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Investigation on the Elastic Modulus of Rubber-like Materials by Straight Blade Indentation Using Numerical Analysis

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Abstract. The indentation technique has been proven to be useful in determining mechanical properties of materials, but it is rarely applied to rubber-like materials (elastomers). It is difficult to describe accurately the mechanical properties of an elastomer by theoretical formulation due to its complex material behaviour. Indentation of a Styrene Butadiene Rubber (SBR-0) material by a rigid straight blade with a tip angle of 45 and 60 degrees was performed to estimate the elastic modulus. Indentation was carried out numerically by finite element analysis (FEA) and for the elastomer the hyper-elastic material model of Mooney-Rivlin is used. The estimated elastic modulus was calculated based on the contact depth. The predicted result was also verified by tensile test results. It was found that the predicted elastic modulus of the elastomer agrees with the tensile test result.

Introduction

The indentation technique has been proven useful in probing mechanical properties of materials, but it is rarely applied to elastomers. It relates to ‘‘hardness” that has been classically referred to the indentation of substrates and implies a permanent dent in the surface of the substrate after unloading. This cannot be observed at elastomer surfaces at ambient temperatures, because of the complete rebound of the surface as soon as the indenter is withdrawn. In rubber technology, the indentation test has been known to be a measure of an elastic modulus [1] that is a main mechanical property related to “hardness” of the material. In addition to shore durometer test which is frequently used to measure the rubber hardness, the indentation test was also issued by ASTM [2]. This indentation method obtains the hardness of rubber by the difference of penetration depth of a specified dimension of ball indenter.

An indentation analysis by a spherical and a conical indenter was performed experimentally, analytically, and numerically [3,4]. A result showed that an analysis by using the linear or second order elasticity theory give results with a small depth of indentation of a blunt conical indenter or a large spherical radius. However, it requires a strain energy function (SEF) for large depth of indentation. In rubber mechanics, strain energy function represents stress-strain relation which is developed from a variety of models that conform to uniaxial tension experiments up to a certain level of straining [1]. However, comparison between direct stress-strain analysis and energy method was also performed to find the elastic modulus of polyurethane rubber [5].

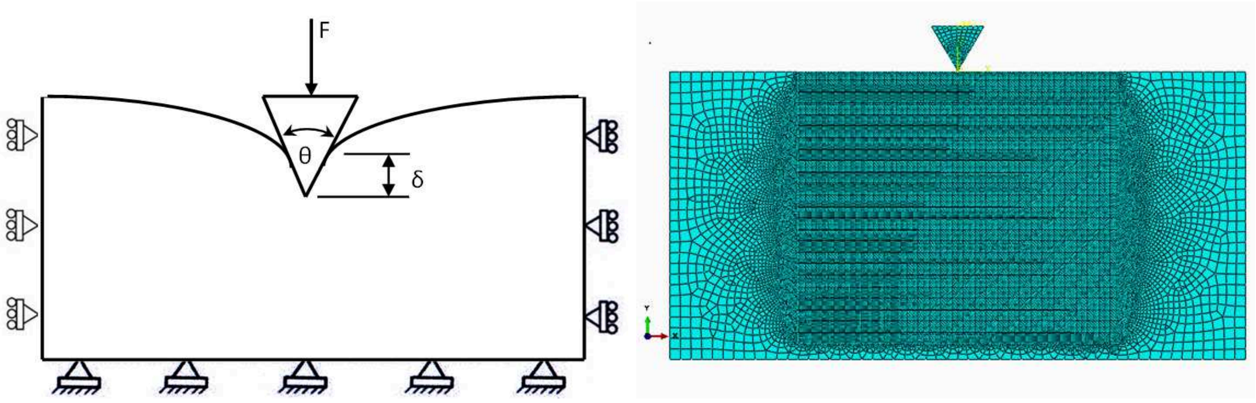
In rubber abrasion by blade abrader, the periodic pattern on the abraded rubber surface was formed [6]. Experimentally, the interesting result was stated that length of pattern spacing formed was depended on hardness or elastic modulus of the rubber. High hardness of the rubber forms short pattern spacing and vice versa [7]. Therefore, the rubber hardness plays an important role in the rubber abrasion.

In general, the elastic modulus of rubber can be determined by a tensile test method but it is not simple to conduct such test compared to the indentation test method. Most of the indentation tests use an axisymmetric indenter such as sphere and cone. The blade is widely used in cutting or abrasion tests as an indenter. In order to estimate the elastic modulus of elastomer before starting the abrasion, this paper models the blade indentation on an elastomer using finite element analysis. The elastic modulus of the elastomer is then determined based on the depth of the contact.

Methods

The finite element analysis of the present work was performed using a commercial finite element software package, ABAQUS 6.11 [8] with some built-in strain energy function model for a hyperelastic material. A straight rigid blade indenter was pressed on an elastomer surface. The blade tip angle θ of 45 and 60 degrees were used. The SBR-0 (Unfilled Styrene Butadiene Rubber) with the Mooney-Rivlin strain energy function (SEF) was used as elastomer and assumed as an incompressible material. The SEF data were adopted from Liang’s experiment [9].

Fig. 1(a) shows a schematic illustration of the rigid blade indentation of an elastomeric surface in two dimensions, where F is the indenter load, θ is the blade tip angle and δ is the depth of contact, while the thickness of the elastomeric material t is perpendicular to this figure. Boundary conditions of the contact system are depicted in this figure.The elastomer material was modeled as a plane strain condition with a 10 mm height, 20 mm width and 10 mm thickness. The finite element mesh of the indentation is presented in Fig. 1(b) that the fine mesh is applied at the middle part of the material than at the edges. By performing the previous procedure, the resulted deformation and stress around the indenter can be observed accurately. A load of 5 N was applied to simulate the indentation. The results are presented in the form of the indentation depth, the depth of contact δ and the stress distribution. These results are then used to estimate the elastic modulus of the elastomer.

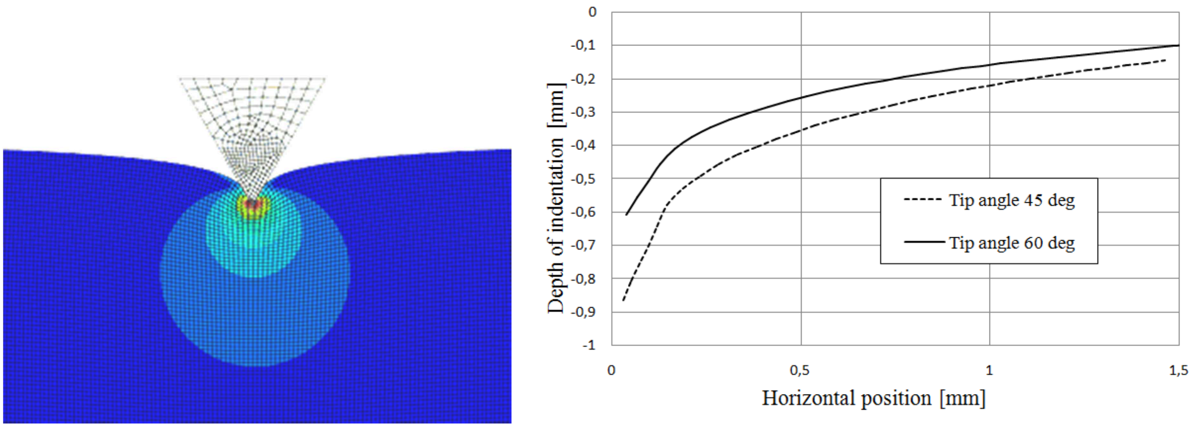


(a) (b)

Fig. 1. (a) Schematic illustration of the indentation model; a rigid blade on an elastomer surface and (b) the generated FEA mesh for the indentation model.

Results and Discussion

Fig. 2(a) shows the surface contour of the 5 N indentation for a 60 degree tip angle from the finite element analysis. The von Mises stress distribution is also demonstrated in this figure. The highest contact stress and deformation are located at the blade tip indenter. Fig. 2(b) shows the plot of the depth of the indentation as a function of the horizontal position for the 45 and 60 degree blade tip angle. It can be seen that the contact depth of the blade tip angle of 60 degrees is about 0.25 mm and the contact depth of the blade tip angle of 45 degrees is about 0.35 mm. This because the 45 degree tip angle is sharper than the 60 degree blade tip angle, therefore, the contact stress and the contact depth will be higher.



(a) (b)

Fig.2. (a) The surface contour of the 5 N indentation for 60 degree tip angle. (b) The plot of the depth of indentation as a function of the horizontal position for the 45 and 60 degree blade tip angle.

The elastic modulus E of the indented material (elastomer) is estimated through the simple theoretical formulation of [10] which is depended on load (F), thickness (t), tip angle (θ) and contact depth (δ). The strain ε of indented material can be approximated as $\varepsilon \approx 0.5 \cot\left(\frac{\theta}{2}\right)$, however, this formulation is not feasible for extremely sharp indenter [10], so the equation reads,

$$E = \frac{\sigma}{\varepsilon} = \frac{F}{A\varepsilon} = \frac{F}{2t\varepsilon\delta \tan\left(\frac{\theta}{2}\right)} = \frac{F}{t\delta} \qquad (1)$$

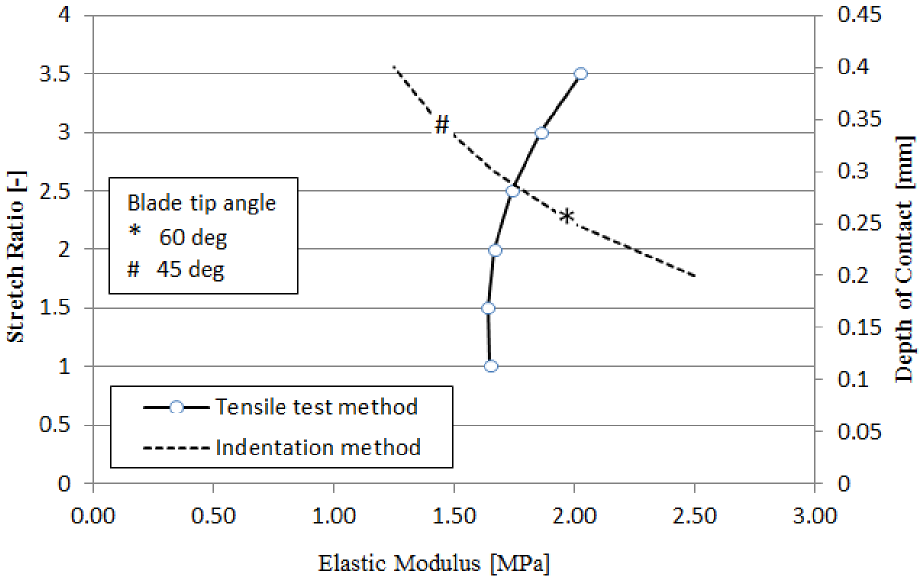


Fig.3.The elastic modulus of the SBR-0 elastomer predicted based on the 45 and 60 degree blade tip angle FEM indentation method, and the tensile test method.

Moreover, the elastic modulus of the rubber can be estimated by means of tensile test method. Later, this study adopts Liang's experiment [9] on the tensile test of this rubber which resulted in the relationship between engineering stress (σ) and stretch ratio (λ) i. e. the ratio of streched to the unstrecthed length. By assuming that the rubber material is incompressible, the elastic modulus (E) can be expressed as [1,11],

$$E = \frac{\sigma\lambda}{\lambda - 1} \tag{2}$$

Fig. 3 exhibits the comparison of the elastic modulus of the SBR-0 elastomer predicted from the 45 and 60 degree blade tip angle. Here, finite element method (FEM) indentation in eq. (1) and the tensile test method in eq. (2) are compared. Result of the 45 degree blade tip angle FEM indentation gives a larger contact depth and a smaller elastic modulus than the 60 degree blade tip angle FEM indentation. The estimated elastic modulus is about 2.00 MPa for the 60 degree blade tip angle FEM indentation and about 1.43 MPa for the 45 degree blade tip angle FEM indentation. The interesting thing is that the elastic modulus from the tensile test method is in the range of 1.64 to 2.07 MPa. It means that the proposed indentation method is able to estimate the elastic modulus of the elastomer.

Conclusion

The indentation of an elastomer material by a rigid straight blade with the tip angle of 45 and 60 degree was performed to estimate the elastic modulus. The finite element analysis was employed to simulate the indentation process. For the elastomer used the hyper-elastic material model of Mooney-Rivlin is used. It was found that the indentation of the 45 degree blade tip angle yield to a lower elastic modulus and a larger contact depth compared to the indentation with the 60 degree blade tip angle. The predicted results were also verified by a tensile test method result. It was found that the predicted elastic modulus of the elastomer agrees with the tensile test results.

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