Experimental Methods for Engineering Mechanics

Group 6 - Bonus Contribution

Module 2: DIC AND PLANAR ELASTICITY

How to model a hyperelastic elastomer in Finite Element Analysis (FEA)?

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1 Background

1.1 Motivation

Elite Double 32 (vinylpolysiloxane (a-silicone)) is the material used in Module 2: "DIC and Planar Elasticity" to prepare the samples. It can be seen in figure 1. The common name for this material is silicone rubber as well.

Figure 1: Base and Catalyst Containers of Elite Double 32. This material is used to cast the samples for the tensile tests to be performed.

This material exhibits an elastomeric behavior withstanding high deformations elastically. Depending on the extension (strain) specified on the tensile testing machine, elastomers may be elongated anywhere between zero to sometimes more than ten times their lengths before they fracture. For this reason, rubbers and elastomers in general have a non-linear dependency between stress and strain but are still elastic. Additionally, most of them behave as incompressible materials with a possion's ratio of $\simeq$ 0.5 meaning their volume remains the same when they are deformed. All the work done to deform elastomers is stored as internal energy and recovered upon unloading. This notion will be employed to develop constitutive models for these elastomers. A typical stress-strain curve for an elastomer can be seen in figure 2 where it is compared with the plots of a thermoset and a thermoplastic [1].

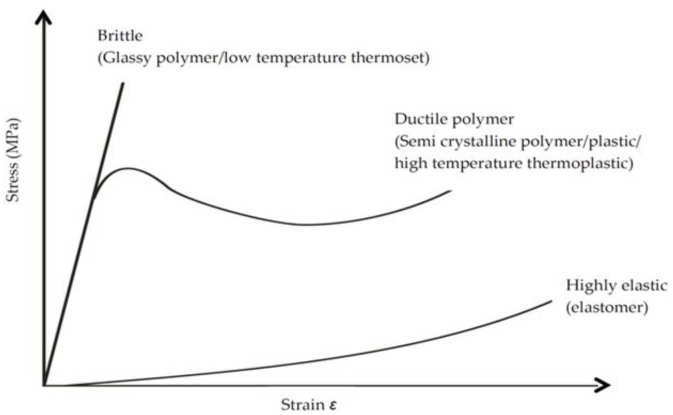


Figure 2: Stress versus Strain Curve for Polymers. This figure shows the typical stress-strain curves for the three main branches of polymers: thermosets, thermoplastics, and elastomers. Indeed, elastomers withstand high strains and feature an increasing stress with increasing strain.

Given the following behavior, caution must be exercised when modeling the behavior of elastomers in finite element analyses using software. That is why this contribution was developed as a guide to properly model elastomers and to clearly distinguish between the available models.

1.2 Existing Hyperelasticity Models

Several models have been developed to reproduce the behavior of elastomers. Each model has its own intricacies as well as advantages and disadvantages. Constitutive models are based on the strain energy density for these materials which itself is the amount of energy stored in a unit volume of the material. Strain in this case depends on deformation thus depends on the type of loading. The main and common modes of deformation are uniaxial tension, biaxial tension, and planar shear. These modes can be seen in figure 3.

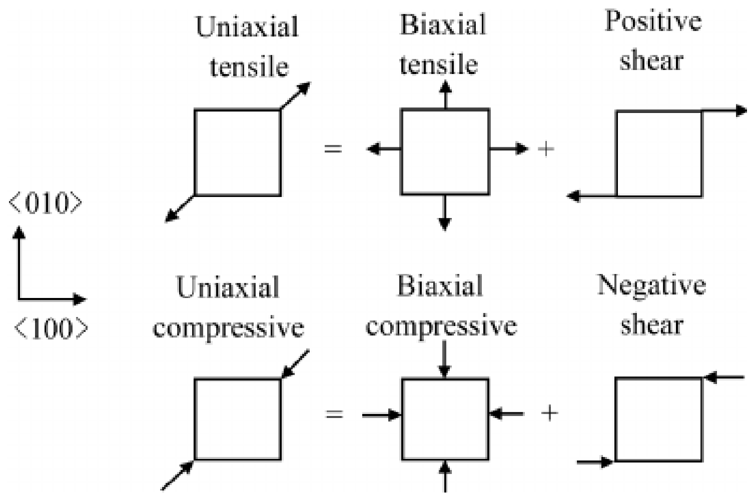


Figure 3: Different Loading Modes. This is a schematic of the three main loading modes: uniaxial, biaxial, and shear. Uniaxial and biaxial loads can be tensile or compressive. Shear can be either positive or negative [2].

Confined compression tests are also held to calculate the material volumetric response, but these tests are usually not performed if the material is assumed incompressible. Materials may also be calibrated following one deformation mode only; thus, the model faithfully reproduces the material behavior in this deformation mode only. Then, a certain hyperelastic model is chosen and fitted to the experimental data. This means parameters and in this case hyperelasticity constants are extracted and become material properties. When curve-fitting is performed, a quantity called the cumulative mismatch is calculated and it is the difference between the experimental data and the model prediction. This calculated quantity at every point forms a function, the least-square function, which we seek to minimize by linear or non-linear regression depending on the model type and number of constants. Several hyperelastic models are available in ANSYS and are listed in figure 4 below.

Figure 4: Hyperelasticity Models Available in ANSYS. Tabular experimental data or hyperelasticity coefficients can be used to define hyperelastic materials in ANSYS.

2 Software Implementation (ANSYS)

The following sections include captures from the ANSYS software interface, yet is to a significant extent similar to other FEA tools.

2.1 Geometry

Model your geometry using any CAD tool (or even Spaceclaim from ANSYS) and import it to a Static Structural module on ANSYS Workbench as can be seen in figure 5.

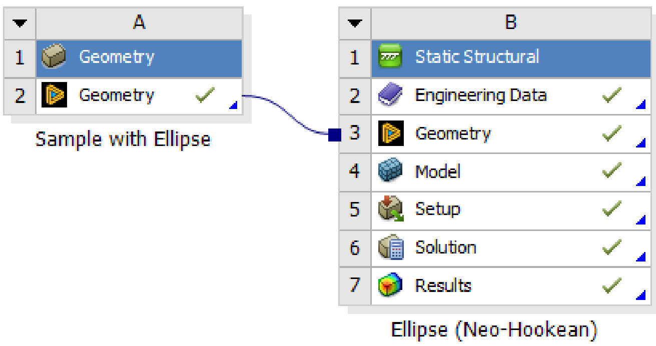


Figure 5: ANSYS Workbench. The sample geometry is imported from a Geometry Module to a Static Structural module which includes the material data, meshing tools, and solver.

Make sure to properly design the surfaces where the grippers of the tensile machine hold the sample. Model your part in a suitable orientation in the coordinate system. Our chosen geometry can be seen in figure 6.

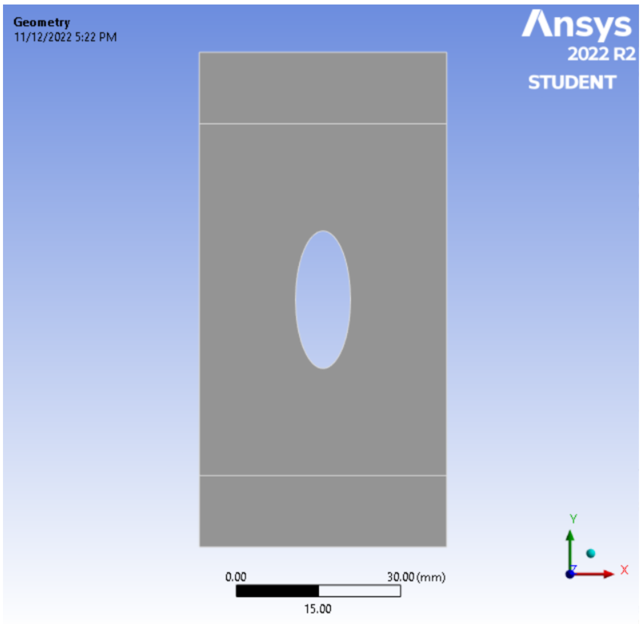


Figure 6: Sample Geometry. The sample geometry chosen is a rectangular shape with a vertical elliptical void in its middle.

2.2 Material Definition & Assignment

The material properties for silicone rubber were retrieved from [3]. The density and isotropic elasticity parameters were inputted to an existing elastomer sample in the ANSYS material library. The elastomer sample we chose is the one modeled by the Neo-Hookean approach. The Neo-Hookean model is the simplest hyperelasticity model, and explanation of this choice follows. This method is not very accurate in predicting large strain deformations, yet it is still used for two main reasons. First, it only requires two input parameters. These two parameters can even be reduced to one if the material is nearly incompressible. The Neo-Hookean model would then only need the initial shear modulus to be defined. This also implies few experimental tests are required to define the model. Second, this model is compatible in the sense that other types of deformations can be predicted from the one type of deformation first used [4]. This model also suits the range of elongation used in our tests. It is accurate for strains ranging from $0-100\%$. In our case, a strain of about 15% is specified.

2.2.1 Comparison between Models

As mentioned earlier, many hyperelasticity models exist. In this part, we compare between three common models: Neo-Hookean, Mooney-Rivlin, and Ogden [5].

Neo-Hookean:

- One experiment is required to obtain the model parameters.
- Accurately simulates the following strain range: $0-100\%$
- Almost always stable

Mooney-Rivlin:

- At least two experiments are required to obtain the model parameters.
- Accurately simulates the following strain range: $0-150, 200\%$

- Unstable when subjected to biaxial loads

Ogden:

- Three or more experiments are required to obtain the model parameters.
- Accurately simulates the following strain range: $0 - Failure$
- Stability depends on the chosen parameters

Several other limitations and specific restrictions to these and other methods exist, but we just summarize a few relevant ones to get started with a hyperelasticity simulation in FEA.

The finalized properties of the elastomer using the Neo-Hookean model can be seen in figure 7.

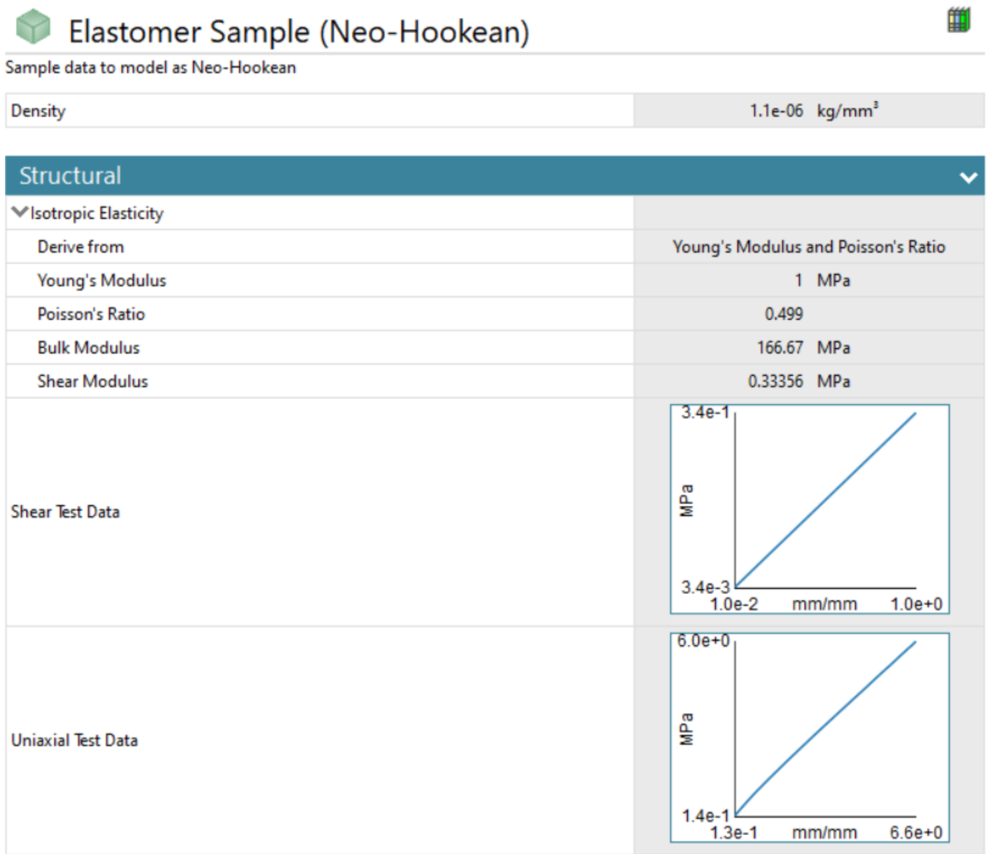


Figure 7: Material Definition. The density and isotropic elasticity parameters are inputted. The available Neo-Hookean test data from ANSYS are used.

2.3 Meshing

The distribution of the nodes and elements across the geometry is very important to avoid stress singularities. That is why we refine our mesh using the following techniques.

1. An inflation is applied on the ellipse edge.
2. The element size of the middle face is decreased.
3. The element size of the ellipse side face is decreased.
4. The meshing method is specified as Patch Conforming with Tetrahedrons.

5. The element size of the gripper attachment faces is decreased.
6. The element size across the ellipse edge is decreased.
7. The element size along the vertical thickness face is decreased since it turned out to be the location of the maximum stress.

The final mesh can be seen in figure 8.

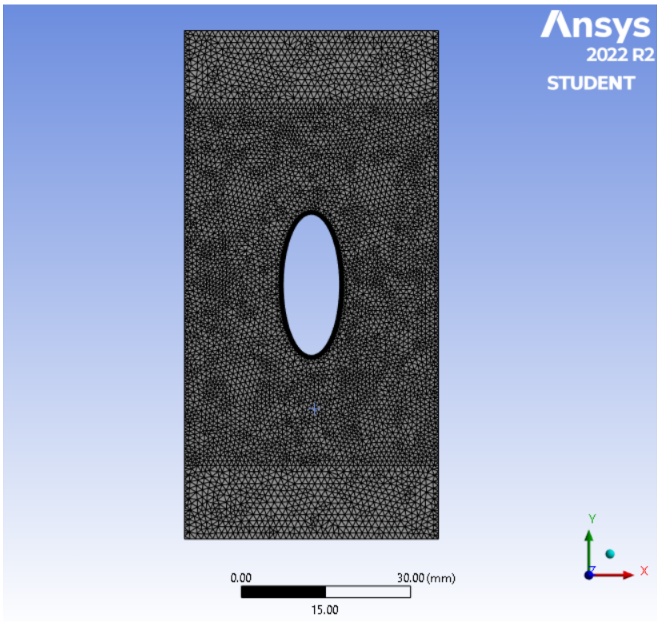


Figure 8: Meshed Geometry. Several mesh refinements were used to avoid coarse meshing.

2.4 Boundary Conditions

The lower two faces were fixed. The upper two faces were allowed to move a distance of 10 mm along the y-direction simulating the tensile testing machine conditions. The imposed boundary conditions are available in figure 9.

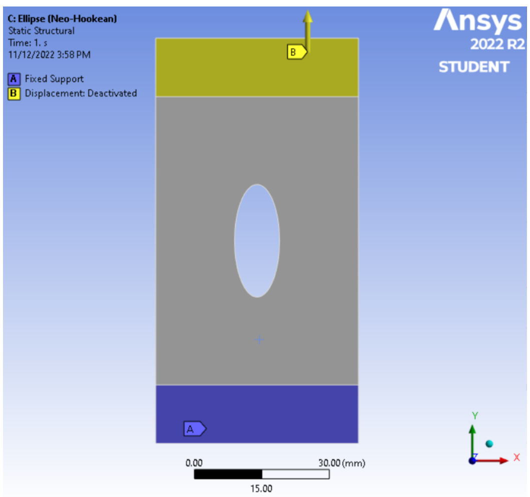
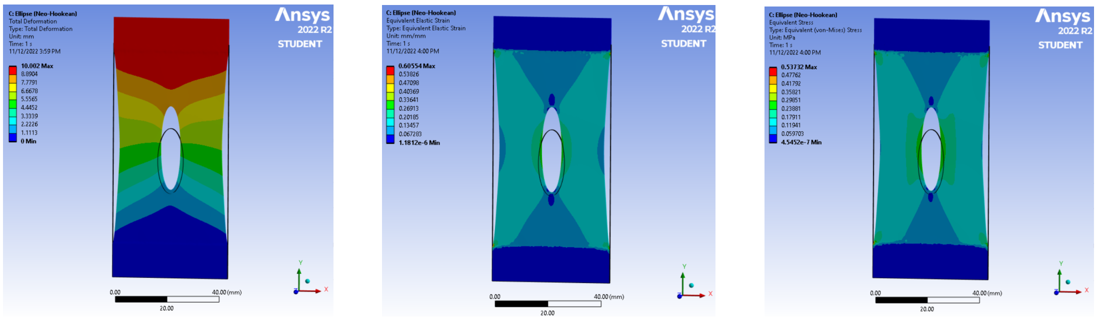


Figure 9: Boundary Conditions. A fixed support and displacement constraint was imposed to model the tensile test.

2.5 Solutions

Figure 10a, 10b, 10c show the deformation, strain, and stress results respectively.



(a) Deformation (mm) (b) Strain (mm/mm) (c) Stress (MPa)

Figure 10: ANSYS Results. We solve for the deformation, strain, and stress distribution across the geometry.

3 Analysis

Deformation, strain, and stress data from the tensile testing machine are extracted. These quantities are as well exported from ANSYS. We plot the Load-Deformation curve in figure 11 and the Stress-Strain curve in figure 12.

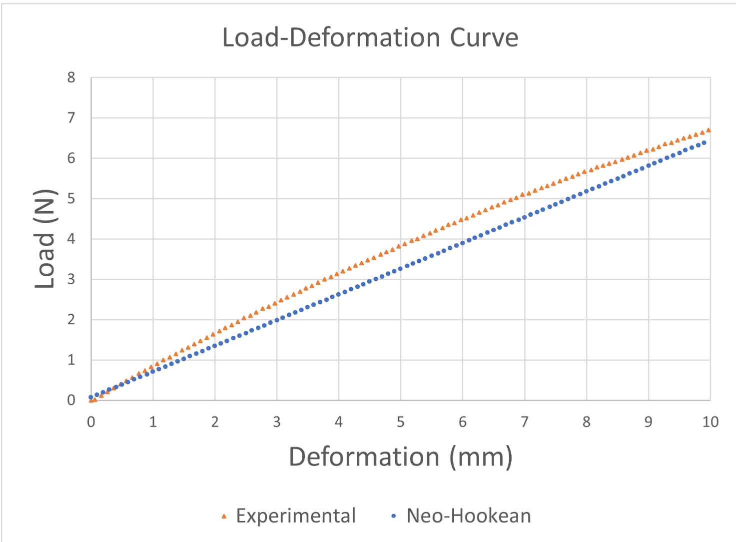


Figure 11: Load-Deformation Curve. Load (N) is plotted on the vertical axis. Deformation (mm) is plotted on the horizontal axis. The experimental data is plotted in orange. The Neo-Hookean data is plotted in blue.

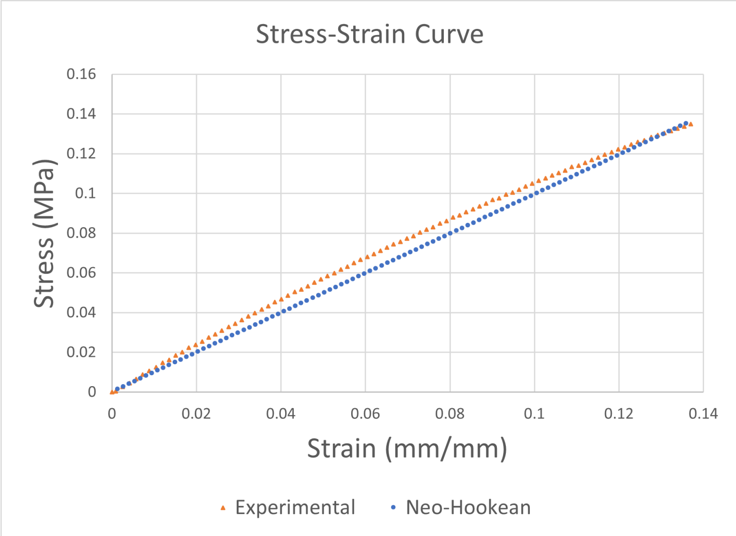


Figure 12: Stress-Strain Curve. Stress (MPa) is plotted on the vertical axis. Strain (mm/mm) is plotted on the horizontal axis. The experimental data is plotted in orange. The Neo-Hookean data is plotted in blue.

Over the chosen range of strain, the experimental and model data follow a similar trend with a slight deviation. We expect this deviation to be much larger as the strain values increase in another possible setup. This is because of the inability of the Neo-Hookean model to simulate hyperelasticity for very high strains.

4 Conclusion

In conclusion, we have modeled the silicone rubber used as a Neo-Hookean hyperelastic material. The experimental and FEA data agree over the range of strain imposed. The model should be chosen carefully to avoid erroneous simulation of the data. As future steps, we may as well compare the experimental data we measure in the laboratory to other hyperelasticity models from ANSYS and check how accurately they reproduce the hyperelasticity of the silicone rubber we used. We can as well elongate the sample two or three times its length and show how some models fail in simulating its behavior. Finally, we will compare the results from DIC (Digital Image Correlation) with those we obtain experimentally and from FEA.

5 References

[1] Sk Haque et al. "Application and Suitability of Polymeric Materials as Insulators in Electrical Equipment". In: *Energies* 14 (May 2021), p. 2758. DOI: `10.3390/en14102758`.

[2] Zhao Shuo et al. "Impacts of additive uniaxial strain on hole mobility in bulk Si and strained-Si p-MOSFETs". In: *Journal of Semiconductors* 30 (Oct. 2009), p. 104001. DOI: `10.1088/1674-4926/30/10/104001`.

[3] From EDAX et al. *Properties: Silicone rubber*. Nov. 2022. URL: `https://www.azom.com/properties.aspx?ArticleID=920`.

[4] WELSIM - Engineering Simulation Software. *Neo-Hookean hyperelastic model for Nonlinear Finite Element Analysis*. Jan. 2020. URL: `https://getwelsim.medium.com/neo-hookean-hyperelastic-model-for-nonlinear-finite-element-analysis-16ac996aa507`.

[5] Ajay Harish. *How to choose an FEA hyperelastic material?* June 2021. URL: `https://www.simscale.com/blog/how-to-choose-hyperelastic-material/`.