

Materials Testing for Finite Element Tire Model

2010-01-0418

Published
04/12/2010

X. Yang, O. A. Olatunbosun and E. O. Bolarinwa
School of Mechanical Engineering, University of Birmingham, UK

Copyright © 2010 SAE International

ABSTRACT

The use of accurate tire material properties is a major requirement for conducting a successful tire analysis using finite element method (FEM). Obtaining these material properties however poses a major challenge for tire modelers and researchers due to the complex nature of tire material and associated proprietary protections of constituent material properties by tire manufactures. In view of this limitation, a simple and effective procedure for generating tire materials data used in tire finite element analysis (FEA) is presented in this paper. All the tire test specimens were extracted from a tire product based on special considerations such as specimen dimension and shape, test standard, precondition of specimen and test condition for cords. The required material properties of tire rubber component, including hyperelasticity and viscoelasticity were obtained using simple uni-axial tension test. The reinforcement elastic modulus was established from Dynamic Mechanical Analysis (DMA) in low frequency range. The rubber nonlinear material property was modeled in ABAQUS/CAE. The method used to select an appropriate rubber strain energy model is also presented. In the absence of a tire geometric profile from the manufacturer, an image processing method was adopted. The comparison of tire vertical stiffness and footprint area between model and test results showed good correlation. Preliminary application of the model for tire Noise, Vibration and Harshness (NVH) was also established. Hence FEA of tire behavior for different operating conditions can now be carried out with tire material properties generated from materials testing.

INTRODUCTION

Due to the inherent limitations and cost of tire testing devices, theoretical and numerical tire models have been widely implemented to investigate tire behavior in the past decades. With the appearance and development of FEM, FEA

has been used to simplify the design process and assist tire tests. The application of FEA strengthens its status significantly in the field of tire Noise, Vibration and Harshness (NVH) which is studied widely in the vehicle industry. However, the prediction accuracy of tire finite element model is determined significantly by the tire material property. It is known that a better understanding of tire material property and its mechanism in tire service can lead to optimized tire design with increased tire life. Therefore, an appropriate and effective tire material property test procedure is necessitated based on the limited availability and sources of tire material specimens and test rigs for tire modelers and researchers. In this paper, the essential tire material properties are generated by testing, while the validity of the corresponding tire finite element model for predicting tire macroscopic behavior is discussed.

As a composite material product, the tire is usually constructed using rubber and reinforcements. Thus the aim of a proper tire design is to obtain the best balance of properties for a particular type of tire service [1]. In order to provide a clear view on tire material component distribution, a slick sports tire for Formula Student (FS) is cut and investigated in this study as shown in [Fig.1](#)

[Figure 1](#) shows that the tire consists of different rubber components with embedded reinforcements. The dominant component of tire is rubber including tread, undertread, sidewall, apex and inner-liner. The reinforcement of tire includes belts, carcass, bead, cap ply and bead reinforcement.

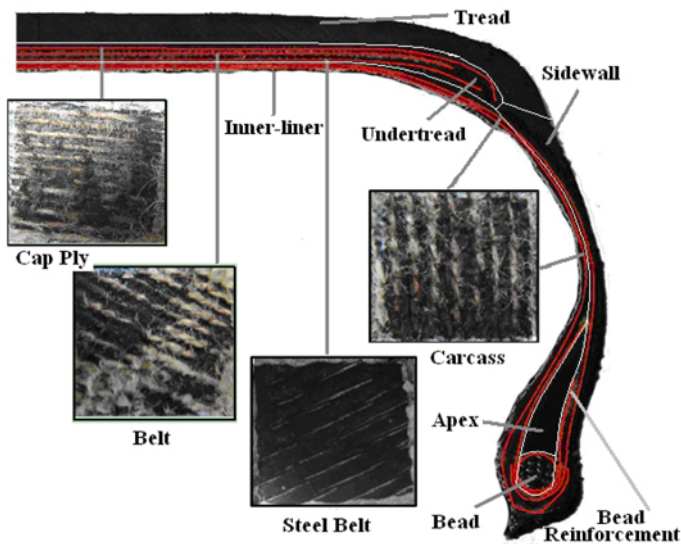


Figure 1. Distribution of tire material component

Since the different proportions of rubber and carbon black are mixed according to the requirement of tire, the rubber material properties for different components vary [2]. The properties of rubber change with time and are affected by the environment. Hence, rubber deteriorates when exposed to heat, oils, chemicals, sunlight, and the weather [3]. As an incompressible or nearly incompressible material, rubber shows nonlinear elasticity under large strains, which makes it necessary to include nonlinear behavior in the finite element model. There are many theories presented to describe these material properties, such as the penalty finite element analysis of incompressible materials and the nonlinear incompressible elasticity, etc. [4, 5]. During tire finite element modeling process, the material properties of rubber of concern are usually the hyperelasticity, viscoelasticity and thermodynamics. However, the rubber material properties are usually difficult to obtain from the rubber manufacturers, because the information about compounding, mixing, processing, assembly and vulcanization is confidential.

The material properties of cords, high modulus and low elongation, provide the support frame for rubber and carry most of the external loads. As the main structure of tire belt and sidewall, the cord-rubber composite material shows its advantages in different tire service conditions. The cords usually consist of nylon or polyester and also show nonlinear characteristics for large strain.

In this study, a basic and practical procedure for obtaining tire material property by testing is described. Simple requirements are adopted based on limited availability and sources of material specimens. The determination of necessary material property for both rubber and reinforcement (cords) component is achieved. An image-based tire finite element model was built without any

information support from the tire manufacturer. The whole procedure of modeling a tire was realized by using a method which can be practically adopted by tire researchers and modelers. It consists of using image processing to obtain the cross-section geometry and material testing to obtain the properties of the constituent materials.

MATERIAL AND EXPERIMENT

The hyperelastic and viscoelastic material characteristics of rubber and the elastic material characteristics of reinforcement are vital for an accurate finite element tire model and are therefore presented in the following sections.

HYPERELASTIC MATERIAL PROPERTY OF RUBBER

The hyperelastic property of rubber provides a general strain energy potential function to describe its highly nonlinear and nearly incompressible material behavior. The combination of uni-axial, biaxial tension and pure shear, which requires complex test procedure and suitable test rig, has been suggested for best practice in determination of rubber hyperelasticity [6]. However there is an alternative simple method using the uni-axial tension test to obtain minimum data for modeling rubber hyperelasticity.

In the FEA of elastomers, material models are characterized by different forms of their strain energy functions. For only uni-axial tension test, Neo Hookean and Yeoh material constitutive models are suggested and supported by ABAQUS [7]. However, Neo-Hookean model also shows a limitation that the determination of the coefficients from one deformation mode (uni-axial tension) has limited value to predict behavior in other deformation modes as described by P.Ghosh et al. [8]. Thus, the Yeoh strain energy function only including the first principal strain invariant I_1 is suggested by P. Ghosh for modeling hyperelasticity material property using uni-axial tension test data as Eq. (1).

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \quad (1)$$

Where the C_{i0} ($i=1, 2, 3$) is the constant to be determined. The stress-strain relation of uni-axial tension is given in Eq. (2):

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

Where σ is the normal stress, and λ is the stretch defined as the ratio of the deformed gauge length L divided by the initial gauge length L_0 . The strain invariant is expressed as

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (3)$$

The principal stretches are $\lambda_1 = \lambda$ and $\lambda_2 = \lambda_3$. For incompressibility, $\lambda_1 \lambda_2 \lambda_3 = 1$. Therefore,

$$I_1 = \lambda^2 + \lambda^2 + \lambda^2 = \lambda^2 + \frac{2}{\lambda} \quad (4)$$

The Yeoh strain energy function in hyperelastic material model has the advantage of covering a much wider range of deformation than other models and can also predict the stress-strain behavior in different deformation modes from data gained in one simple deformation mode like uni-axial tension. Furthermore, it can predict the shear modulus variation with increasing deformation. As a compromise of the material model accuracy and computational cost, the Yeoh model is used for modeling hyperelastic property of rubber herein.

HYPERELASTIC MATERIAL PROPERTY TEST

In this study, the rubber specimen of tread, sidewall, inner-liner and apex are manually extracted from a tire product and cut into proper strips with irregular contours. Due to the absence of support from tire manufacturers, the types of test and the attainable strain states that could be experimentally achieved are restricted [9]. The specimens from which material properties were determined were not cut to any specific standard sizes, but depended only on the available material that could be recovered from the cut sections of the tire. Because the experiment is non-destructive, there is no need to use a dumbbell shaped specimen that is commonly used to prevent specimen failure in the clamps. There is also not an absolute specimen size requirement. In this case the length of a strip specimen is at least 10 times longer than the width and the thickness so that the strip sample can provide the same reliable test data as the dumbbell sample [10].

Test rig under remote computer control is used for the testing of rubber hyperelastic material property shown in Fig.2. All the tests are carried out at room temperature condition. The boundary condition is without lateral constraint, and the specimen is tensioned in direction 2.

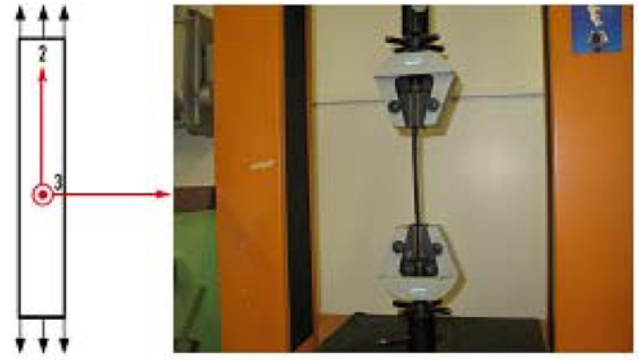


Figure 2. Uni-axial tension test configuration

During the uni-axial testing of rubber, the specimens are pre-conditioned at the speed of 50mm/min for ten cycles. The maximum loading strain varies, depending on the rubber component, for example the apex usually experiences smaller strain than the other rubber components. The maximum loading strain is suggested to cover the conditions the particular rubber component experiences in tire service. Five minutes relaxation time was given in pre-conditioning between unloading and reloading of the sample. The effect of pre-conditioning is to eliminate the stress-softening effect. At the end of the pre-conditioning cycles, samples are removed from the clamp and given one hour relaxation time before the formal test [8]. The pre-conditioning state is shown in Fig.3. With the increasing of pre-conditioning cycles, the stress-strain relationship becomes stable.

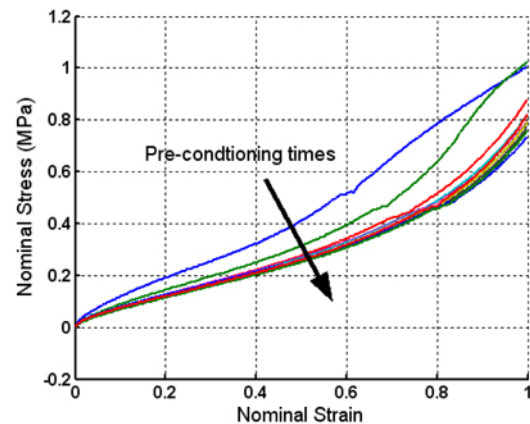


Figure 3. Pre-conditioning of rubber uni-axial test

During the formal test, the samples were stretched to the designed maximum strain at the speed of 50mm/min. This procedure is repeated at least three times in order to obtain a realistic average test data.