CHAPTER 6

ROLLING RESISTANCE SIMULATION OF TIRES USING STATIC FINITE ELEMENT ANALYSIS

Tire rolling resistance is a key performance index in the tire industry that addresses the tire quality parameters as well as environmental concern. Reduction of tire rolling resistance is a major technical challenge so as to reduce the fuel consumption. Rolling resistance of tires could be reduced by changing the compound formulation as well as the tire design.

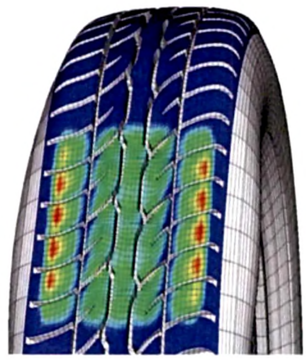

Fig. 6.1: Simulated PCR tire foot print

With the development of tire mechanics and computational technology, tire deformation, rolling resistance, and temperature distribution under roiling conditions could be predicted with a fair amount of accuracy using the finite element analysis (FEA). Commercial software's for the prediction of the tire rolling resistance that arises from the non linear viscoelastic characteristics of rubber are yet to be developed.

This Chapter gives a brief description of elastic tire simulation using Abaqus software that can analyze the tire deformation, stress, and strain under the static inflation and footprint load conditions, emphasizing the tire material hysteresis loss. A finite element program has been developed that uses non linear viscoelastic property of rubber and predicts the tire rolling resistance and temperature distribution. Rolling resistance of PCR and TBR tires with nanocomposite based tread were predicted using this investigation.

6.1 ELASTIC TIRE SIMULATION USING FEA

The whole work was done in three major steps;

I. Elastic tire simulation was carried out using commercial finite element code Abaqus. The simulation includes several steps like (a) FE tire model generation, (b) Material parameter identification, (c) Material modeling and (d) Steady Sate Rolling Simulation

II. Energy dissipation and rolling resistance were evaluated by using internally developed code. The code extracts the strain energy results of the model and the same is post processed with viscous material data. The dissipation energy is calculated based on Equ. 6.1 by taking the product of elastic strain energy and the loss tangent of materials. Computation of tire rolling resistance of both PCR and TBR tires with respective Control compounds and nanocomposites developed for their respective tread applications.

III. Measurement of rolling resistance of tires with Control compounds in In-door Drum type Pulley wheel testing equipment and validation of simulation results of tires with Control compounds against experimentally determined values.

6.1.1 FE Model Generation

The first step is to import tire geometry prepared in Auto CAD to Abaqus CAE and make partition of each tire component as shown in Figure 6.2 and 6.3. A half axi-symmetric tire model was used for 2D analysis. The tire cross section contains different rubber compounds and reinforcing materials. The fabric and steel cords were meshed with SFMGAX1 elements with twist degrees of freedom. The rubber matrix was modeled with hybrid elements like CGAX4H and CGAX3H with twist. The bead was modeled with CGAX4 elements with twist. The symmetric model generation capability was used to create a full 3-d model by revolving the axisymmetric mesh about a prescribed axis. Symmetric results transfer functionality was used to transfer the solution from the axisymmetric model onto the full 3-D model generated by Symmetric Model Generation. The transferred solution acts as the base state for the footprint loading.

6.1.2 Material Properties

A tire usually consists of several rubber components, in addition to several cords and rubber composites. In PCR tire four different types of materials are used and these are rubber compounds, textile fabrics, steel cords and bead wire whereas in TBR tire three types of materials are used such as Rubber compounds, Steel cords and Bead wires. Elastic tire simulation requires uni-axial stress-strain properties of rubber compounds, reinforcing material like Polyester and Nylon fabric and Steel cord. For bead wire elastic modulus and Poisson's ration is need.

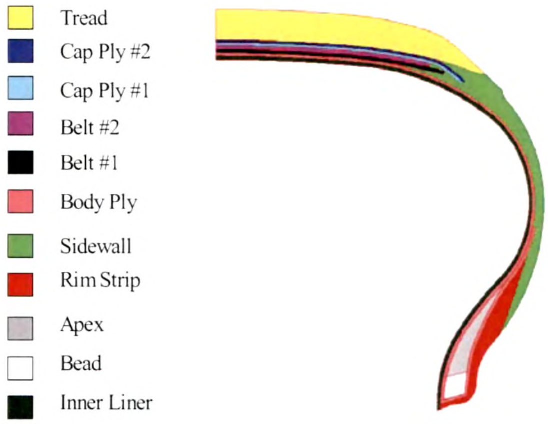

Fig. 6.2- PCR tire geometry: half tire cross section

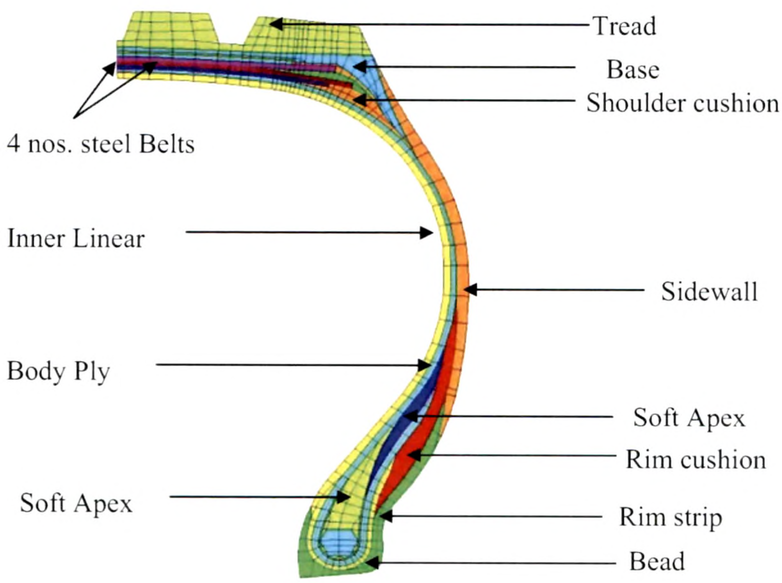

Fig. 6.3- TBR tire geometry: half tire cross section

6.1.3 Material modeling

FE analyses of rubber components need a constitutive model to represent the stress-strain relationship of the material. In commercial code, several material models are available to describe the mechanical behaviour of rubber. The choice of material model depends on several factors like strain range, complexity of loading condition and availability of experimental data. According to external loading, each tire component exhibits considerably distinguished deformation response. Rubber displays large non linear deformation and almost incompressible response, while steel and fabric cords resist most tension as well as compression loads and consequently produce small strain. Generally hyper-elastic material models are used for to describe high deformation. Therefore, Yeoh's hyperelastic material model was chosen for rubber materials and Marlow model for reinforcements such as fabric and steel cords. Bead was modeled as a elastic material.

Yeoh's model is capable of predicting stress-strain behaviour in different deformation modes from data obtained in one simple deformation mode like uniaxial tension.The strain energy function of Yeoh's model is expressed as

$$W= C_{10}(I_1-3) + C_{20}(I_1-3)^2 + C_{30}(I_1-3)^3 \quad \text{(6.1)}$$

The uni-axial stress-strain equation in terms of strain invariant (I) and principle stretch (λ) expresses as;

$$\sigma /(\lambda - \lambda^{-1}) = 2C_{10} + 4C_{20} (I_1-3) + 6C_{30} (I_1-3)^2 \quad \text{(6.2)}$$

Where σ is the nominal stress and I_1 is the first strain invariant

Hyper-elastic material models for rubber and fabric are shown in Fig.6.4 and Fig. 6.5 respectively. Steel cords reinforcements is represented by Marlow model implemented in Abaqus uses first strain invariant only and capture the behaviour of experimental data obtained from uni-axial tension and compression test very close as shown in Fig. 6.6.

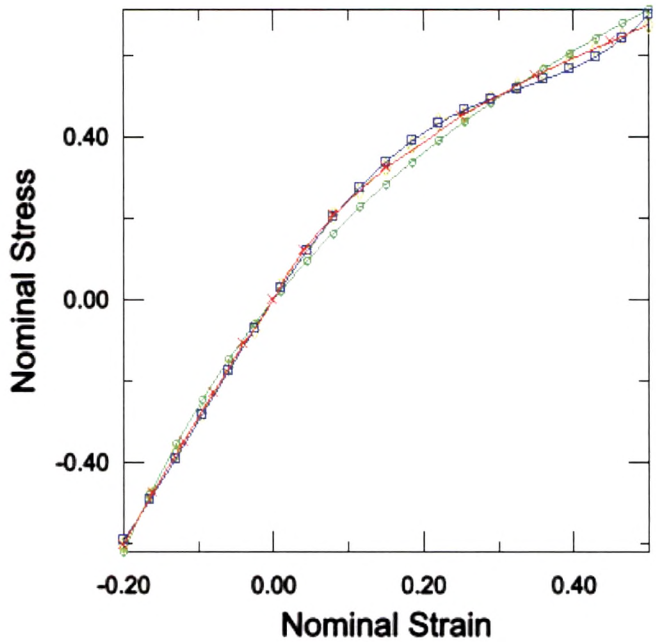

Fig. 6.4- Hyper-elastic material models for NR/BR dual filler (organoclay-carbon black) nanocomposite

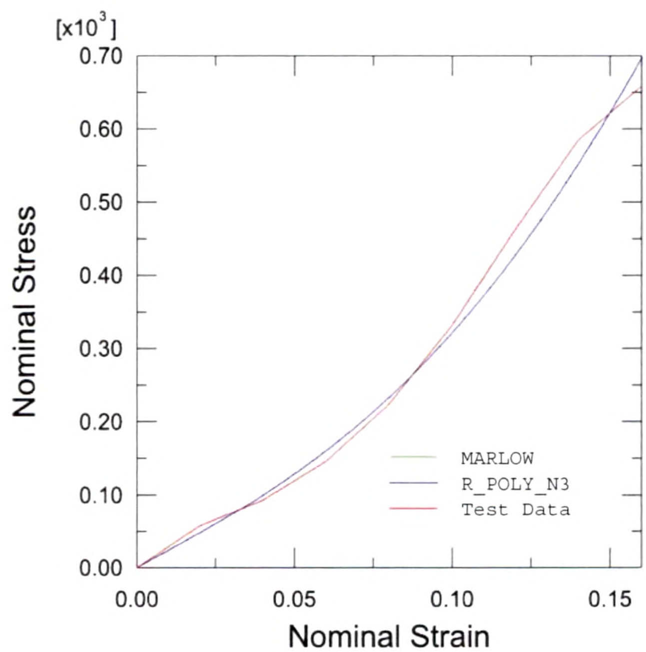

Fig. 6.5- Marlow's model for Nylon 66 tire cord

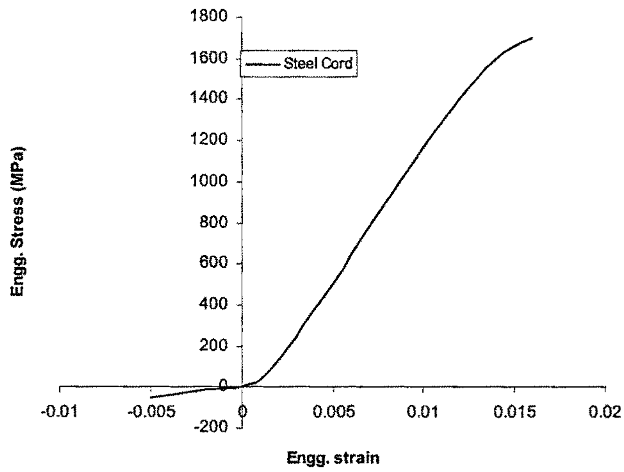

Fig. 6.6-Marlow's material model for steel cord reinforcement

6.1.4 Steady Sate Rolling Simulation

The whole analysis was carried out in three steps (a) 2D axisymmetric analysis (b) 3D footprint loading and (c) Steady state rolling analysis with full 3D tire model.

6.2 ROLLING RESISTANCE SOFTWARE DEVELOPMENT

6.2.1 Introduction

One of most practical way to predict rolling resistance of tires using standard finite element analysis was adopted in this investigation. A rolling resistance software code was developed keeping focus on three requirements: (1) easy input data preparation, (2) shorter computation time, and (3) adequate accuracy.

The method implements a steady state rolling simulation (3D non linear elastic analysis using Abaqus software). The strain energy and principal strains thus obtained, together with the loss factors (Tan δ) of the materials determined separately in the laboratory, are used to estimate the energy dissipation of a rolling tire through post processing.

6.2.2 Prediction of tire rolling resistance and temperature distributions using standard FEA (Fig. 6.7).

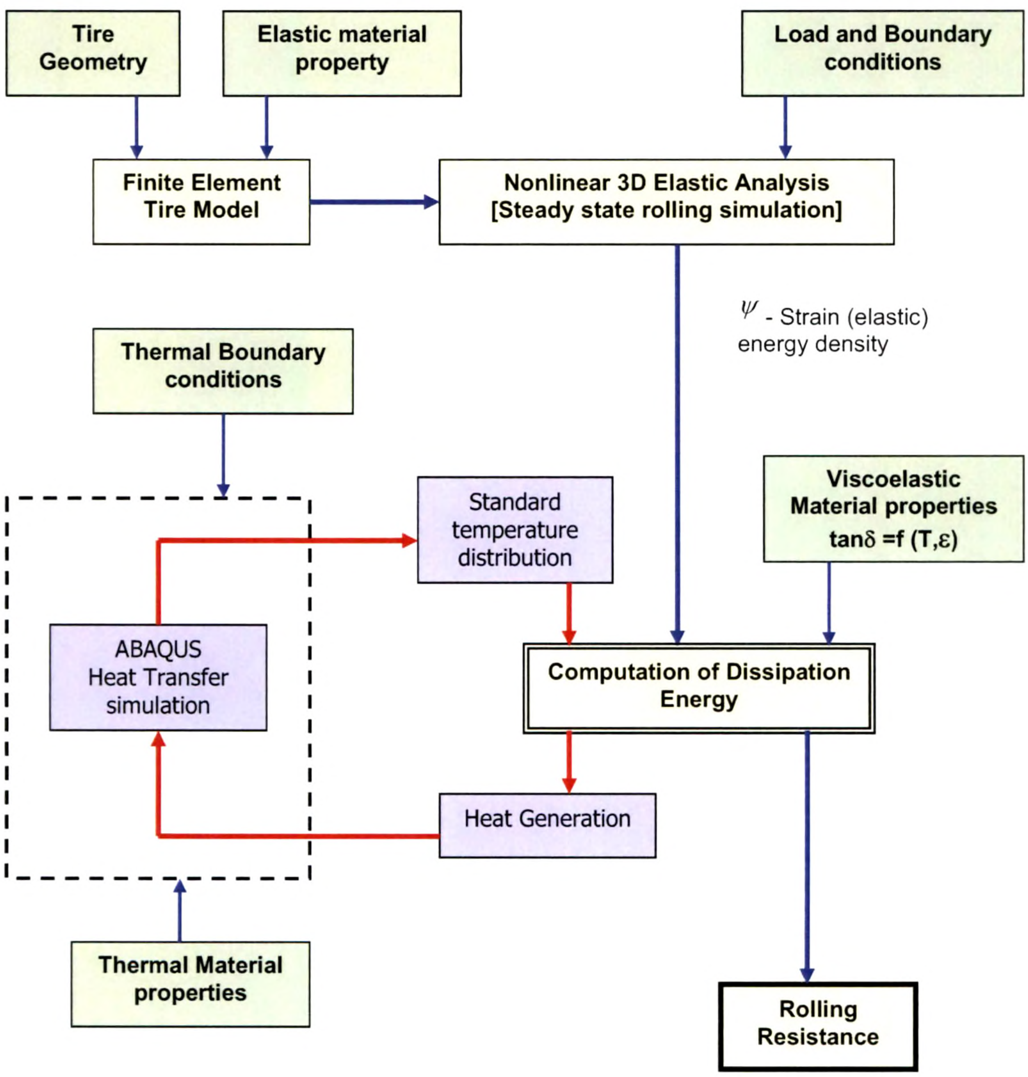

Fig. 6.7- Flow diagram of prediction of tire rolling resistance using FEA

This is a semi coupled thermo-mechanical method where the loss properties are updated as a function of strain and temperature. This simulation tool can be used for studying the relationship between compound and design variables and the rolling resistance of tires.

Elastic materials do not show any dissipation and hence elastic tire simulation does not provide any energy dissipation. Dissipation was computed in post-processing using loss material properties. Dissipation (Loss) can be described by so-called Tan δ quantity which is a ratio of loss modulus (dissipated energy) to storage modulus (elastic energy) in a harmonic loading.

The post processing approach was adopted in this investigation to calculate the energy dissipation, since the alternative approach based on non-linear steady state viscoelastic simulation requires extensive computation. The non-linear viscoelastic behavior was incorporated by providing strain and temperature dependent dynamic viscoelastic properties of rubber. In this study only hysteresis losses of rubber components were considered. The hysteresis loss of fabric was neglected because they were very small compared to rubber.

6.2.3 The methodology used in RR code development

Pure elastic simulation was carried out using standard finite element method. Both Static as well as steady state rolling tire simulation can be used in this investigation. In this procedure, tire is adaptively discretised along the circumference (Fig. 6.8a) in such a way that footprint area has finer mesh and mesh remains stationary and tire revolves during rolling simulation. Tire cross section is also discretised into elements (Fig. 6.8b) and every element represents a ring along the circumference as shown if Fig. 6.8c.

Every element is determined by a number of material points called integration points and the dissipated energy was evaluated at the integration points. Integration of dissipated energy is was multiplied with material volume and summed over integration point of all elements to obtain total dissipation. The dissipation depends on the amplitude of the strain energy density induced by a harmonic loading. In tire, the loading of a material point is non harmonic so it has to be replaced by a set of harmonic functions because Tan δ quantity which is used to get dissipation energy is measured in harmonic loading (Fig. 6.9).

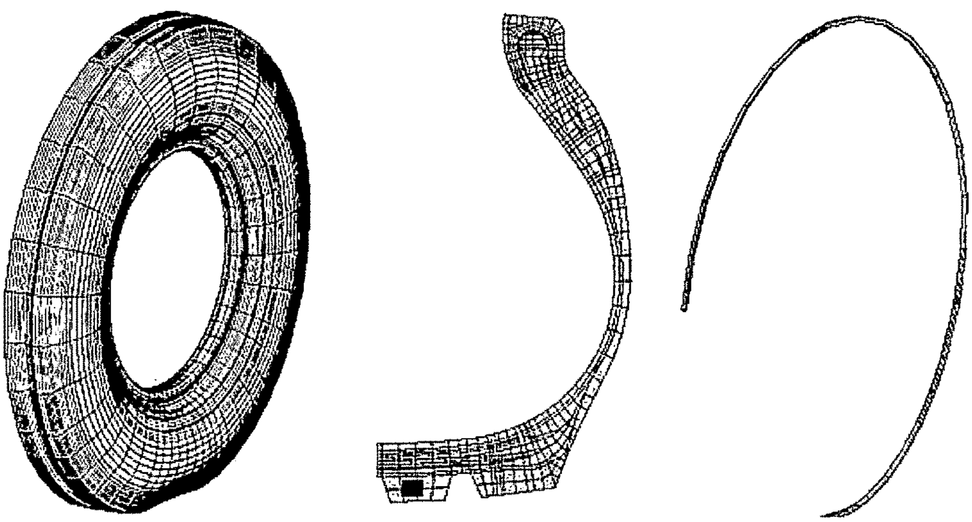

Fig. 6.8- Tire cross section and elemental ring along the circumference

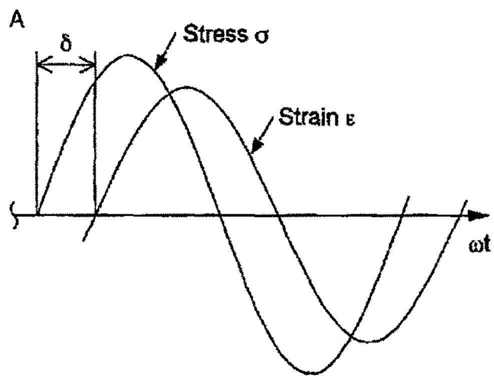

Fig. 6.9- Stress-strain relationship of viscoelastic materials under cyclic loading-phase lag between stress and strain

Non-harmonic function can be composed from a number of harmonic functions (trigonometric interpolation) using Fourier-Series transformation. However, data has to fulfil several requirements like data has to be equidistant; number of data points has to correlate with the number of series, etc. Due to the given adaptive discretisation along the circumference, the data has to be converted to fulfil these requirements. With increasing n, frequency increases and amplitude decreases and solution of dissipation converged. The conversion of non-harmonic to harmonic function using Fourier Transform is shown is Fig. 6.10.

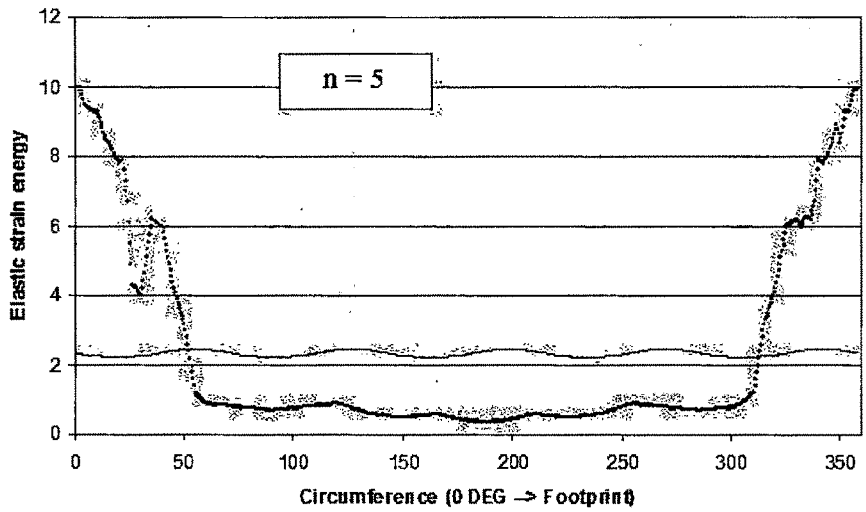

Fig. 6.10- Transformation of Non harmonic to harmonic function using Fourier Series

6.2.4 Computation of energy dissipation and rolling resistance

The total energy loss per one tire revolution is calculated by summation over the circumferential rings of the rubber as per the Equ. 6.1.

$$\psi^{diss} = \sum_{i=1}^{\infty} i2\pi\psi_i Tan\delta_i \quad (6.1)$$

Where, *Ψ – Strain (elastic) energy*

ψ^{diss} – Dissipated energy in one full rotation

Tan δ = Loss Modulus (E'')/Storage Modulus (E')

Rolling resistance was computed by dividing the total dissipated energy in one revolution by the distance travelled in one revolution using Equ. 6.2.

$$F_{RR} = -\psi^{diss} / 2\pi r \quad (6.2)$$

Where, F_{RR} - Rolling Resistance

$2\pi r$ - Circumferential length

6.2.5 Temperature equation

Rubber shows strong visco-elastic effects during cyclic deformation. Visco-elastic properties can by described with a combination of springs and dashpots as represented by Maxwell-element (Fig. 6.11). Response of the rubber material depends on the strain rate experienced by it.

Elastic materials do not show any dissipation and hence elastic tire simulation does not provide any energy dissipation. Dissipation (Loss) can be described by so-called Tan δ quantity which is a ratio of loss modulus (dissipated energy) to storage modulus (elastic energy) in a harmonic loading (Equ. 6.3). Hysteresis loop of rubber is shown in Fig. 6.12

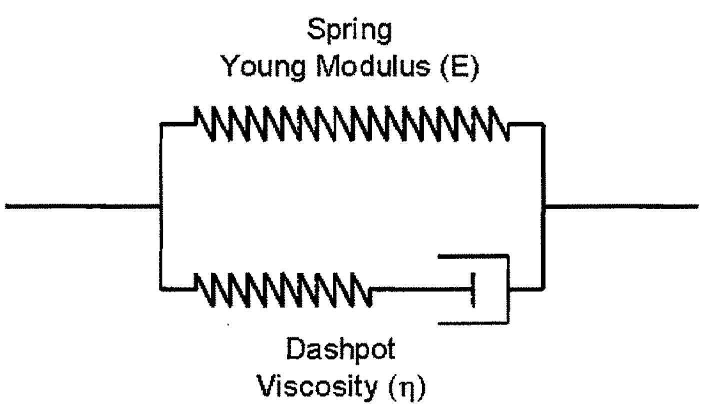

Fig. 6.11- Maxwell model: rubber is represented by spring and dashpot

Dependency of Tan δ on strain is very strong and greatly influences simulation results. Temperature also has a strong influence and it has to be considered. No significant dependency on frequency in the working range was observed.

$$Tan\delta = \frac{E''}{E'} = \frac{\psi^{diss}}{\psi} \quad \text{.......... (6.3)}$$

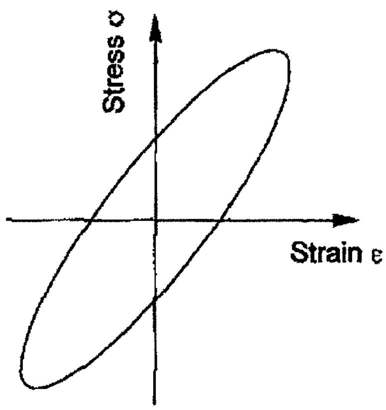

Fig. 6.12- Hysteresis loop of viscoelastic materials under cyclic loading.

A "Loss energy-Strain-Temperature" Equation was developed to capture the combined effect of strain and temperature on Tan δ (loss) is presented in Equ. 6.4.

$$\textbf{Tan } \delta_{i(Ts)} = \textbf{Tan } \delta_{i(To)} \, \mathbf{e}^{-\xi\,(Ts-To)} \quad \text{.......... (6.4)}$$

Where,

$\xi = -\,[Tm/Ts\ \{Ln\ (Tan\ \delta_{i(Tm)}/Tan\ \delta_{i(To)})\}]/(Tm-To)$

To and Tm – Two reference temperatures

Ts –working temperatures

ξ– factor

Tan $\delta_{i(To)}$, Tan $\delta_{i(Tm)}$ and Tan $\delta_{i(Ts)}$ --- Tan gent delta values at temp To, Tm and Ts

The strain sweep (Strain versus Tan δ) starting from 0.1% to 40% single strain amplitude (SSA) was carried out at two reference temperatures To (30°C) and Tm (100°C) using dynamic mechanical analyzer. The strain sweep (Strain versus Tan δ) curve at Ts (50°C) was created using Equation 6.4 and compared with strain sweep curve determined experimentally at 50°C. The strain sweep curve (strain versus Tan δ) predicted from the Equ.6.4 are similar to the experimentally determined strain sweep curve and this showed very good correlation between experimental and predicted data as shown in Fig. 6.13.

To evaluate the energy dissipation at any integration point in a tire cross section, loss energy at that particular strain and temperature is required and to calculate the Loss energy, Tan δ at the same conditions is required. The measurement of Tan δ at any strain and temperature is not physically possible but with the help of Equ. 6.4, this could be predicted conveniently with reasonable accuracy.

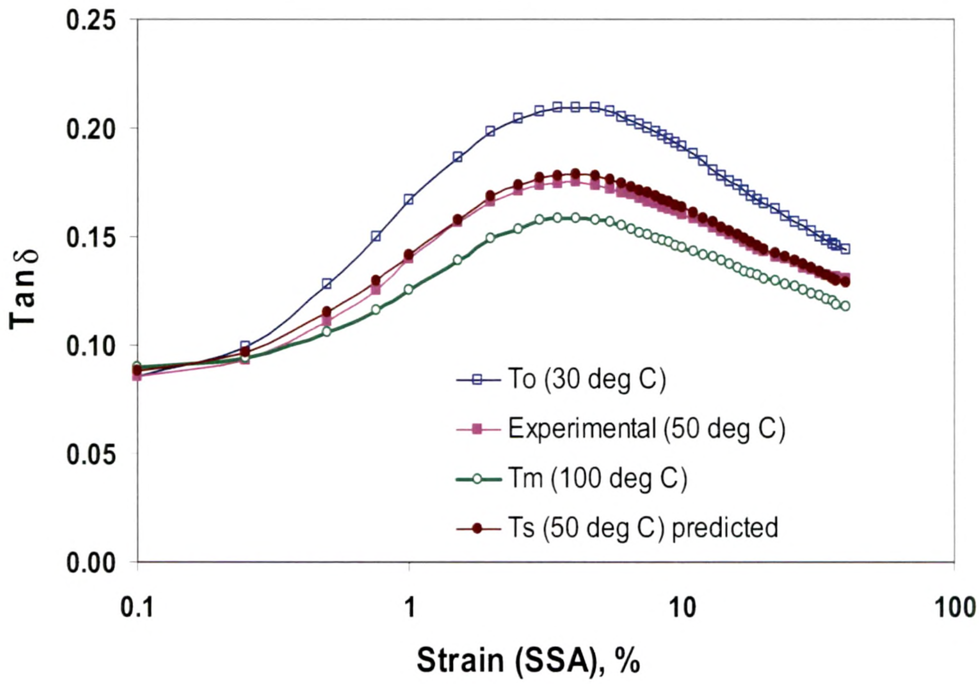

Fig. 6.13- Strain versus Tan δ at 10 Hz

6.2.6 Temperature distribution in a tire

The temperature distribution was done using standard ABAQUS heat transfer simulation. Tire was divided into finite elements and the material was evaluated at every integration points in the elements. In tire, dissipated energy acts as a heat source and to evaluate tire temperature. thermal conductivity of materials and heat transfer film coefficients are required. Heat capacity is not needed due to the stationary characteristic of the problem. The red colour indicates maximum temperature (~150°C) followed by yellow, green, sky and blue colour.

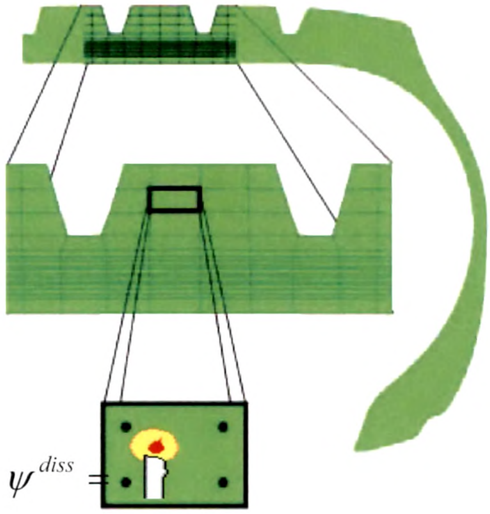

Fig. 6.14- Element and integration points in a PCR tire cross-section

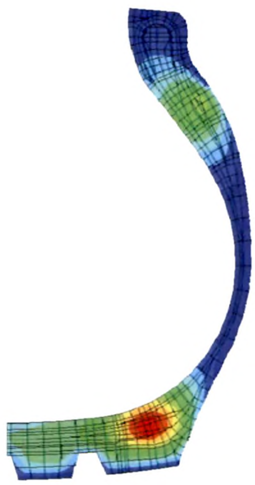

Fig. 6.15- Temperature distribution in a TBR tire cross-section

Using this rolling resistance code developed with FEA on Abaqus platform the rolling resistances were predicted with appropriate inputs of material properties and other constitutive equations and models discussed in this chapter. The results obtained are elaborated in the next Chapter