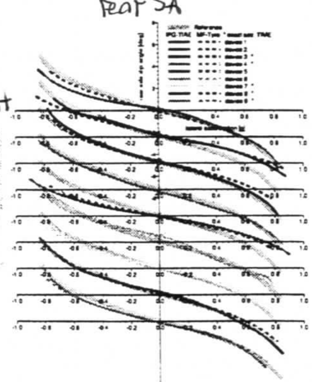





## Validation of the procedure

Comparison simulation results with vehicle cruising tests:

- 5 devices fully followed the TIME procedure: [illegible]on within 10%
- no additional tuning applied




## Conclusions

- Surface curvature and properties have a large influence on tyre F&M properties
- When correlating vehicle modelling results to vehicle tests, tyre test conditions must be consistent with the vehicle driving conditions
- The TIME procedure is based on 'realistic' steady state cornering conditions derived from vehicle test data (cruising type of test)
- The test benches showed a prediction of the vehicle steady state cornering behaviour within a range of 10%, when a direct implementation of tyre TIME measurements into a vehicle&tyre model is applied, without any further adjustment

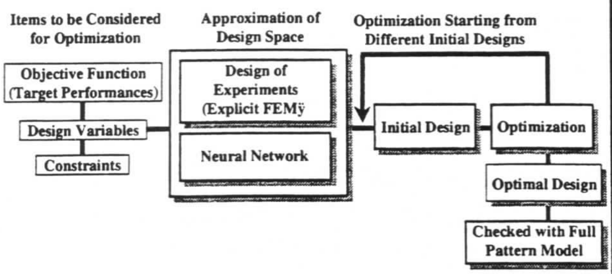
Paper Number 4.2

# Optimization for Motorcycle Tire using Explicit FEM

*Masafumi Koide, Hisashi Heguri, Tatsuhiko Kamegawa,*
*Yukio Nakajima, Hiroshi Ogawa,*
Bridgestone Corporation

A new procedure for tread shape design of motorcycle tires is proposed, in which the explicit FEM is combined with the neural network to optimize the cornering property. The camber thrust, which is one of the most significant cornering performances of the motorcycle tire, is simulated by the explicit FEM, and the prediction is in good agreement with the experiment. The objective function is both the linearity of camber thrust and the pressure uniformity in the contact area. The optimized tread shape design was verified to be effective to improve handling performance at the proving ground.

## Flow Chart of the Proposed Optimization Procedure




## Case Study and FEM Model

Case Study

M 120/70ZR17

- Inflation Pressure 250kPa
- Vertical Load 1.5kN
- Velocity 30km/h
- Camber Angle 0? 45 degree

Objective Function

- The Linearity of the Camber Thrust
- The Uniformity of the Contact Pressure Distribution

Constraints

- Max. width ±3mm

FEM model of Explicit FEM

M120/70ZR17

## Subjective Evaluation at Proving Ground

| Tire Performances | Conventional Contour | Optimal Contour |
|---|---|---|
| Straight Stability | 6.0 | 6.5 |
| Cornering Stability | 5.5 | 6.0 |
| Handling | 9.0 | 9.5 |

Paper Number 4.3

# Effects in The Simulation of Steady State Tire Characteristics (F&M)

*Axel Becker, Kathrin Thiele, Burkhard Pollak, Dong Zheng,*
Continental AG

The total handling simulation chain is composed by three parts: the static and steady state tire characteristics (Forces & Moments), the objective vehicle handling behavior and the correlations between objective evaluations and subjective judgement.

An overview about all three parts will be given in the lecture with special focus on the first part, the simulation of tire forces & moments.

The physical basics are the effective consideration of the rolling kinematics, an appropriate frictional description of the interaction between the tread and the ground surface and the consideration of tread pattern influences. Important for the daily use are effective simulation procedures which will be discussed.

The accuracy of the developed simulation approach is proven by several parameter variations. Interesting mechanical effects especially in the footprint behavior and of constructional parameters are investigated.

**Paper Number 5.1**

# High-Frequency Validation of a Tire Modal Model

*Dave D. Johansen, E. D. Pan,* The Goodyear Tire & Rubber Company
*Randy L. Mayes,* Sandia National Laboratories

For the last 15 years the vehicle industry has been utilizing a tire modal model which can be attached to a vehicle model for a full vehicle NVH simulation. In recent years, the CAE simulation work has been getting more emphasis for the purpose of reducing cost and cycle time. One of the goals is to use these prediction tools to impact the prototype development process. To achieve this goal, the accuracy of each component of the full tire-vehicle model is key to the success of this process. The automotive industry has been working very hard to improve the accuracy of their model. They have requested that tire suppliers demonstrate the accuracy of their tire models by providing results detailing the correlation of analytical and test results. The authors recognize the necessity of an accurate tire model to support both external customers and internal applications and have improved the accuracy of the tire modal model. This paper describes a process developed to experimentally validate these improvements in tire modal models.

Modal test results are a combination of the modes of the test object (tire/wheel) and the test fixture. To minimize the influence of the fixture on the tire results, a test stand that adds little mass or stiffness has been developed. The components of this test stand have been characterized and incorporated into the modal model. Additionally, the influence of tire non-linearity due to time or force level has been minimized by simultaneously acquiring 128 channels of force and acceleration data.

Enhancements in testing techniques have enabled modal tests of tires to be conducted up to 300 Hz. In this frequency range there are approximately 50 tire modes for a typical passenger tire. In order to differentiate these modes, a naming convention has been developed according to the fundamental characteristics of the mode shape: center-line symmetry, number of lobes and tread motion.

A high correlation between test and modal model results up to 300 Hz has been achieved. Examples are shown comparing the results of frequency, mode shape and FRF comparisons.

Paper Number 5.2

## New Predictive Model For the Study Of Vertical Forces (Up To 250 Hz) Induced On the Tyre By Road Irregularities

*Damiano Belluzzo*, *Federico Mancosu* Pirelli Tyres S.p.a.,
*Federico Cheli*, Associated Professor of Politecnico di Milano,
*Roberto Sangalli*, Pirelli Tyres S.p.a.

A physical model has been developed in order to study forces induced on the tyre by road irregularities. It works in a range of frequencies 0 - 250 Hz, i.e. up to frequencies that are felt by the passengers as noise and vibrations, but it can be easily improved to 400 Hz.

The model can resolve road irregularities with wavelength greater than 5 cm (pavement megatexture). The parameters of this model have been identified by comparison with special virtual tests done on a 3D finite element model of the tyre, i.e. without using any experimental data.

Once built, the model can be used to analyse the forces transmitted by the tyre to the vehicle while passing over various pavement textures for testing both the tyre-vehicle system and the pavement textures.

Since the model doesn't require any experimental data, it can be used to predict the dynamical characteristics of tyres which haven't been built yet, speeding up the optimisation process of tyres under development.

Due to its characteristics, this model appears to be a powerful tool for vehicle multibody code joint analysis of vehicle and tyre, but it would require vehicle models with a similar frequency response range, currently not reported in literature.

The model, up to now restricted to the study of the vertical component of forces and system displacements, has been then validated using a simplified model of the vehicle having sufficient frequency response range. The model predictions of the internal vehicle vibrations have been compared with experimental data, giving a good matching.

**Paper Number 5.3**

Cancelled

# Quantification of Tire and Wheel Model Quality

*James J. Lee,*
*Hao Pham,*
*Archie E. Ni,*
Ford Motor Company

Modal tire models have been used in the computer aided engineering (CAE) model of a vehicle to evaluate noise, vibration and harshness (NVH) performances and to drive vehicle design. In recent years, reduced number of prototype vehicles, shorter cycle time, and cost reduction, have put an increased demand for high quality models for up front analysis. The model validation/correlation, however, has been mostly subjective and difficult due to product and test variability. This paper proposes an objective method to quantify model quality based on statistics. A statistical energy analysis (SEA) tire model quality is quantified as an example to the method. This method has also been used at Ford to direct model modifications to make the most significant quality improvement. A finite element (FEA) wheel model is used to demonstrate this part.

KEY WORDS:

model quality, tire noise, road noise, statistical energy analysis, finite element analysis, vehicle NVH, wheel modeling, wheel vibration

Paper Number 6.1

Cancelled?

## Study on Rubber Composite Heat Conductivity

*You Shan Wang, Yan Lin Wang*
Hualin Group Co., Ltd

The heat conductive properties of three kinds of rubber composites are systematically investigated in this paper. The results show that the heat conductivity in the longitudinal direction of fiber of every one of three rubber composites is higher than that of its matrix material, the rubber material, but in the lateral direction is similar. Based on the experimental results a relation between the rubber composite conductivity and temperature is proposed. The principle and apparatus for measuring heat conductivity of rubber composite with the quasi-steady state method is described.

KEYWORDS: rubber composite, heat conductivity, quasi-steady state method.

**Paper Number 6.2**

# Inverse Design Methodology of a Tire

*Masataka Koishi*, The Yokohama Rubber Co.,Ltd.,
*Sanjay Govindjee*, University of California, Berkeley

Since rubber components, such as a tire usually suffer large deformation, we should consider large deformed shapes under some loading condition in mold design of a structure made of rubber materials. A new numerical procedure for an initial shape determination problem of a tire is presented here. The proposed methodology enables us to predict an initial shape corresponding to the prescribed deformed configuration and Cauchy traction of a tire. The finite element formulation of the inverse design methodology of Govindjee and Mihalic is extended to predict an initial shape of a tire. Numerical examples illustrating the methodology in tire design are presented.

## What is the Inverse Shape Determination ?

The Yokohama Rubber Co., Ltd.

- **Standard (Forward) Problem**

| Input | Standard FEA | Solution |
|---|---|---|
| Undeformed Shape | ⇨ | Deformed Shape |
| Initial Configuration | | |

- **Inverse Shape Determination Problem**

| Input | Inverse FEA | Solution |
|---|---|---|
| Deformed Shape | ⇨ | Undeformed Shape |
| Desired Configuration | | To-be Manufactured Shape |

Inverse shape determination is a class of ***inverse problem*** ;
to-be manufactured shapes can be predicted for prescribed deformed configurations, Cauchy traction and boundary conditions

## Three Field Mixed Inverse FE Formulation

The Yokohama Rubber Co., Ltd.

- **Weak Form Equations**

$$G(\varphi,\theta;\beta)=\int_{f\hat{O}}[j-\theta]\beta\, d f\bar{O}=0 \quad \beta : f\bar{O}\rightarrow \mathbf{R}$$

$$G(\varphi,p;\alpha)=\int_{f\hat{O}}[\hat{p}(\theta)-p]\alpha\, d f\bar{O}=0 \quad \alpha : f\bar{O}\rightarrow \mathbf{R}$$

$$G(\varphi,p;f\mathring{A})=\int_{f\hat{O}}[\mathbf{s}:\mathrm{grad}[f\mathring{A}+p\,\mathrm{div}(f\mathring{A}]d f\bar{O}-\int_{f\hat{O}} f\mathring{A}\bar{\mathbf{b}}\, d f\bar{O}-\int_{\partial f\hat{O}} f\mathring{A}\bar{\mathbf{t}}\, ds=0 \quad f\mathring{A} f\bar{O}\rightarrow \mathbf{R}^3$$

- **Q1/P0 Approximation**

Constant approximation per element for $\beta,\alpha,\theta$ and $p$

- **Tangential Operator**

$$D_1G(\varphi;f\mathring{A}[\mathbf{v}]=\int_{\omega_e}\mathrm{sym}[\mathrm{grad}(f\mathring{A}]:\left[2\frac{\partial \mathbf{s}}{\partial \mathbf{c}}\right]:\mathrm{sym}[\mathbf{f}^T\mathrm{grad}(\mathbf{v})]\, d f\bar{O}$$

$$+\left(\int_{\omega_e}\mathrm{div}(f\mathring{A}d\omega\right)\frac{d\hat{p}(\theta)/d\theta}{v_e}\left(\int_{\Omega_e}\mathrm{DIV}(\mathbf{v})d\Omega\right)$$

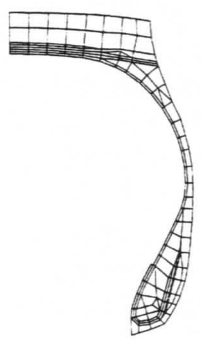
## Ex.3: Layout Determination of a Cured TB Tire

The Yokohama Rubber Co., Ltd.

✓ **Objective**
- To predict an undeformed (to-be manufactured) layout of a cured tire from a desired deformed configuration under prescribed load and boundary condition with temperature change

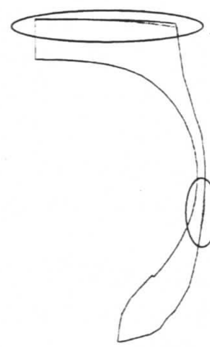
✓ **Problem Set Up**
- Tire size : 11R22.5
- Inflation pressure : 700kPa
- Boundary condition : Rim mounting
- Temperature change : 450K to 300K
- CTE of rubber : 7.7E-5
- CTE of steel wire : 1.2E-5

✓ **FE Model**
- Number of nodes : 177
- Number of elements : 151



## Shape Modification on Deformed Configuration

The Yokohama Rubber Co., Ltd.



**Shape Modifications ;**
- *Crown radius*
- *Sidewall radius*

**Dash line :**
Deformed shape based on the initial design

**Solid line :**
Desired deformed shape (modified)

***Remark :***
- ***Modification can be done on deformed shape not on undeformed shape.***

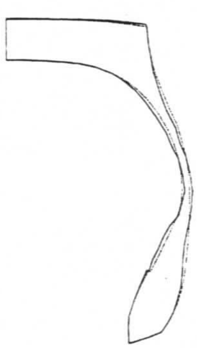
## Resulting to-be Manufactured Configuration

The Yokohama Rubber Co., Ltd.

**Dash line :**
Initial layout of a cured tire

**Solid line :**
To-be manufactured layout obtained by the proposed Procedure

***Remarks :***
- *The resulting to-be manufactured shape is complicated and is not obtained by intuition.*
- *We do not need an initial design for the proposed procedure. We only need a desired deformed configuration.*



## Summary

The Yokohama Rubber Co., Ltd.

✓ An ***inverse design methodology of tires*** is proposed here.

✓ We only need to consider a desired deformed shape under known loading conditions, and then we are able to predict a to-be manufactured shape.

✓ Numerical examples show the effectiveness of the proposed inverse design methodology.

✓ The proposed procedure can also be easily integrated with other numerical design procedure, such as optimization technique.

**Paper Number 6.3**

## Prediction of Tire Shape Change During Post Cure Inflation

*R. H. Kennedy,*
Hankook Tire Co., Ltd.

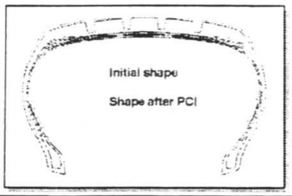
One step in the tire manufacturing process is post cure inflation. In this step, the tire is cooled from cure temperature to below the glass transition temperature of the fabric cords while being held at a constant inflation pressure. Due to the thermal effects and creep of the component materials, the shape of the tire will be different after the post cure inflation than before. This change in tire shape from that in the mold drawings should be accounted for in performing finite element analyses to predict tire performance characteristics.

This paper describes a modeling methodology that predicts the tire's shape change through the post cure inflation process using the finite element method. This is a complex process to represent analytically, with many different mechanisms contributing to the deformations of the tire. These include thermal expansion / shrinkage of the rubber and cords as they cool, creep of both the rubber and fabric cords, and change in material moduli. Since these mechanical effects are temperature dependent, the model uses results from the thermal history prediction model presented previously.

Several tire constructions and sizes were run through the model to compare predicted dimensions to measurements. Selected results are presented to show the accuracy of the modeling procedure.

## Post Cure Inflation in the Tire Manufacturing Process

| Curing | Post Cure Inflation (PCI) | Cool to Room Temperature |
|---|---|---|
| Tire at curing temperature | Cool below body ply cord glass transition temp. while inflated | Final cooling |
| Tire has mold shape | Tire changes shape due to creep and thermal strain | Tire changes shape due to thermal strain |




- Change in tire shape during Post Cure Inflation will affect prediction of tire performance

HANKOOK

## Model Description

### Load History

- A sequence of load steps is required to represent the various loading features applied during PCI

| Load step | Notes |
|---|---|
| Change bead width to PCI chuck width | • Typically molded bead width is different than PCI chuck width |
| Inflate to PCI pressure | • Tire at initial temperature from thermal analysis<br>• Fabric cord modulus representative of elevated temperature state |
| Hold at inflated state for PCI time as tire cools | • Temperature history input from thermal analysis<br>• Viscoelastic creep and thermal expansion / contraction<br>• Fabric cord modulus changes with temperature |
| Deflate to 0 pressure | • Tire temperature still above room temperature<br>• Fabric cord modulus representative of this state |
| Cool to room temperature | • Tire unloaded<br>• Thermal expansion / contraction |

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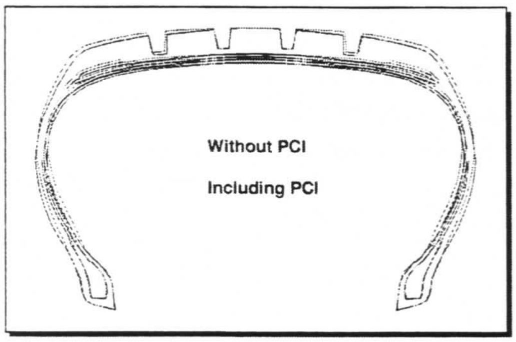
## Predicted Shapes - P185/65R14

### Uninflated Shapes On Measurement Rim

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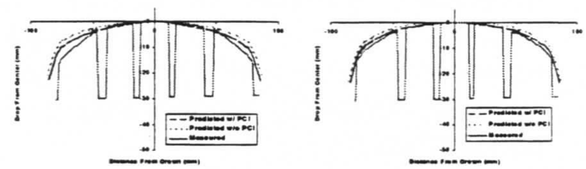
## Tread Profile - P185/65R14

- Measured and predicted tread surface profiles plotted as a drop from the center point




- Including PCI produces predicted tread profile much closer to the measured tread profile, especially in the inflated state

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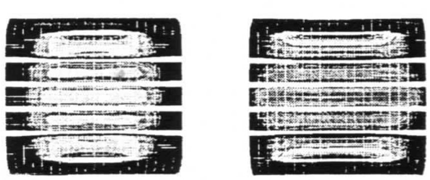
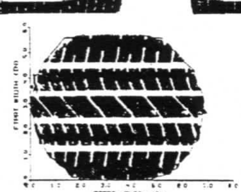
## Predicted & Measured Footprints

### P185/65R14 241 kPa & 5000 N





Much improved shape when PCI included

HANKOOK

**Paper Number 6.4**

# Temperature Gradients Around A Rubber Fatigue Crack Tip

*Cheng Shaw, Vladimir Kerchman, Perry Marteny,*
The Goodyear Tire & Rubber Company

IR thermography was used to produce images of the surface temperature profiles of filled 100% NR and 100% SBR samples in a series of simple tensile fatigue cut growth experiments run under constant stroke conditions. The measurements were made in order to determine to what extent the non-uniform temperature fields reflect and affect fatigue cut growth behavior. The measured temperature gradients are expected to relate to kinetics of rubber fracture and identify regions within the specimen which are undergoing accelerated micro-damage. Correlations were sought between temperature gradients and the crack propagation direction/rate, crack propagation as a function of the angle of the initial cut, initiation of crack branching as well as the catastrophic failure. Coupled mechanical and thermal FEA based modeling was done using an accurate evaluation of energy dissipation in a highly non-uniform cyclic deformation. Predicted and measured surface temperatures are in a good agreement. Accounting for the heat build-up ahead of an advancing crack can improve numerical models that quantify fatigue cut growth behavior in rubber compounds.

**Paper Number 7.1**

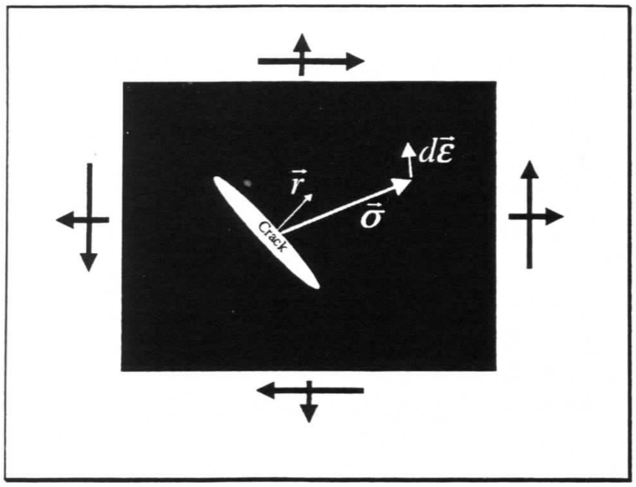
## Multiaxial Fatigue Crack Initiation in Rubber

*Will Mars*, Cooper Tire and Rubber Company

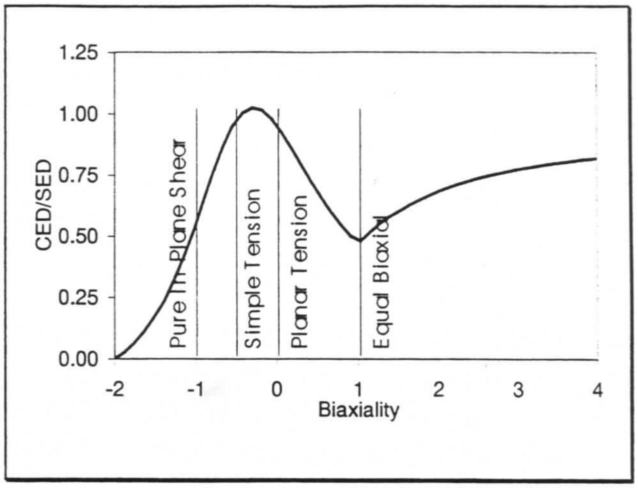
This paper describes a new model for predicting multiaxial fatigue crack initiation in rubber. The work is motivated by a need to predict crack initiation life in tires, based on strain histories obtained via Finite Element Analysis. The new model avoids the need to explicitly include cracks in the Finite Element Model, when the cracks are small compared to the strain gradient.

The model links the far-field strain state to the energy release rate of an assumed intrinsic flaw. This is accomplished through the cracking energy density. The cracking energy density is the portion of the total elastic strain energy density that is available to be released on a given material plane. The model includes an algorithm to select the material plane which minimizes the life prediction for a given strain history.

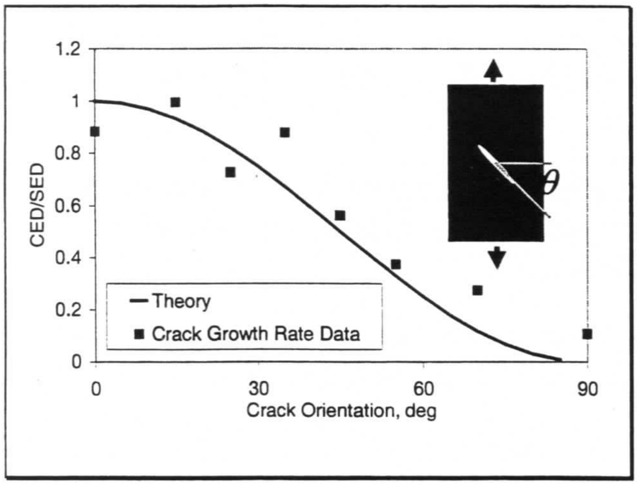
The consequences of the theory for simple strain histories are presented, as well as predictions for more complicated histories. Results from recent combined axial/torsion fatigue experiments are also presented.



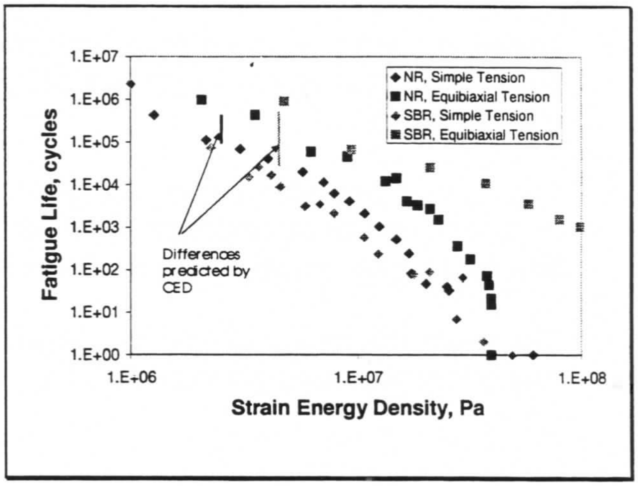
$d\vec{\varepsilon}$
$\vec{r}$
$\vec{\sigma}$
Crack

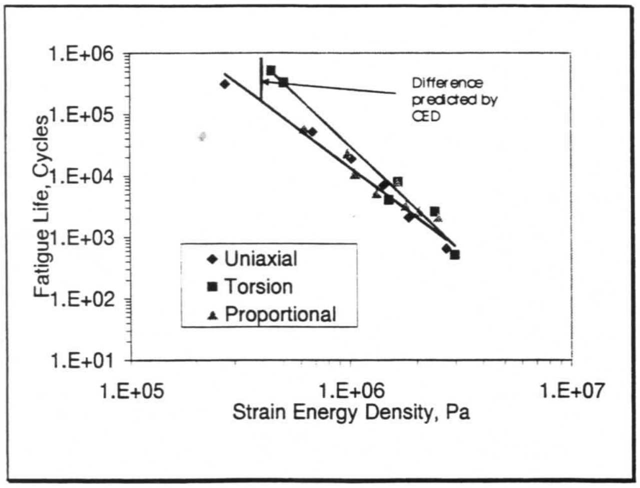
CED/SED
Biaxiality
Pure Th Plane Shear
Simple Tension
Planar Tension
Equal Biaxial

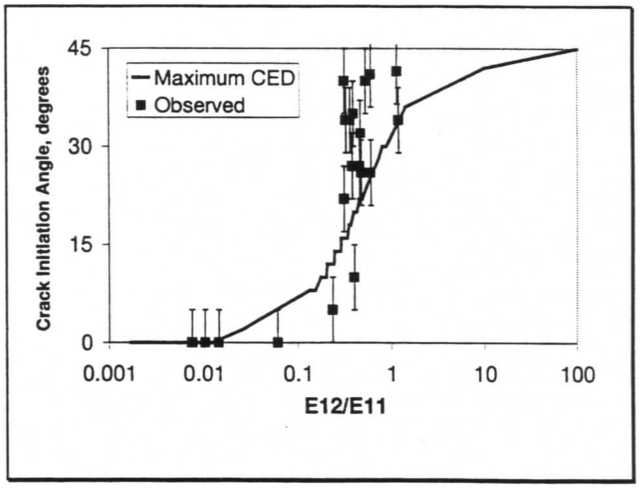
CED/SED
Crack Orientation, deg
Theory
Crack Growth Rate Data
$\theta$

Fatigue Life, cycles
Strain Energy Density, Pa
NR, Simple Tension
NR, Equibiaxial Tension
SBR, Simple Tension
SBR, Equibiaxial Tension
Differences predicted by CED

Fatigue Life, Cycles
Strain Energy Density, Pa
Difference predicted by CED
Uniaxial
Torsion
Proportional

Crack Initiation Angle, degrees
E12/E11
Maximum CED
Observed

**Paper Number 7.2**

# Truck Tire Zipper Break: A Testing Method For the Reproduction Of the Failure In Lab

*Fabrizio Crema, Carlo Di Bernardo,*
Pirelli Pneumatici S.p.A

The zipper break phenomenon afflicts truck tires with an incidence that grows at the increasing severity of use even if, in some cases, the failure occurs at an early stage of tire life. Moreover, the zipper break is a disruptive defect and there are no premonitory signs before it happens.

This paper shows the results of experimental activities carried out in a testing laboratory in order to reproduce the zipper break.

These activities resulted in a test device and in a test method by which it is possible to reproduce the zipper break by means of the same mechanism that causes the failure in use.

The test method allows comparing the performances of different tire structures as to carcass breaking resistance with an appropriate value of standard deviation. In this field some critical points have been found.

Therefore the test methodology might represent a very useful instrument for the designers in studying and testing the fatigue behavior of the steel cord.

**Paper Number 7.3**

## Torsional Crack Growth Test To Simulate Belt Edge Deformation

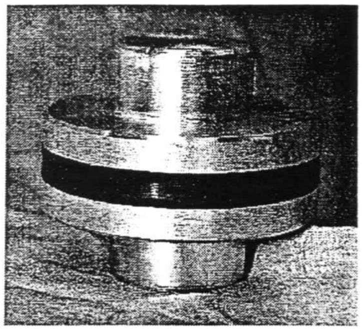
*Thomas S. Fleischman, Vladimir Kerchman, Thomas G. Ebbott*
The Goodyear Tire & Rubber Company

The study of fatigue crack growth resistance for tire compounds and composites is motivated by the high deformation cycles inherent in some tire regions. One example is the belt edge region of radial tires where load transfer from the cords to the rubber can produce large shear strains in the rubber between plies.

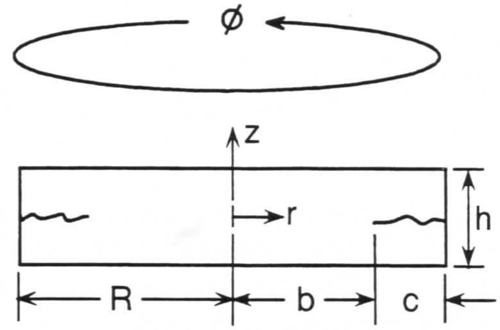
A test has been developed to simulate crack growth in shear (mode III) for characterizing candidate tire compounds. A rubber disk with a circumferential pre-crack is tested in cyclic torsion in order to simulate the interlaminar shear cycles found in tires. Analysis of the cracked torsional disk geometry is more complicated than analysis of the more common edge-cracked strip, pure shear sheet or trouser tear specimens. Theoretical, numerical (FEA) and experimental methods have all been employed to help understand and quantify the response. A recent improvement to the analysis considers nonlinear elastic material behavior which is characteristic of carbon black-filled tire compounds. Plots of crack growth rate versus energy release rate are used for comparison with results from more standard geometries using thin sheets.

The fracture surfaces sometimes show non-planar crack deviation and branching. Radial fatigue markings show evidence of the crack's deviation from planar growth. Circumferential striations, indicative of per-cycle crack growth, are observed at high deformation loading. Overall, agreement between the results from the torsional test and from thin sheet geometries is best with lightly reinforced compounds; crack branching often complicates results for more highly reinforced compounds.

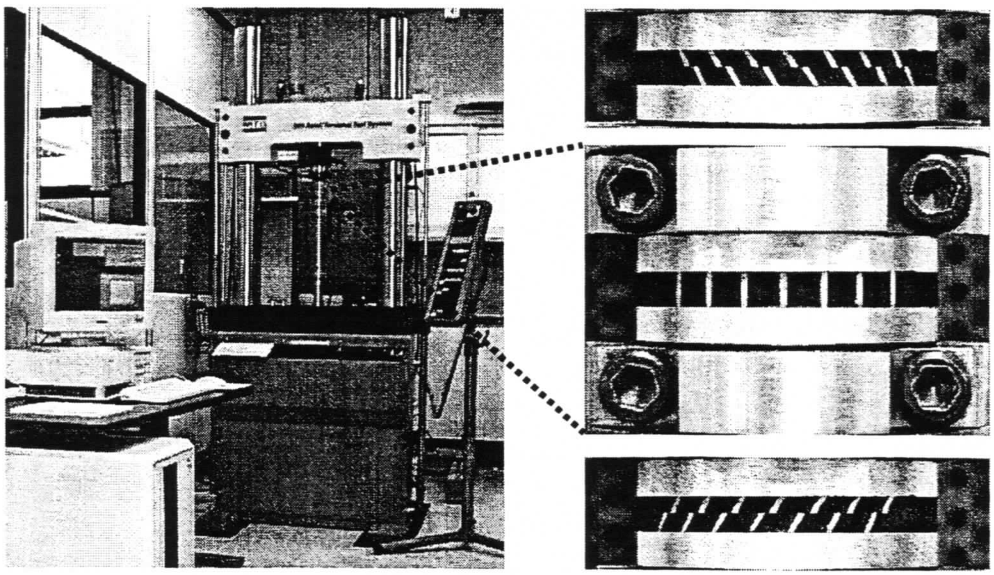
# Torsional Crack Growth Test To Simulate Belt Edge Deformation



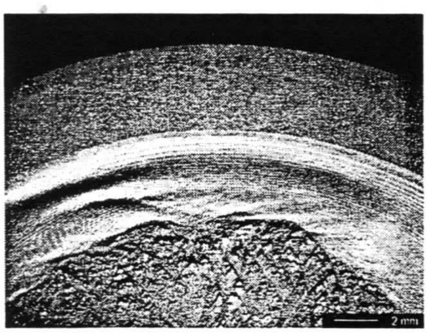
**Specimen**



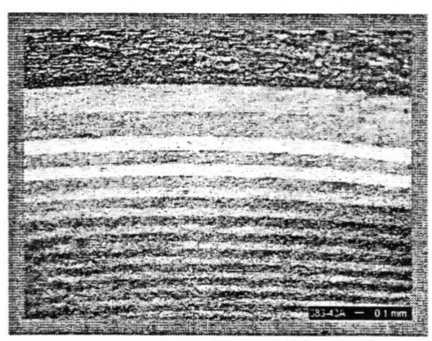

**Notation**



**Torsional Crack Growth Test**



**Fatigue Zones**



**Fatigue Striations**

**Paper Number 7.4**

## Predictions of Mixed-Mode Fracture in Particulate Composite Using Damage Criterion

*Chi L. Chow, Wai H. Tai,*
Department of Mechanical Engineering, University of Michigan-Dearborn,
*Jimmy C. T. Liu*, Philips Laboratory, Edward AFB, California

In this paper, a damage-coupled Mooney-Rivin hyperelastic material model and a damage failure criterion are developed based on the theory of damage mechanics. The model is applied to predict the crack initiation angle and fracture load of particulate composite plate under mixed load. The prediction is achieved by implementing the damage model in a finite element package ABAQUS through its user-specified material subroutine. The inclined angles of the pre-crack are 0 = 0°, 15°, 30°, 45°, 60°, and 75°. The predictions are compared with the test results and found them with satisfactory agreement.

**Paper Number S.1**

## A Study On The Severity Of Cracks In Radial Tires Using Finite Elements

*Fardad Niknam Moghadam,*
*Ghodratollah Karami,*
*Mansour Kamran,*
Rubber Industries Engineering & Research, Co. Ltd, Tehran, Iran

A finite element analysis of a tire having surface cracks is carried out. The cracked regions have been assumed to happen on the crown region in the form of groove cracks or on the side-wall regions. The tire is modelled both in three or two-dimensional forms using a combination of composite shell elements, solid elements in 3D and two-dimensional elements in 2D analysis. The loading may be assumed to come from the inflation pressure and the contact loads in the contacted region. Gap elements are used to simulate the interface of the tire and the road. To study the effects of the cracked regions, the concepts of strength together with fracture mechanics are employed. In special, J-integral contours are used to evaluate the stress-intensity factors at the crack tip to determine the severity of cracks. Cracks at different places, orientations and under different combination of loading are assumed. A series of results based on the change of parameters are thus presented. The results were found to acknowledge the experiments.