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A Review On Methodology Of Material Characterization And Finite Element Modelling Of Rubber-Like Materials

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Abstract : *Hyperelastic materials such as rubbers are widely used in industrial applications. To prevent failure of the components, it is necessary to understand the characteristics of the hyperlasitc materials. Finite Element Analysis is important to assure the safety and reliability of hyperelastic components. This paper reviews the Finite Element Analysis approach for hyperelastic materials and also the various tests required to define the material properties of the hyperelastic materials such as rubber.*

Keywords *– Biaxial test, Finite Element Analysis, Hyperelastic Material, Hyperelastic Models, Rubber, Shear Test, Uniaxial Test*

I. INTRODUCTION

In today's world, hyperelastic materials are widely used in industrial applications. This is because of their properties such as large elastic deformation, excellent energy absorption and damping characteristics [1]. Rubber is an example of hyperelastic material. The applications include rubber diaphragms, O-rings, gaskets, vibration isolators, tires, etc. Engineers are familiar with metallic materials whose behavior is predictable. But hyperelastic materials are highly non-linear is nature [2]. It is challenging for engineers to design and predict the nature of the actual component which are made from hyperelastic materials.

Rubber highly differs from metals. It has large elastic deformation which is recoverable, unlike metals and rubber materials are considered to be incompressible, because under the applied load, volume change is negligible and stress-strain curve of rubber is highly non-linear [2]. There are various challenges faced while designing because of the behavior of the rubber. Rubber shows the viscoelastic behavior. But rubber material is modelled as a hyperelastic material, with the help of hyperelastic models. Rubber also shows behavior such as hysteresis, stress relaxation, Mullin's effect, creep, etc which makes it difficult to predict the nature.

In general, rubber-like materials are represented as a strain energy density function 'W' which is based on three strain invariants I_1, I_2 and I_3.[2][3]

$$W = f(I_1, I_2, I_3)$$

The three invariants are defined in terms of principal stretch ratios λ_1, λ_2 and λ_3. They are given by:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$
$$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2$$
$$I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2$$

λ is the ratio of final length to the original length in the given direction.

II. HYPERELASTIC MODELS

There are three types of hyperelastic models. They are listed below:

1. Statistical modelsPhenomenological models
2. Response function models

Statistical model attempts to derive elastic properties from idealized models of the molecular structure of the rubber. Statistical mechanics based models are Arruda-Boyce model and Gent model, which are nearly or fully incompressible models based on the 1st strain invariant. Phenomenological model treats the problem from the continuum mechanics point of view. Examples of such models include Neo-Hookean model, Polynomial model, Mooney-Rivlin model and Yeoh model. These models are based on the strain invariants. Response function model is the derivatives of the elastic potential functions. Example of such model includes an Ogden model which is based on the principal stretch ratio.[2]

There are various hyperelastic models available in FE softwares such as ANSYS. They are listed below:

1. Neo-Hookean Model
2. Mooney-Rivlin Model
3. Ogden Model
4. Polynomial Model
5. Yeoh Model

6. Arruda-Boyce Model

The appropriate hyperelastic model is chosen for the finite element analysis. The procedure is explained in the curve fitting section. Generally, it is known that Neo-Hookean model gives the best curve fit in the initial range up to 30% strains. Neo-Hookean model does not predict the accurate phenomena of rubber at large strains. There are four types of Mooney-Rivlin model known as 2 parameter, 3 parameter, 5 parameter and 9 parameter Mooney-Rivlin Models. As we increase the parameters, accuracy of the Mooney-Rivlin Model increases. Mooney-Rivlin model can be used up to 200% strains. Ogden model is widely used because unlike other models, this model is defined by principal stretch ratios. This model can be used for large strains up to 700%. Yeoh model is mostly used when all testing data is not available. Yeoh model can be used when only one testing data is available. The curve fitting is done in the FE software to find out the required hyperelastic constants.[4]

III. MECHANICAL TESTING

To define the material properties of rubber, stress-strain data of various tests is required. This data is given as a input to the FE software and by performing the curve fitting, appropriate hyperelastic model is chosen. The various required mechanical tests are explained below:

3.1 Uniaxial Tension Test: This test is performed on the dumbbell specimen. There are two standards available for this test, which are ASTM D412 standard and ISO 37 standard [6][7]. This test should be performed in the ambient temperature and strain rate should be 500mm/min according to standard. This test is performed until the failure of the specimen and stress-strain data is recorded during the test.[6][7]

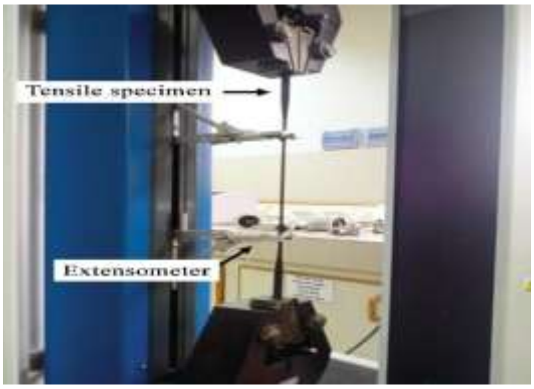
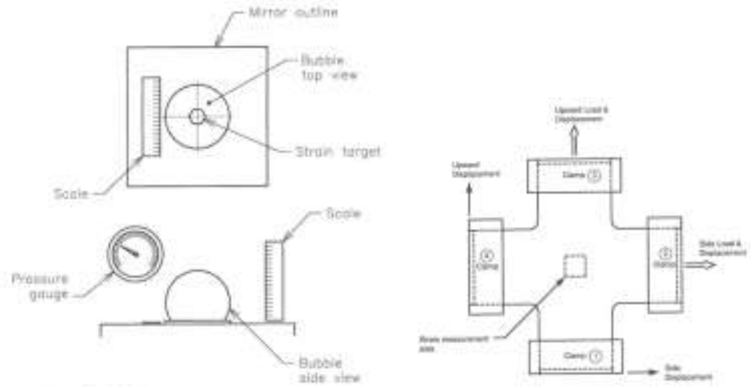


Fig.1 Uniaxial Tension Test

3.2 Uniaxial Compression Set: This test is performed on the button specimen. There are two standards available for this test, which are ASTM D595 standard and ISO7743 standard [8][9]. This test is performed at ambient temperature. Stress-strain and force deflection data is obtained from this test. Unlike uniaxial tension test, uniaxial compression test specimen is of button shape with diameter 29mm and thickness 12.5mm.[8][9]

Fig.2 Uniaxial Compression Test

3.3 Biaxial Test: The standard for this test is not available. Two methods are available for biaxial testing. One method is a classic bubble test. This test requires a circular diaphragm of 2mm thickness. In this test, inflation of the diaphragm is done by applying pressure and measurements of the diaphragm are done with the help of camera. Pressure is incremented in small steps to achieve the proper results. The true equi-biaxial stress state can be achieved in this test. Other method of biaxial test is a cross specimen with non-contacting laser extensometer for strain measurement.[5]



(a) (b)

Fig. 3 Biaxial test : (a) Bubble Test (b) Cross specimen test

3.4 Shear Test: Many times during the application, components fail due to shearing action. So shear test of the rubber is necessary. There are two types of shear test available: Simple Shear Test and Pure Shear Test.

3.4.1 Simple Shear Test: There are two types of simple shear tests available. One is dual lap shear test and other is quad lap shear test. In dual lap shear test, two rubber specimens are bonded between the three steel plates. During the testing, two outside plates are fixed and middle plate is displaced by the machine. Due to this, shear occurs in the rubber specimen. The standard for this test is ASTM D945. Quad lap shear test uses the same concept. Instead of using two rubber specimens, in the quad lap test, four rubber specimens are used.[2][5][10]

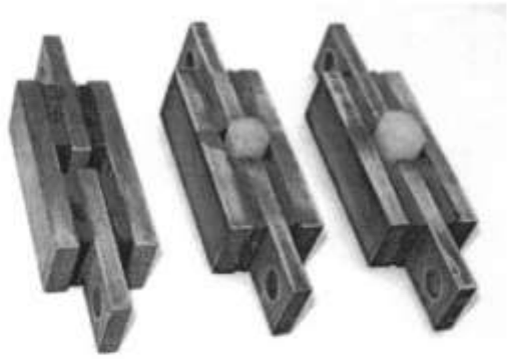


Fig. 4 Quad Lap Shear Test [10]

3.4.2 Pure Shear Test: This test is also known as Planar Tension Test, because this test is a wide tension test. As rubber material is nearly incompressible, a state of pure shear stress exists in the specimen during testing. The width of the specimen is kept more than the length of the specimen to avoid the specimen thinning in the lateral direction. That's why width to length ratio is kept more than 10:1. The strains during the testing can be either measured by the non-contacting extensometers or by calculating the strains directly from the grip travel of the machine.[2][3][5]

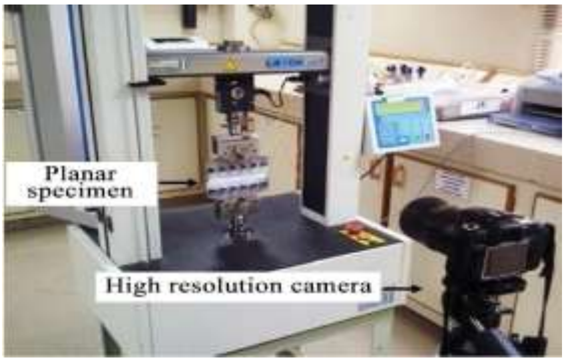


Fig. 5 Pure Shear test

3.5 Volumetric Test: This test is also known as bulk modulus test. This is because; initial slope of the curve obtained during this test gives the bulk modulus. This test examines the ability of the material to compress. In this test, a button like specimen is used. It is compressed by increasing the pressure. So pressure versus volume ratio graph is obtained.[2]

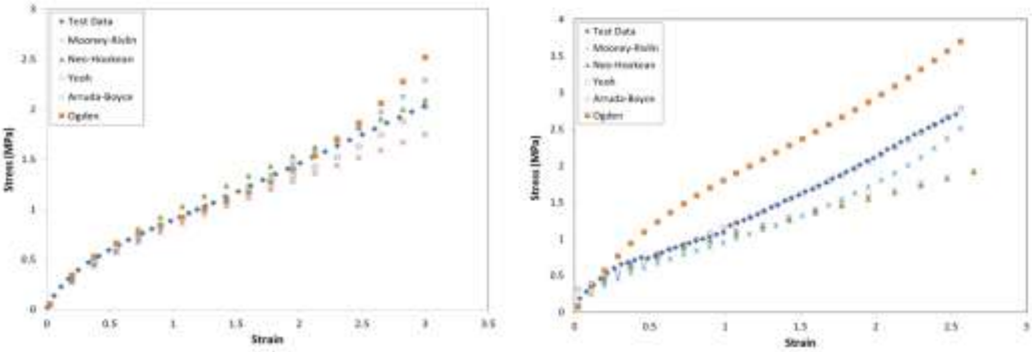
Fig. 6 Volumetric Test

IV. CURVE FITTING AND FEA

The data obtained from the mechanical tests should be engineering stress and engineering strain. Only engineering stress strain data is used for the curve fitting. This is unlike metals, where true stress and true strain data is required.

The only exception for this is volumetric test, where true stress data is required.

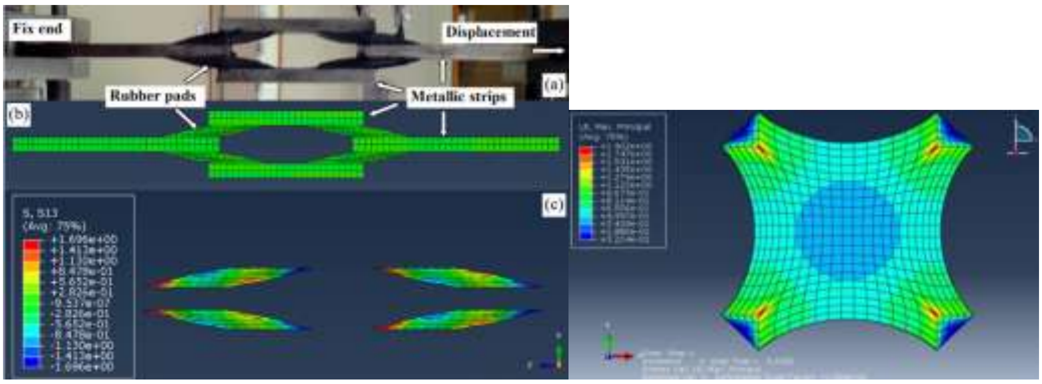
The data obtained from the mechanical tests is given as an input to the FE software. Appropriate hyperelastic models are used and with the help of curve fitting, material constants of the hyperelastic models are obtained. Best way to check whether material is defined properly in the FE software is by conducting the analysis of performed test itself and compare the FEA results with experimental data.[2]



(a) (b)

Fig. 7 Curve Fitting: (a) Quad Lap Shear Test Data (b) Biaxial Test data

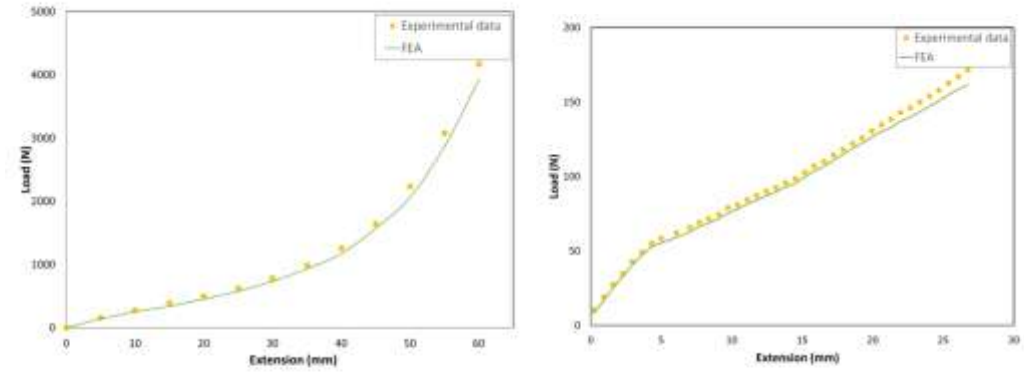
In the paper [2], uniaxial tension test, biaxial test, shear test and volumetric test was performed. Curve fitting of the data was done in the Abaqus software. With curve fitting, it was found that, Yeoh model was giving better fit with the experimental data. So Yeoh model was chosen and its material constants were calculated in the Abaqus. FEA of shear test and biaxial test was carried out. It was found that, FEA results and experimental results are matched.



(a) (b)

Fig. 8 FEA: (a) FEA of Shear Test (b) FEA of biaxial Test

By defining the material with the help of hyperelastic model, FEA of the actual component can be carried out. As we can see in this paper [2], experimental results are closely matched with the FEA results.



(a) (b)

Fig. 9 Comparison of experimental and FEA results: (a) Shear Test (b) Biaxial Test

V. CONCLUSION

Rubber like material is highly non-linear in nature. It becomes difficult to model such material in finite element software. One way to solve this problem is by performing the actual mechanical tests of the rubber material. By performing the mechanical tests and by substituting the stress strain data to the FE software, finite element analysis of the rubber components can be carried out.

Curve fitting of the experimental data is important. With curve fitting, appropriate hyperelastic model can be selected. Selecting proper hyperelastic model is important, as they can vary the FEA results. One can inspect whether the selected model is correct or not, by performing the FEA of mechanical test. If the results match with the experimental data, one can say that selected model is correct and can be used for analysis of actual component.

As per the paper [2], we can conclude that using the experimental data and the appropriate hyperelastic model, rubber properties get defined.

Performing the mechanical tests is necessary, because every rubber material behaves differently. This behavior can be predicted with the help of mechanical test data.

Due to lack of knowledge and resources, many design engineers use the stress strain curve of uniaxial tension test to define the material. But uniaxial tension test data alone is not enough to define the material properties. One objective of this review paper is to throw the light on different tests available whose stress strain data is required during the analysis.

While mechanical tests can capture most of the rubber behavior, various other tests are required which can determine the effects of temperature, Mullin's effect, compression set, creep, etc. Finite element analysis cannot capture such effects. So experimental study, along with FEA is necessary.

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