Using Abaqus to Model Permanent Set in Rubber: Assessment and Sensitivity Study

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Abstract: *Permanent set in applications using rubber is a common problem. Modeling of this phenomenon is available in the literature; however, the permanent set material models are not widely used because of their limitations and lack of validation. Recently, one permanent set model was implemented using Abaqus. To validate this model in actual applications, it was assessed through a series of button compression set tests at three temperatures. The sensitivity of the permanent set model to multiple hyperelastic models was studied. Some minor issues were observed in the application of the model with regard to field temperature, and a workaround solution was identified. The model was otherwise verified and validated through compression set test results. Differences between the permanent set definition commonly used in physical testing and the observed behavior in actual applications were also investigated, and implications are discussed.*

Keywords*: constitutive model, rubber, permanent set, physical test, verification, and validation*

1. Introduction

Typically, hyperelastic models are used for modeling rubber behaviors in tires, bushings, and seals, which yields reasonable predictions for some applications. When rubber is subjected to cyclic load or extended high temperature exposure, permanent set can be appreciable, and modeling of permanent set is of significant importance. The typical cyclic response of rubber material consists of three main components: hyperelastic response during loading, the Mullins effect or softening during unloading, and permanent deformation. Comprehensive modeling of rubber behavior would require accounting for all three phenomena. Hyperelastic models are abundant and widely used as an elementary representation of rubber behavior. Several rubber models also exist that account for rubber softening upon cyclic loading. Permanent set models for rubber materials are available in the literature, and one such model (Govindarajan et al., 2007) is implemented in Abaqus. The permanent set material models are not widely used in practice because of their limitations and lack of material data and validation. This work attempts to verify and validate the permanent set model compared to mechanical button compression test data.

2. Theoretical Background

The stress strain curve of a typical rubber under cyclic uniaxial loading conditions is similar to that shown in Figure 1. Two observations are readily apparent: 1) loading and unloading curves do not follow the same path (unloading curve indicates softening behavior) and 2) when stress is reduced to zero, the strain is not zero. The first phenomenon is related to the so-called Mullins effect, or rubber softening under cyclic loading conditions. The second phenomenon is related to permanent set. Many models are available to represent the hyperelastic behavior of rubber (Simulia.com, 2016).

One model that describes the Mullins effect and is implemented in Abaqus is by Ogden and Roxburgh (1999). In this model, the damage in a rubber is described by the following equation. The evolution of the scalar damage variable η is written as

$$\eta = 1 - \frac{1}{r} erf\left(\frac{\overline{W}^{\max} - \overline{W}^{primary}}{m + \beta \overline{W}^{\max}}\right)$$

In this equation, W^{primary} is the deviatoric part of strain energy in the primary loading path; $W^{\max}$ is the

maximum value of W^{primary} at the material point; *r*, *m*, and β are material parameters; and erf () is the

error function.

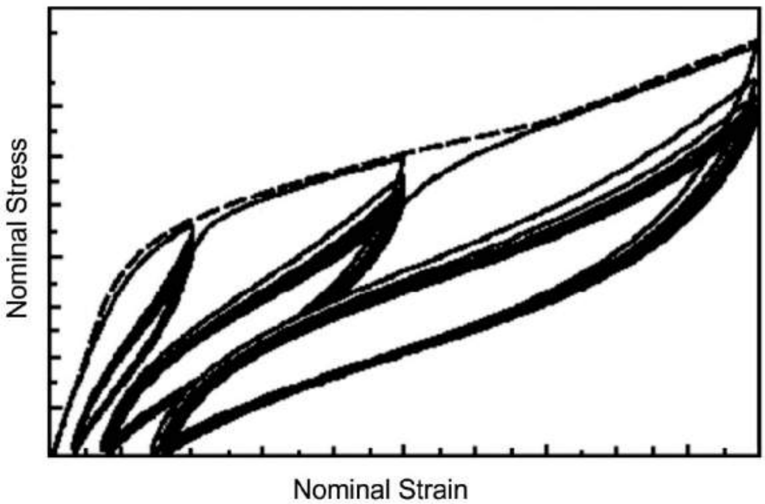

Figure 1: Representative cyclic stress strain curve.

The basic idea of the permanent set model by Govindarajan et al. (2007) can be summarized as decomposing the deformation gradient multiplicatively as follows:

$$F = F^{e} \cdot F^{p}$$

It is assumed that F^e and the corresponding stress will follow any appropriate hyperelastic material model that can account for the Mullins effect, and F^p and the corresponding stress will follow isotropic hardening Von Mises plasticity. In Abaqus, a special plug-in is needed to determine parameters in the model from physical test data.

It should be mentioned that the models considered for hyperelastic behavior, Mullins effect, and permanent set do not account for time and rate, viscoelasticity, or hysteresis effects.

3. Button Compression Test

A quasi-static compression test was performed on an ASTM D395 (2016) Type 1 button (Figure 2).

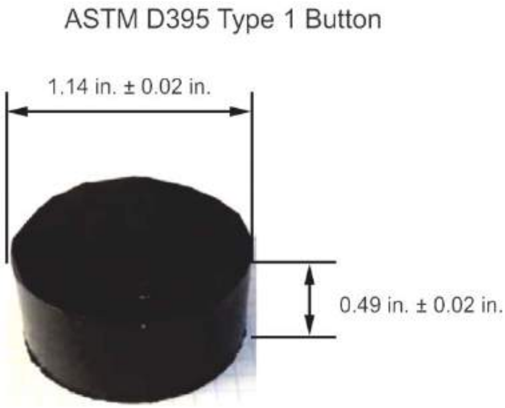

Figure 2: Button test sample per ASTM D395 (2016).

3.1 Test Procedure

Strain controlled compression tests of rubber cyclic stress strain behavior were performed per the following requirements:

- Quasi-static strain controlled compression tests were performed at 73, 115, and 400°F (test performed in temperature chamber); test machine loading speed was 0.5 in./min.
- Maximum compressive strain levels were 10, 25, and 50% for different cycles.
- During each cyclic test, unloading was stopped when the force on the test sample reached zero and reloading began.
- Duplicate tests were conducted for each temperature condition.
- The following test procedure was used on each sample, with the faces of the button lubricated to reduce interfacial friction:
    a. Perform 10 cycles to 10% strain
    b. Continue from Step a), perform 10 cycles to 25% strain
    c. Continue from Step b), perform 10 cycles to 50% strain

Figure 3 shows a typical test measurement.

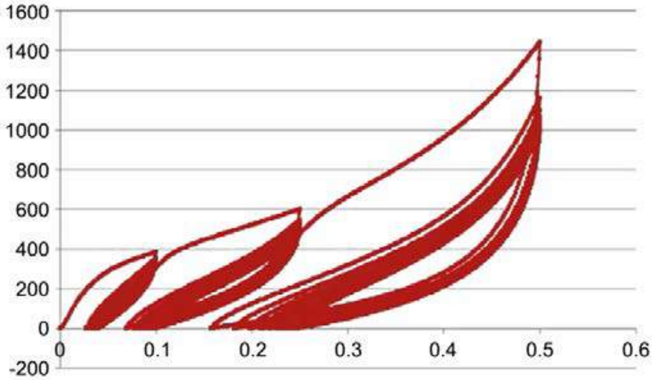

Figure 3: Cyclic test on Compound X at 73°F

Table 1 summarizes the test button properties.

Table 1. Test button properties.

Polymer	Compound X
Shore hardness (durometer)	92
Final anvil height (in.)	0.408
Anvil height (in.)	0.503
Permanent set (%)	-18.9
Diameter (in.)	1.094
Area (in.^{2})	0.93999
Temperature (°F)	73
Loading speed (in./min)	0.5

3.2 Test Results

Compound X was tested twice at each temperature. The results showed good repeatability for all temperatures tested (73, 115, and 400°F) and different Shore hardnesses (92 and 80 durometers), with the 400°F test data having a larger spread. Figure 4 shows the test results at 73°F.

As expected, the 92-durometer Compound X was much stiffer than the 80-durometer Compound X. The difference is significant at high compression strain (e.g., 50% compression strain) (Figure 4). The test data also showed that the higher the temperature, the softer the compound, which was expected (Figure 5).

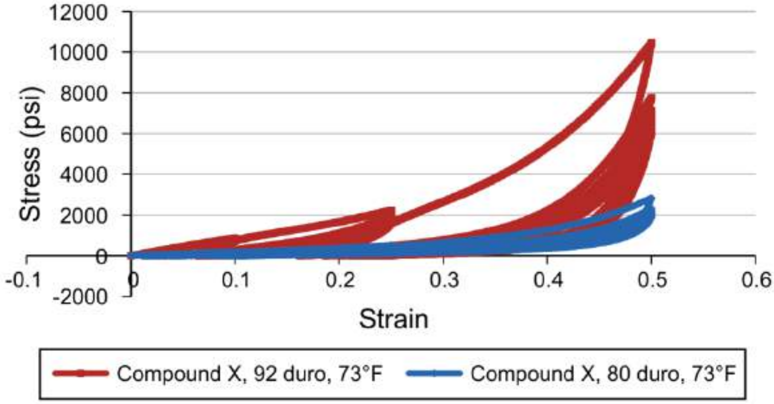

Figure 4: Comparison of 92- and 80-durometer Compound X cyclic behavior.

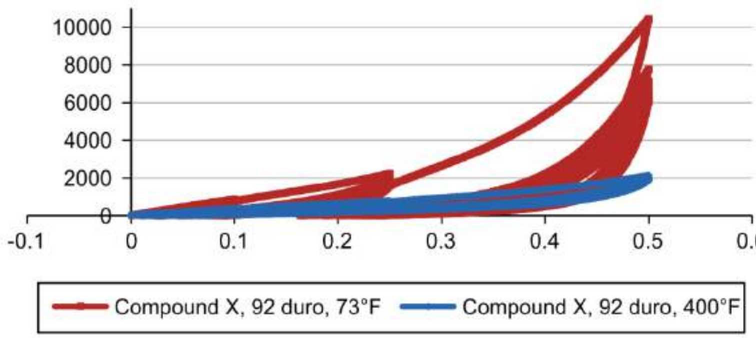

Figure 5: Comparison of 92-durometer Compound X cyclic behavior at 73 and 400°F.

4. Determination of Model Parameters Through Test Data

Because the reference configuration is changed to account for permanent deformation, determination of permanent set model parameters through test data is a complex process. Abaqus has a plug-in to process the test data to determine the model parameters. The plug-in generates proper processed data for the Govindarajan et al. (2007) model. However, the plug-in was not used for model parameter determinations in this study because of two issues associated with using the plug-in in applications: 1) when temperature was involved, the Mullins effect was neglected and 2) the permanent set parameter could not be determined when negative signs were assigned to compressive stress or strain. The following procedure allowed working around these issues to obtain the model parameters.

1) The test data should be in a two-column format (engineering strain, engineering stress) and saved as "rubber.csv" for the Abaqus plug-in to process. Assuming the laboratory data have no signs, save the two-column data (-strain, - stress) as "rubber-compressive.csv."
2) Launch CAE and open the Material module. From there, go to "Plug-ins," "Properties," "Create Rubber-like Material" (Figure 6):
    a) Select "rubber.csv" and click "Continue." Figure 7 shows the screen that will appear.

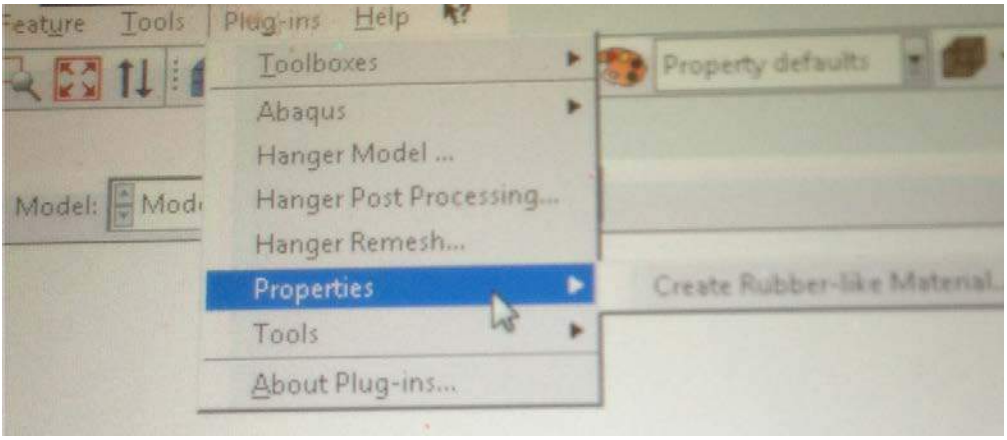

Figure 6: Data processing illustration.

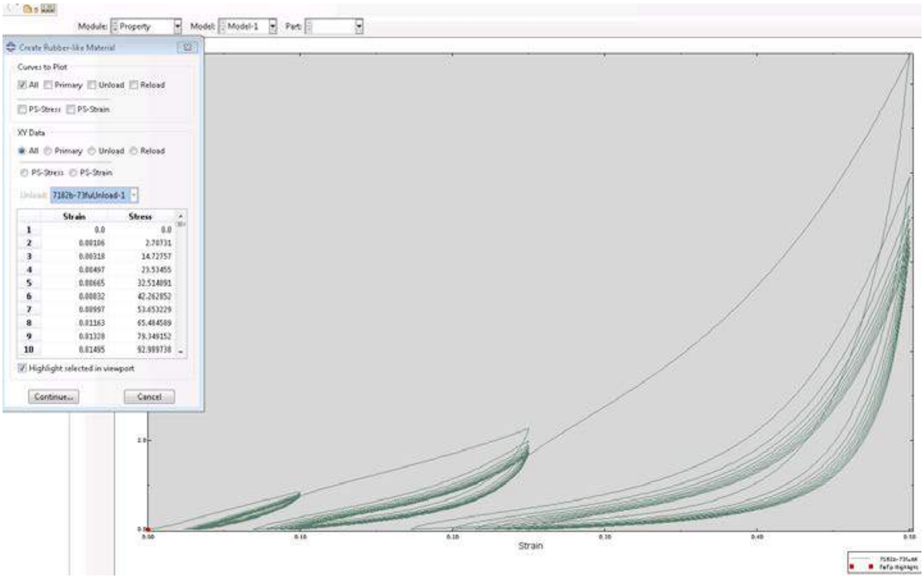

Figure 7: Data loaded into the plug-in for permanent set determination.

b) To evaluate data, uncheck “All” and check “Primary,” “Unload,” and “Reload.” The curves for model parameter determination should appear (Figure 8).

c) Check “PS-Stress” and “PS-Strain.” The corresponding curves should appear (Figure 9).

d) Click “Continue.” An error message should show; correct the error by entering a small number for stress at zero strain (Figure 10).

e) Click “Continue.” Uncheck “Reload.” Type “test-ps” in the “Material name” box and click “Create Material.” A material with the name test-ps will be created in the Material module. Click “Cancel” (Figure 11).

f) Repeat Steps 2a through 2e for material data “rubber-compressive.cvs. However, these data are in the third quadrant. Create a new material test and uncheck “Use permanent set” (Figures 12 and 13).

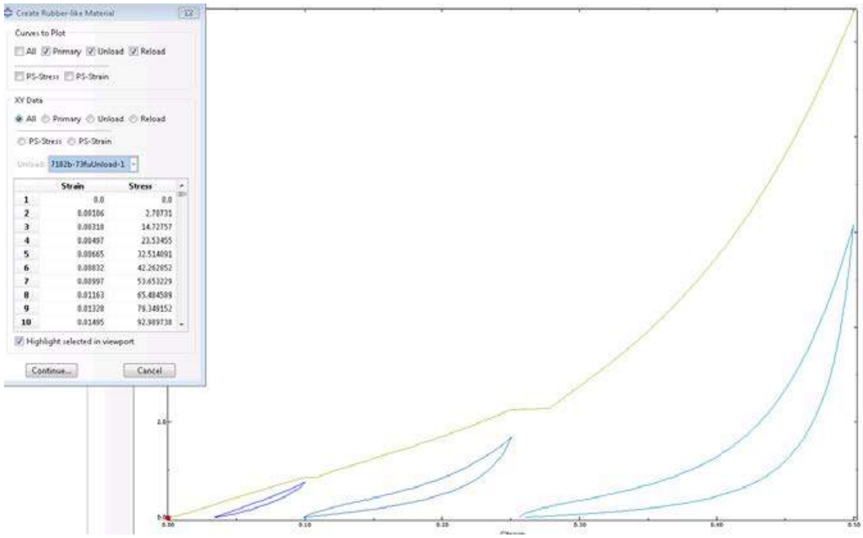

Figure 8: Primary loading-unloading curves extracted.

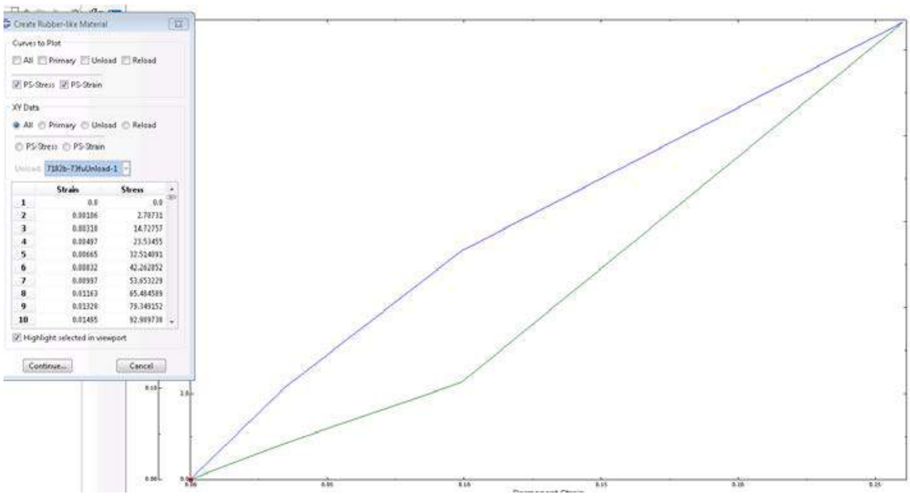

Figure 9: Plastic stress and plastic strain curve.

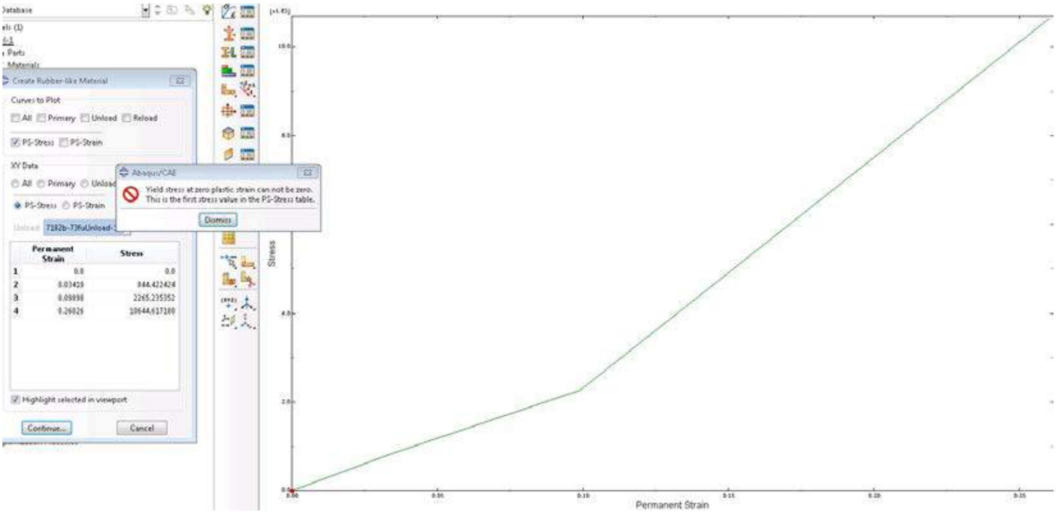

Figure 10: Necessary data adjustment for plug-in.

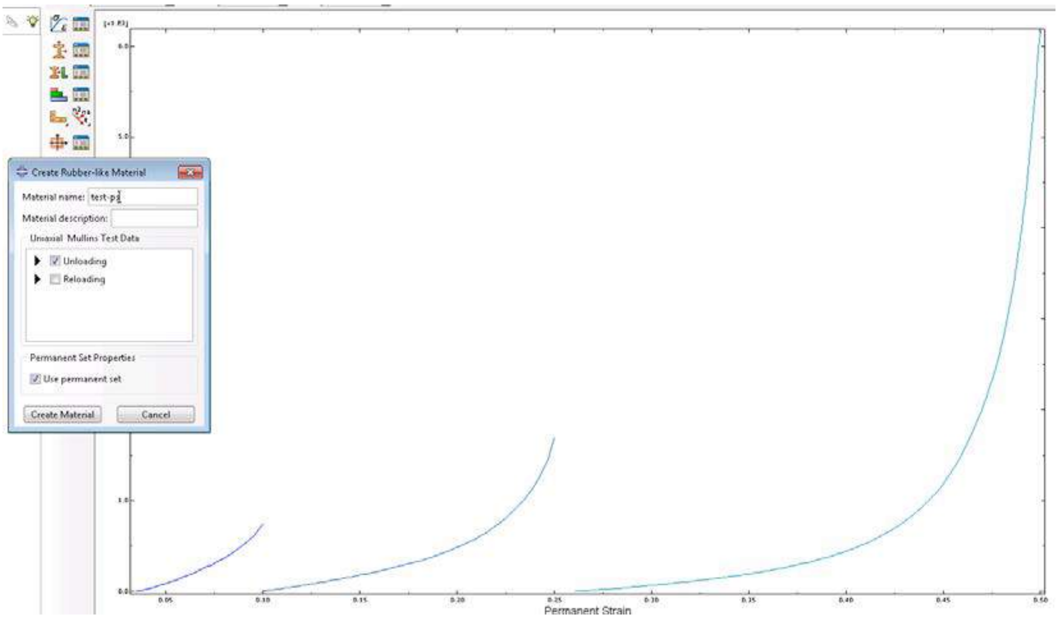

Figure 11: Creation of test-ps file.

Two material data files should be created: "test-ps," which is used for permanent set parameter determination, and "test," which is used to account for the Mullins effect and hyperelastic model parameters.

g) Open material test-ps and select “Plastic.” The yield stress plastic strain table should appear. Copy the table into a blank notepad (note that this deviates from the process in the manual).
h) Close test-ps and open test. Select “Mechanical,” “Plasticity,” and “Plastic” and a table should appear. Copy the data from Step 2g into this table and click “OK.” The revised material test (Figure 14) is the final material to be used for simulation (go to Step 3) (note that this deviates from the process in the manual).

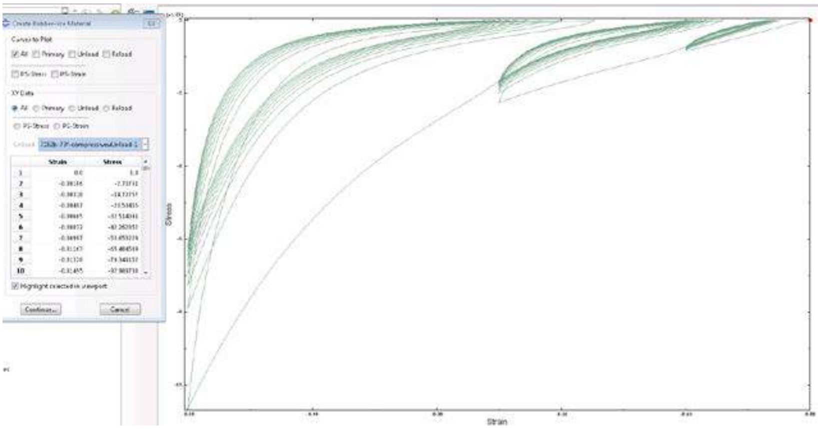

Figure 12: Adjusting the test data with a sign change for compression.

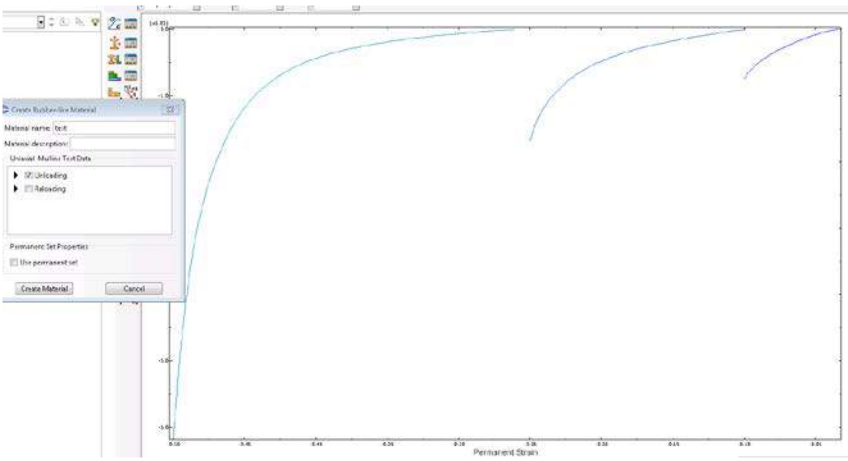

Figure 13. Primary unloading curve for test.csv.

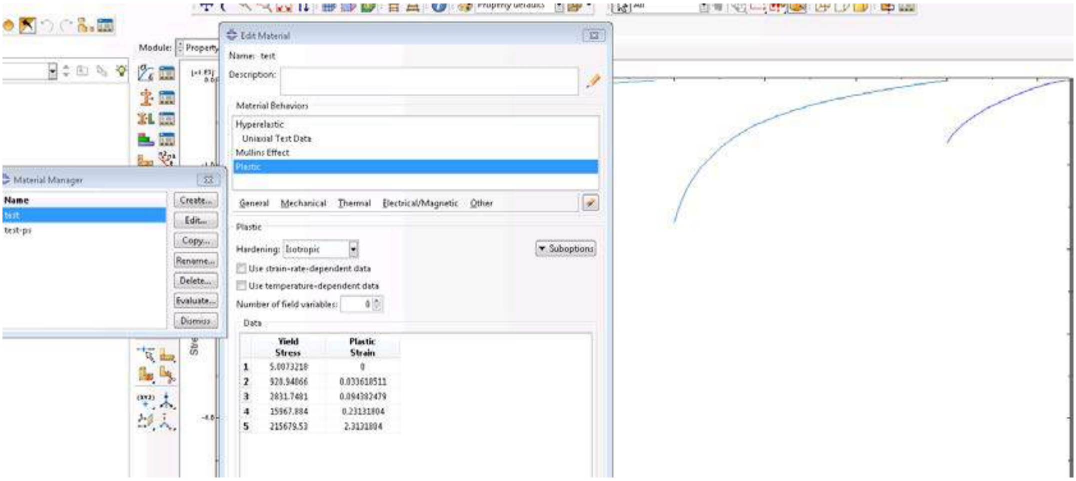

Figure 14: Creation of revised material data test.

3. Because of issues in Abaqus, the material data test typically is not directly used in a model. A simple model is run to obtain model parameters from the revised material data test.
   a) Create a unit cube model in the normal manner (Figure 15). Note the cube is made of rubber, so a hybrid element should be used in the model; create the job test.
   b) In the job module, click the "General" tab and select "Print model definition data."
   c) Run the job. The job has two functions—comparing the model prediction to test data and obtaining model parameters [hyperelasticity, Mullins effect, and permanent set (plasticity)].

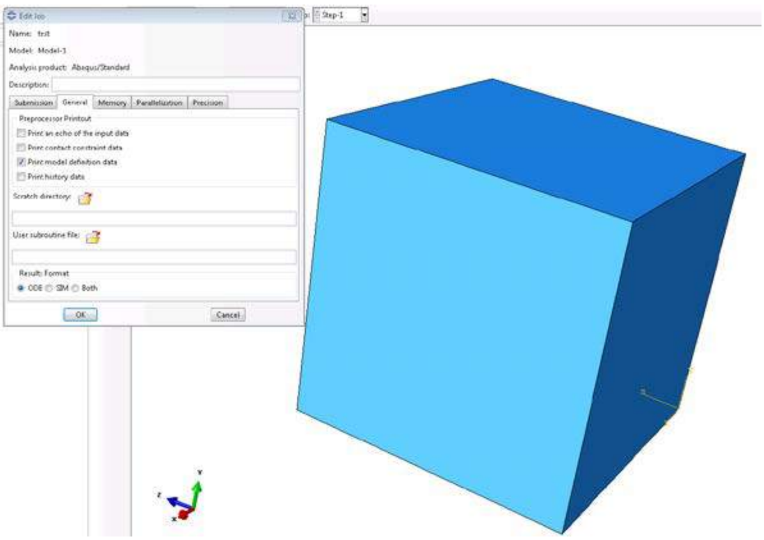

Figure 15: Unit cell model used to determine the full set of model parameters.

The full set of model parameters can be found in the *.dat file once the model runs successfully. The following is the set of model parameters for 92-durometer Compound X at 73°F determined using the previous procedure.

PLASTICITY - MISES YIELD SURFACE WITHISOTROPIC HARDENING
STRESS PLASTIC STRAIN

5.0073, 0.0000
928.94, 3.36185E-02
2831.8, 9.43825E-02
15968, 0.23132
2.15680E5, 2.3132

HYPERELASTICITY - NEO-HOOKEAN STRAIN ENERGY
D1 C10 C01
0.00000000, 1154.54136, 0.00000000

MULLINS EFFECT PROPERTIES
COEFFICIENTS OF THE OGDEN-ROXBURGH DAMAGE FUNCTION

R M BETA
1.11482E+00, 2.63139E+01, 1.11150E-01

5. Verification and Validation of the Permanent Set Model per the Button Tests

The button test is simple to perform. An ASTM D395 (2016) Type 1 button is placed on a flat thick plate with lubricant and compressed from above by a loading fixture. The finite element analysis (FEA) model is an axisymmetric model, with load fixture represented by a rigid flat plate, and the button is constrained vertically (Figure 16).

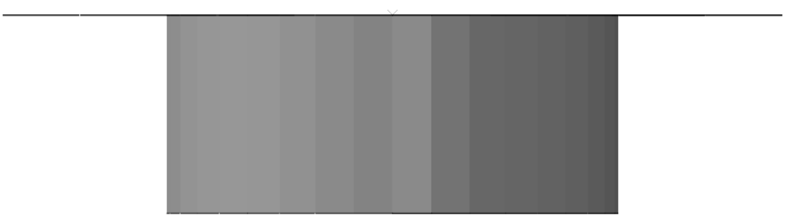

Figure 16: FEA model for button tests.

The button material is represented by a hyperelastic material model accounting for the Mullins effect and permanent set. The material parameters are determined per physical test data (see Section 3) using the procedure outlined in Section 4. It is shown that the higher the compression

(Figure 17), the larger the permanent set, which is expected, and the predicted stress strain response of the button matched the test measurement well (Figure 18).

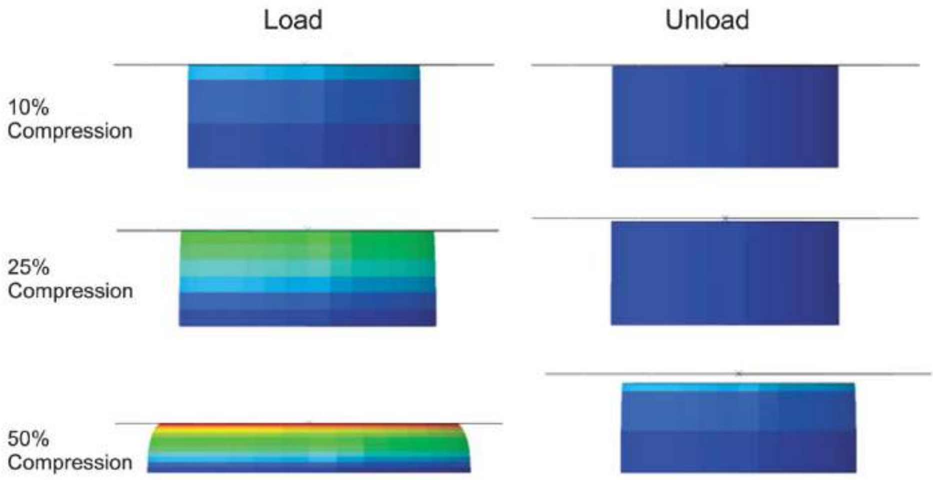

Figure 17: 92-durometer Compound X at 10, 25, and 50% compression.

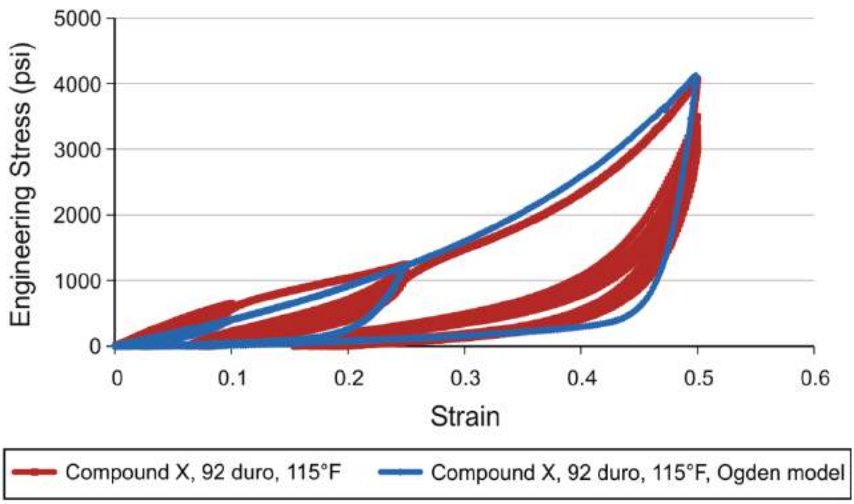

Figure 18: 92-durometer Compound X responses under cyclic compression—prediction vs. test.

It is noted that model prediction is somewhat sensitive to the choice of hyperelastic models (Figure 19). For this particular case, the Ogden and Roxburgh (1999) model showed a better match with test results than the Marlow or Monney-Revlin models.

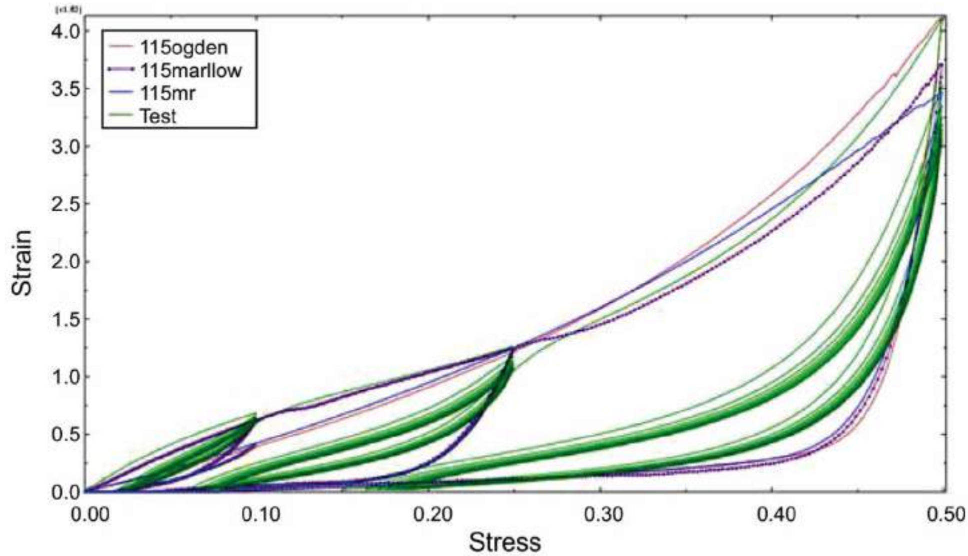

Figure 19: Sensitivity analysis for hyperelastic models.

5. Summary and Concluding Remarks

The permanent set model in Abaqus Version 6.14 was assessed. An issue in the code was identified and a workaround solution was established. The model was verified and validated through compression button test results.

It is noted, however, that the commonly used permanent set definition in physical tests, as outlined in the button test, is different from the compression set tests used in the oil and gas industry. Commonly, the permanent set is defined as the strain at zero stress during cyclic loading of rubber and does not account for the viscoelastic recovery of rubber deformation. Additionally, it does not account for the chemical effects of holding a deformed sample at high temperature for extended periods of time, from days to years, which is typical in oil and gas applications. Despite the verification and validation of the model for the specific cases, the model has limited applications for rubber in high-pressure/high-temperature (HP/HT) downhole environments.

6. References

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7. Acknowledgements

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