A Mechanism for the Validation of Hyperelastic Materials in ANSYS

Megan Lobdell, Brian Croop

DatapointLabs Technical Center for Materials,
Ithaca, USA

Summary

Hyperelastic material models are complex in nature requiring stress-strain properties in uniaxial, biaxial and shear modes. The data need to be self-consistent in order to fit the commonly used material models. Choosing models and fitting this data to these equations adds additional uncertainty to the process. We present a validation mechanism where, using a standardized experiment one can compare results from a simulation and a physical test to obtain a quantified measure of simulation quality. Validated models can be used with greater confidence in the design of real-life components.

Keywords

Hyperelastic, validation, Matereality, ANSYS

1. Introduction

Using simulation to examine and optimize a product is becoming increasingly common. In such a simulation-driven product development (SDPD) environment, it is vital to know how accurately the simulation can predict the real-life applications. Many factors can play a role in simulation accuracy including new material or manufacturing process, quality and appropriateness of material data, parameter conversion, choice of elements, solver accuracy, to name a few. Sometimes the simulation can be compared to a prototype test for the purpose of validation. However this is late in the SDPD process where considerable cost has already been incurred. Furthermore, discerning causes for the differences observed is difficult or sometimes impossible. Validating simulation accuracy prior to commencing design of actual parts and assemblies is cheaper in the long run and can bring confidence and valuable insight to SDPD.

In previous work, we showed the utility of a mid-stage validation to confirm simulation quality for linear analysis of metals, simulations of ductile plastics, and for additively manufactured (3D printed) metals[1,2]. Creating a mid-stage validation for hyperelastic material models is particularly useful. Unlike the elastic-plastic models from our previous papers on validation where the plastic curve is tabulated data from a tensile curve, many hyperelastic models are governed by an equation where the materials' modes of deformation are characterized through its coefficients. In order to simultaneously describe uniaxial, shear, and biaxial deformation modes for the model, the goodness of fit often suffers. In addition, when fitting a material mode there may be variability in the coefficients dependent on the seed values. Comparison of which of two models better represents reality for the material behavior being exhibited can also be done quickly with validation.

The goal of this paper is to create a process using standardized geometry and boundary conditions to test mixed mode deformation, especially for hyperelastics. Our process can be broken into four steps. The material is characterized and hyperelastic models are fitted in Matereality. Validation experiments are designed based on simple compression tests and ones that are modified to also produce shear and uniaxial behavior in the compression button. For these compression tests, an ANSYS simulation is created. This results in three validations that can be extracted from the data: one closed loop validation from the original compression test for the material model, and two open loop validations from when the boundary conditions for the compression test are varied.

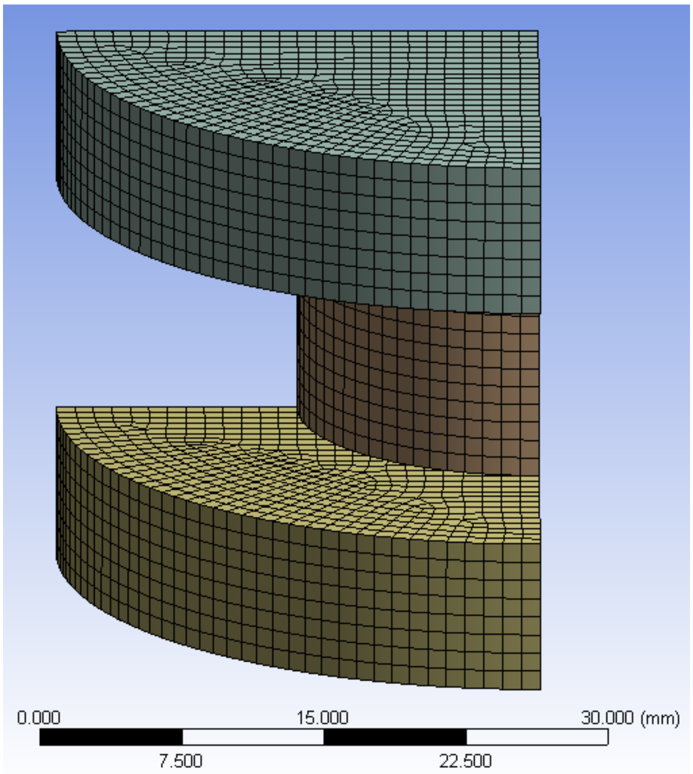

Figure 1 ANSYS Workbench quarter model of compression test.

2. Methods

The methods carried out to perform this validation fall into four sections: material testing, model fitting, validation tests and simulation.

2.1 Material Testing

Specimens were taken from 40A durometer high-temperature silicone rubber sheets obtained from McMaster Carr. To determine stress-strain data for the material model calibration, ASTM D412 Type C specimens were stamped for the tensile tests and rectangular planar tension specimens were cut from 1/8" sheets for the shear experiments. For the uniaxial compression test, ASTM D 575-91(2012) compression buttons were cut from 1/2" sheets. These were then tested on an Instron Universal Testing Machine (UTM) at a strain rate of 20/min. The test procedures used are described in the book by Lobo and Croop [3]. The specimens were not tested to account for the Mullins effect; there was no precycling of the specimens.

The uniaxial compression data was used to compute a biaxial tension curve using the following equations:

$$\varepsilon_b = \sqrt{\frac{1}{-\varepsilon_c + 1}} - 1 \qquad (1)$$

$$\sigma_b = \frac{\sigma_c}{(\varepsilon_c + 1)^3} \qquad (2)$$

the addition of biaxial data provides better stability to the model.

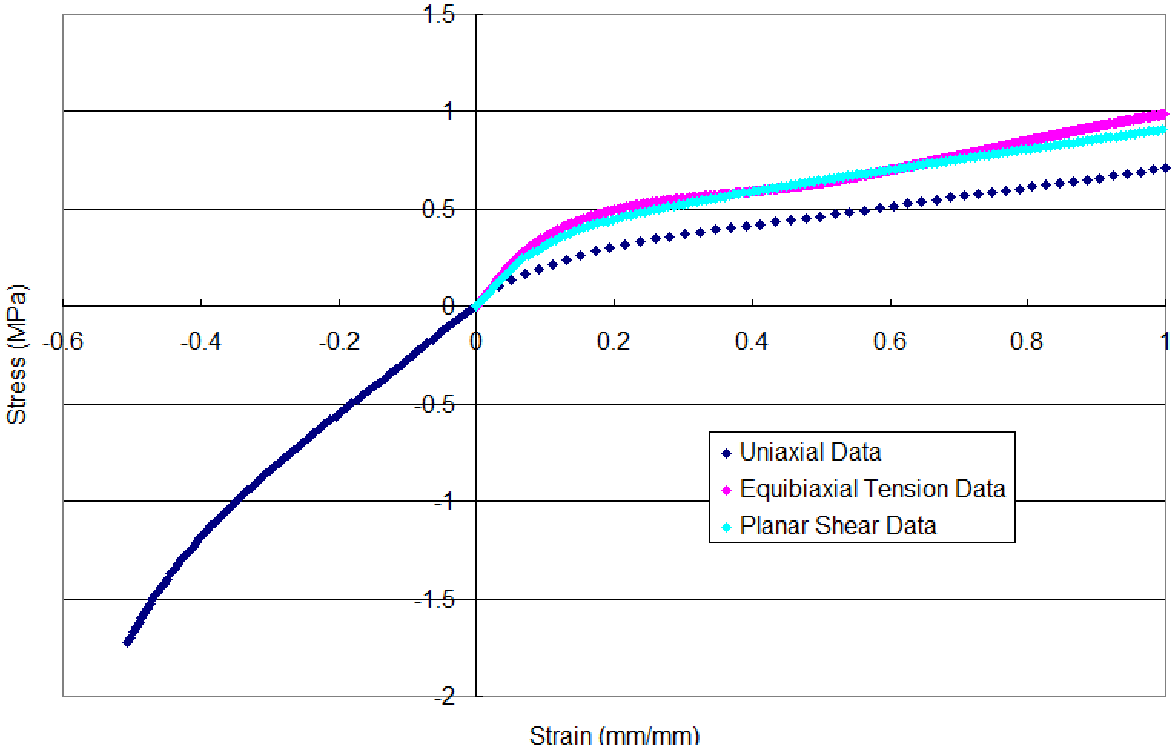

Figure 2 Stress-strain curves for Uniaxial, Equibiaxial, and Planar Shear data

Volumetric compression behavior was measured using a Gnomix pvt apparatus as described in [3].

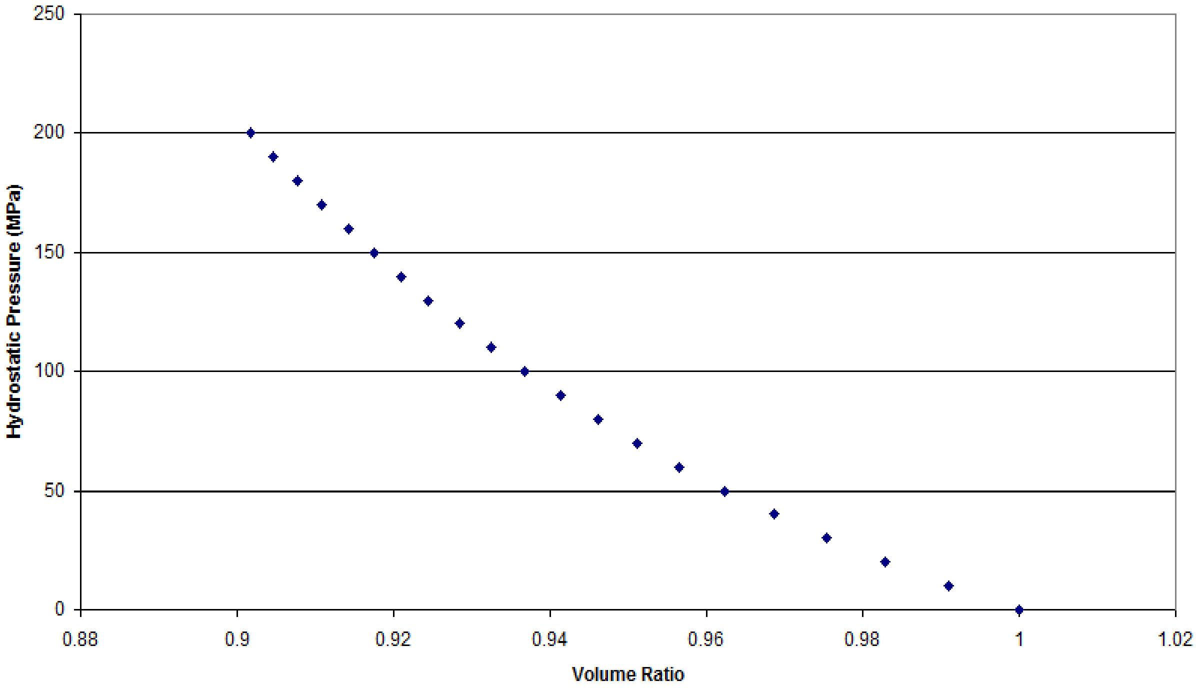

Figure 3 Stress v. Volume Ratio curve for the rubber

2.2 *Model Fitting*

The Matereality CAE Modeler software was used to visualize the hyperelastic data and fit the data to the ANSYS hyperelastic material models. Two commonly used hyperelastic models were selected: 9 parameter Mooney-Rivlin and the Ogden 3rd Order. The Mooney-Rivlin equation (3) from the ANSYS Help Manual [4] is described below, where the C parameters define the model coefficients and the I terms represent the stress invariants. The D term refers to the volumetric behavior:

$$W = c_{10}(\bar{I}_1 - 3) + c_{01}(\bar{I}_1 - 3) + c_{20}(\bar{I}_1 - 3)^2 + c_{11}(\bar{I}_1 - 3)(\bar{I}_2 - 3) + c_{02}(\bar{I}_2 - 3)^2 + c_{30}(\bar{I}_2 - 3)^3 + c_{21}(\bar{I}_1 - 3)(\bar{I}_2 - 3) + c_{12}(\bar{I}_1 - 3)(\bar{I}_2 - 3)^2 + c_{03}(\bar{I}_2 - 3)^3 + \frac{1}{d}(J - 1)^2 \; . \qquad (3)$$

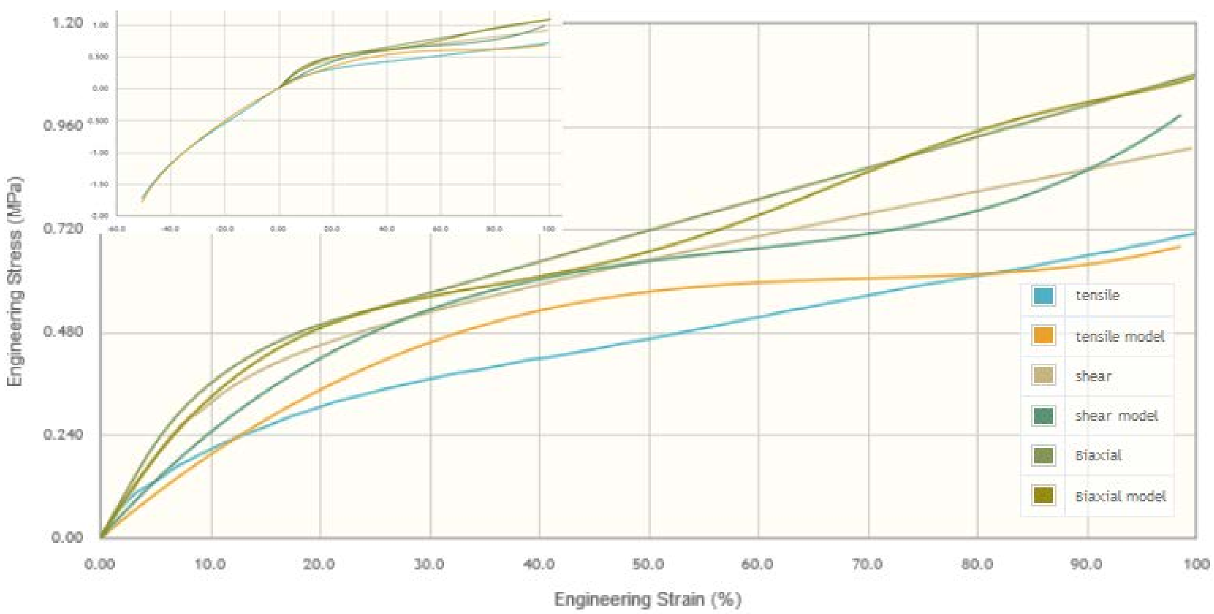

Figure 4: Mooney-Rivlin 9 parameter model plot of both data and model

In the ANSYS material model, the C coefficients are derived from fitting the equation to the tensile, planar, and biaxial data. The additional D coefficient comes from from fitting the stress v.volume ratio data. For comparison and checking, the data were also fit to the same Mooney-Rivlin models in ANSYS (below). These models were seeded differently without any rigor in methodology resulting in different but reasonably comparable fits.

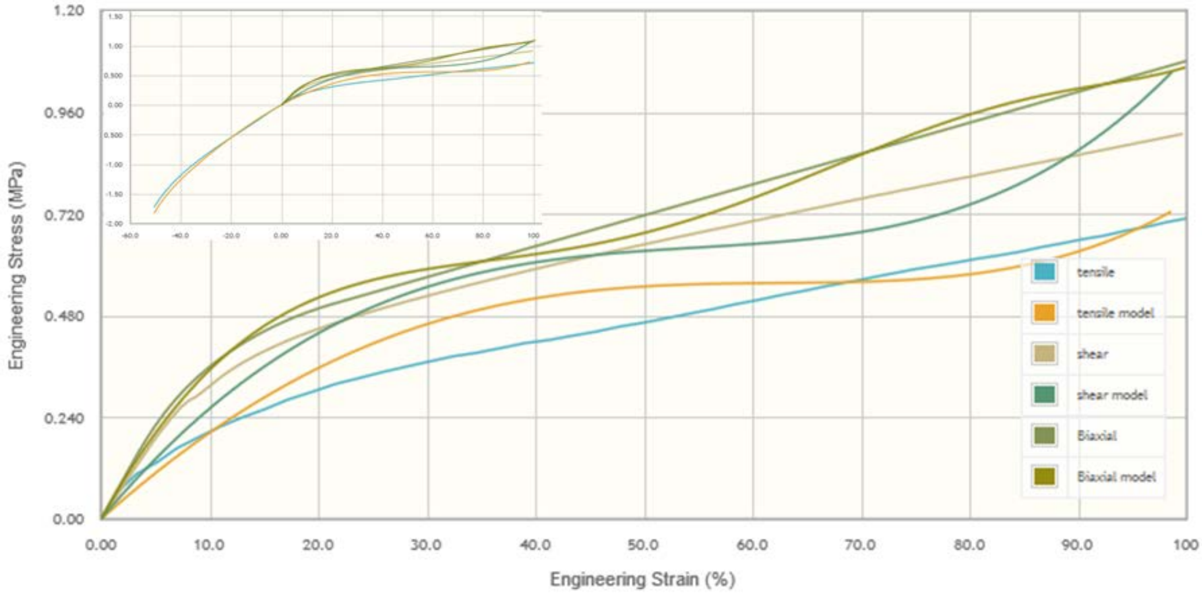

Figure 5 Mooney-Rivlin 9 Parameter model plot of both data and model (ANSYS fit)

Table 1: Mooney-Rivlin and Ogden coefficients fit using ANSYS and Matereality

Mooney-Rivlin	ANSYS fit	Matereality fit		Ogden 3rd Order		
C10	3.47E-01	3.64E-01	MPa	**MU1**	3.715023	MPa
C01	3.52E-02	-5.81E-03	MPa	**MU2**	-1.58648	MPa
C20	-1.36E-01	-1.19E-01	MPa	**MU3**	-1.58647	MPa
C11	2.88E-02	4.54E-02	MPa	**A1**	1.141617	
C02	-7.90E-03	-1.11E-02	MPa	**A2**	0.994652	
C30	2.33E-02	1.38E-02	MPa	**A3**	0.99404	
C21	1.44E-02	1.35E-02	MPa	**D1**	0.001763	1/MPa
C12	-1.15E-02	-9.47E-03	MPa	**D2**	3.1128e-5	1/MPa
C03	1.91E-03	1.56E-03	MPa	**D3**	-1.5446e-6	1/MPa
D1	1.34E-03	1.34E-03	1/MPa			

From the ANSYS Help Manual, described by Ogden equation [4], where λ is the stretch ratio and α are the coefficients; the D terms describe the volmetric behavior. The deviatoric part of the model was fit using Matereality while the volumetric terms were fit in ANSYS.

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\overline{\lambda_1}^{\alpha_i} + \overline{\lambda_2}^{\alpha_i} + \overline{\lambda_3}^{\alpha_i} - 3\right) + \sum_{k=1}^{N} \frac{1}{d_k}(J-1)^{2k}. \qquad (4)$$

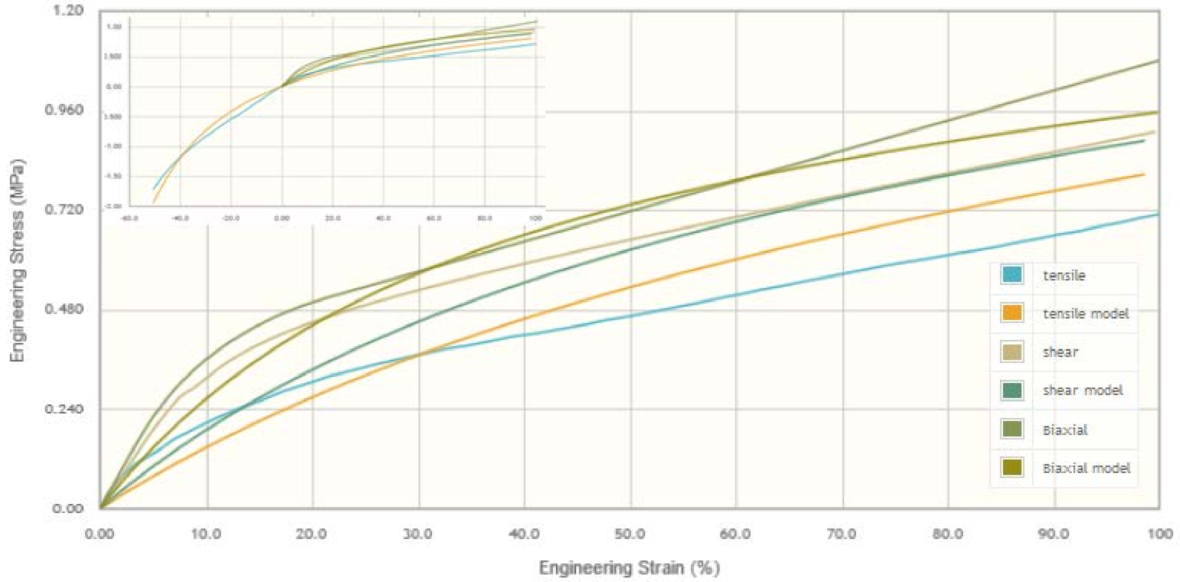

Figure 6 Ogden 3rd Order model plot of both data and model

2.3 Validation Tests

Validation was performed against three compressive experiments: the original uniaxial compressive experiment where both compression platens were lubricated, one fixing both top and bottom compression platens with sand paper to create a no-slip condition and a third case fixing only one side while allowing the other to slide freely against a lubricated surface. These tests were performed at 260 mm/min. Force v. displacement data were recorded to compare to the simulation.

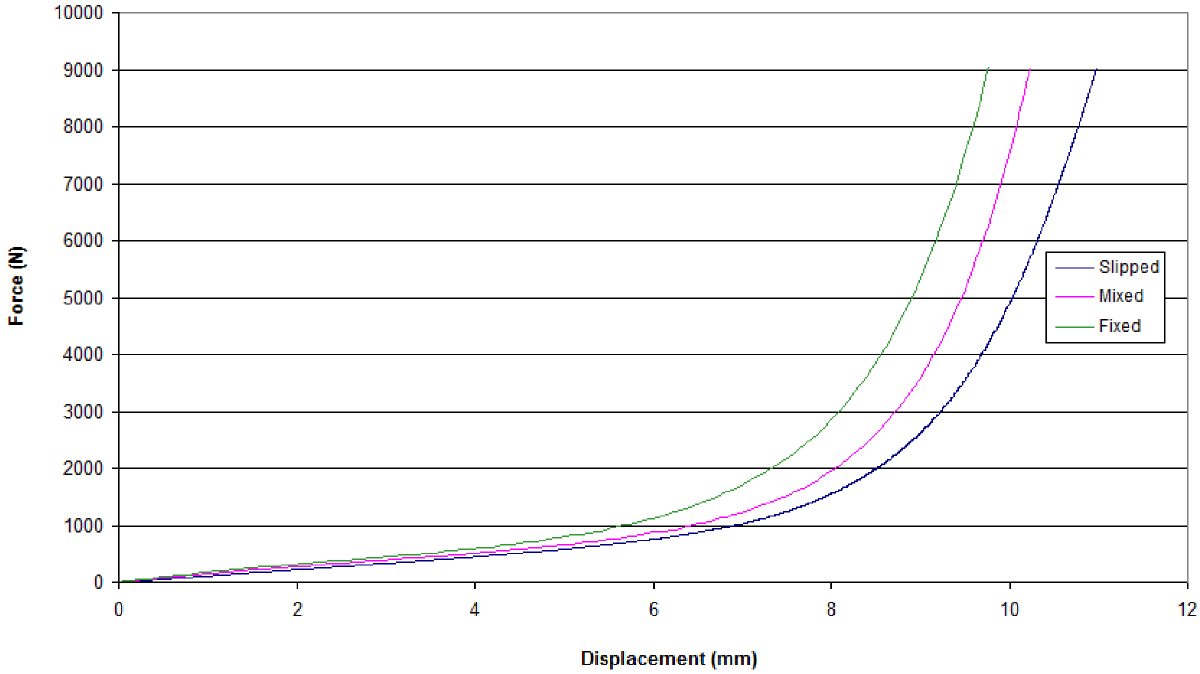

Figure 7 Force v. displacement curves for the compression tests with fixed, mixed, and slip boundary conditions

2.4 Simulation

Using ANSYS Workbench static structural models, three scenarios were created to replicate the different boundary conditions. A quarter model was used to reduce calculating time. A swept hexahedral mesh was used and mesh size was refined to 1 mm. The platens used to deform the specimen were structural steel. In only one case where the nonlinear adaptive region is used, both the platens and the compression button are meshed differently. Adaptive meshing 3D objects uses the SOLID285 element type with a tetrahedral mesh [5].

Force data was taken from the reaction force while the displacement of the moving platen was measured. Below is a table describing the contacts and boundary conditions. In the no-slip contact cases (fixed and mixed), a rough contact is used when the sides of the cylindrical compression specimen come into contact with the platen at large strains.

Table 2: Model Details

Quarter model, symmetry on the x and y faces		
Fixed bottom platen		
Displacement to 6.35mm on the top platen		
Bonded contacts accompany a rough contact for the circumfrential side		
Contact	Location	Type
Slipping	Top	Frictionless
	Bottom	Frictionless
Mixed	Top	Frictionless
	Bottom	Bonded
Fixed	Top	Bonded
	Bottom	Bonded

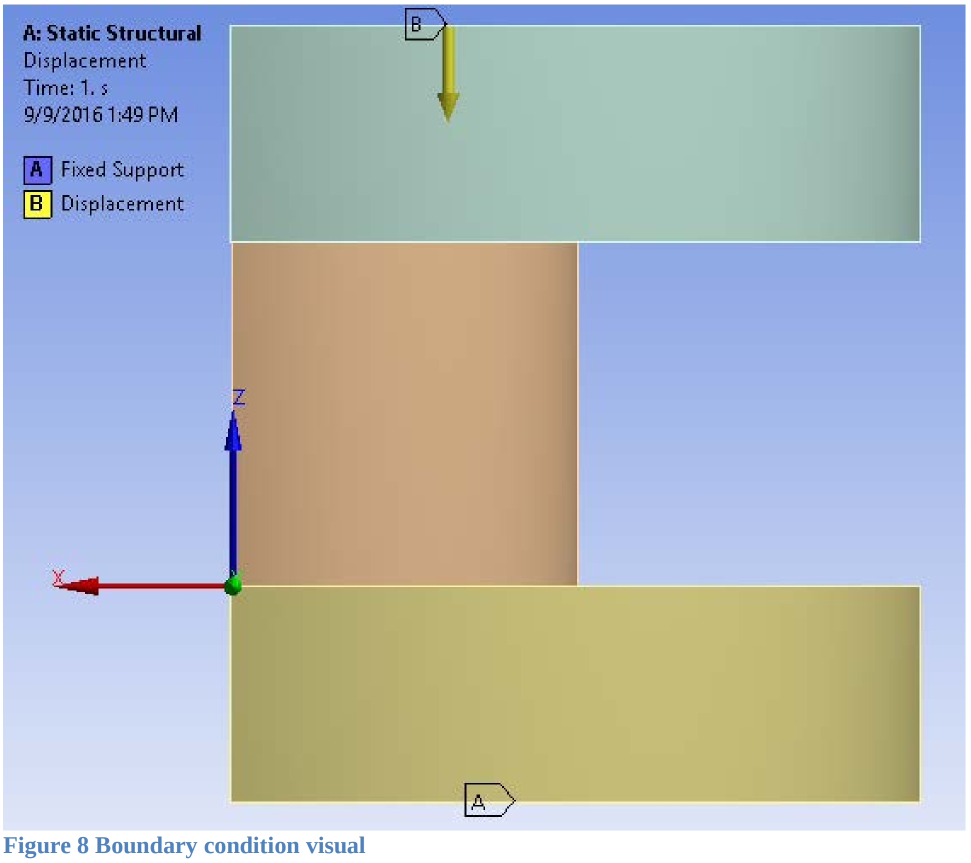

Figure 8 Boundary condition visual

3. Results

The simulations were conducted to about 6.35 mm corresponding to uniaxial compressive strains of approximately 40% in the base case “slipping“ experiment. For each boundary condition the force v. displacement was recorded and the experiment data was compared to the data taken for the simulation. The force v. displacement data was not normalized to take into account the differences between the simulation button dimensions and actual dimensions of the experimental buttons. Table 3 summarizes the force deviation of each material model from its respective experimental curve at a displacement of 5 mm for each of the simulated cases.

Table 3: Deviation from experiment at 5mm displacement

Boundary Condition	Material Model	Percent Error (%)
Slipping	M-R Matereality	+8.8
Fixed	M-R Matereality	+6.1
Mixed	M-R Matereality	-10
Mixed	M-R ANSYS	-8.4
Mixed	Ogden	-8.6

The validation for the slip condition results in the least deviation at around 6%, as shown in Figure 9 below. As expected, there is little deviation thoughout, considering that it is a closed loop validation, in which the data used to create the material model is used in a simulation with the same boundary conditions as the orginal test. Significant element distortion stopped the simulation just below 6 mm of displacement, prior to reaching target displacement.

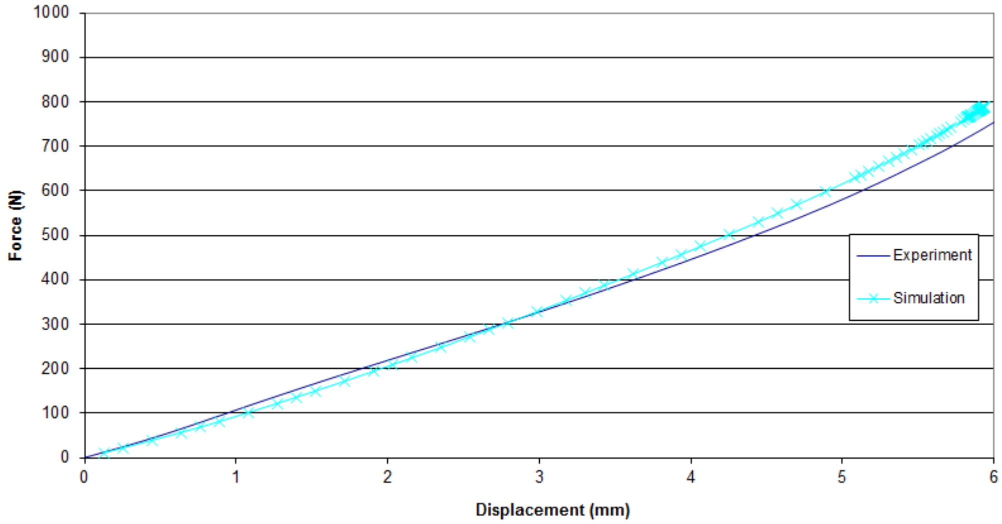

Figure 9 Validation for the slip boundary condition

The validation for the fixed condition faired worse than the slip, deviating 22% away from the experimental curves at the end of the simulation. Again, significant element distortion stopped the simulation prior to reaching target displacement. The increased skewness of the elements as the material deformed could have been a factor behind the greater deviation observed beyond 5 mm.

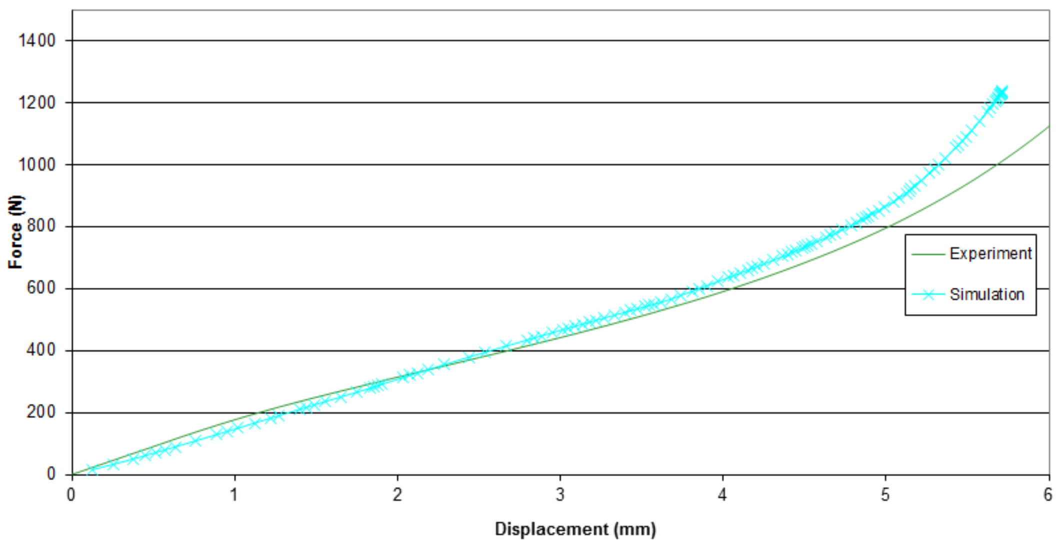

Figure 10 Validation for the fixed boundary condition

There are also issues with contact, where the penetration of the rubber elements into the platen surface is greater than expected when the rough contacts were used. This mesh distortion is apparent after the first few milimeters of deformation in the model providing a possible additional reason for the increased deviation at the end of the simulation.

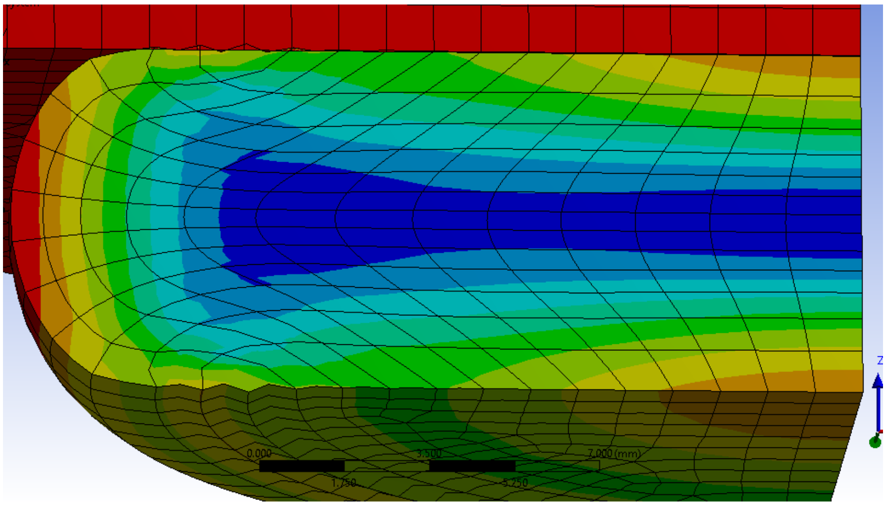

Figure 11 True-scale showing overlap in the button to upper platen and the distortion on button

For the mixed condition validation, the simulation deviates 11% from the experimental data by the final step. The bonded side experienced similar issues with mesh penetration as the fixed case above.

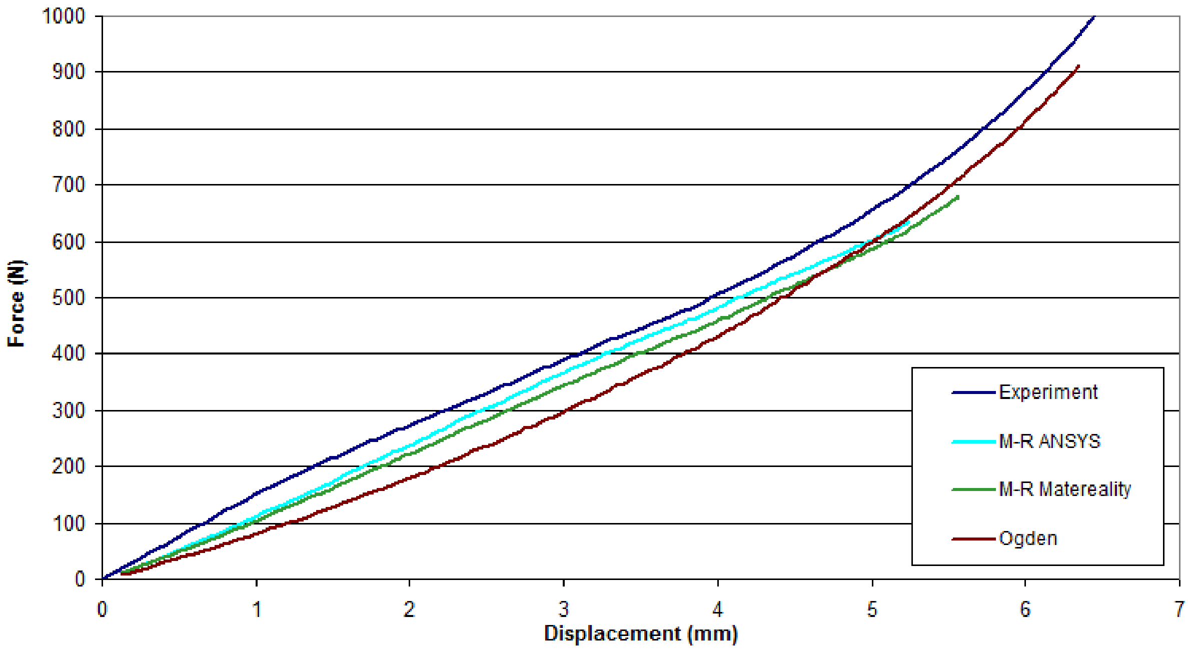

Figure 12 Validation for the mixed boundary condition also comparing several material models

The mixed condition was also used to test different material models and to attempt a nonlinear adaptive mesh region for the simulation. All previous simulations used a Mooney-Rivlin model fitted in Matereality (M-R Matereality). An additional simulation using a Mooney-Rivlin model fit derived using ANSYS (M-R ANSYS) was found to hold slightly closer to the experimental data. The Ogden model appeared to be off with a difference of 34% at 2mm displacement but was able to achieve the target displacement of 6.35 mm. The force deviation between simulation and test at 6.35 mm was 5%.

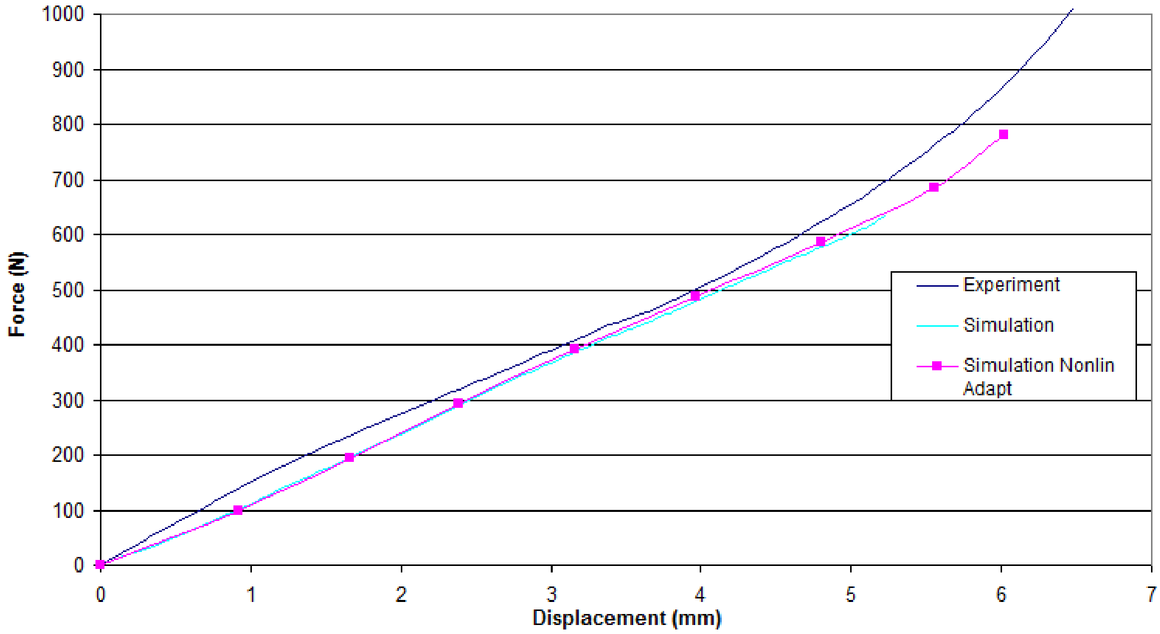

Figure 13 Comparing experiment force v. displacement to basic and adaptive mesh simulation

With the Ogden model as the notable exception, the simulation terminated prior to the target displacement as it was unable to resolve the force imbalance. Some of this is based on the skewness of the elements, and can be partially relieved by nonlinear adaptive meshing, imposing a criterion where adaptive meshing is dependent on element skewness. The simulation with the adaptive mesh tested with the ANSYS-derived Mooney-Rivlin (M-R ANSYS) material model displaced an additional 0.78mm, the final deviation for the adaptive meshed simulation from the experiment was 10%.

4. Conclusions

In our study, simulation of hyperelastic materials in ANSYS yields results of good accuracy up to strains of about 40%. While the closed-loop "slipping" validation is understandably accurate, both the fixed case and the mixed case perform quite well considering the complex contact conditions that manifest at large strains as the rubber folds out against the platen, mimicking situations that can occur often in real-life applications. The appearance of shear and uniaxial modes of deformation in the mixed case result in a modest loss in accuracy. Adaptive meshing appears to have a positive impact when simulating to large strains. The Ogden model seems to be more robust in the same capacity.

Different data fitting programs can yield some variability in the material parameters of hyperelastic models. While some difference was noted in data fits between ANSYS and Matereality, the impact on the simulation appears to be small.

Validation of simulation can quantify differences between the virtual world and reality and should ideally be performed each time a material is being tested for use in simulation. With validation, the data, model and the simulation can be checked using test cases that contain real-life behaviors giving added confidence to the analyst.

6. References

[1] Lobdell M., Croop B., Lobo H., "Finite Element Analysis of Additively Manufactured Products," ANSYS Conference & 33rd CADFEM Users' Meeting, 2015
[2] Wolfrom C., Lobdell M., Lobo H., "Using an Intermediate Validation Step to Increase CAE Confidence," Simulia Conference, 2016
[3] Lobo H, Croop. B, "Determination and Use of Material Properties for Finite Element Analysis", NAFEMS, Ch. 6, pp. 41 (2016)
[4] ANSYS 17.2 Help Manual. 2016
[5] "Workbench Update," Twin Cities ANSYS Users' Meeting. http://www.epsilonfea.com/wp-content/uploads/2015/05/ANSYS-16_v4.pdf, 2015