Paper # 11

ELASTOMER RATE-DEPENDENCE: A TESTING AND MATERIAL MODELING METHODOLOGY

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ABSTRACT

Stress relaxation testing at very early times (fraction of a second) combined with test data from a set of constant strain-rate uniaxial tests is used to create hyperelastic/viscoelastic material models. A robust method of testing the material and a robust method of material model calibration is developed to capture the strain-rate sensitivity of elastomeric materials. This material representation is intended for simulations of dynamic transient loadcases. The focus is on the use of the hyperelastic and viscoelastic Prony series representation in the Abaqus/Standard and Abaqus/Explicit simulation software. This technique and resulting material model represents the material's strain-rate dependence during loading quite accurately and thus can be used effectively to simulate peak load conditions during dynamic transient events. Unfortunately, the resulting hyperelastic plus Prony series viscoelastic material model does not represent the material's hysteresis loop during the load-unload cycle accurately. This paper presents the test methods developed, a sample of material test data, and the resulting material model and material model responses.

KEYWORDS

Elastomer, Rubber, Rate-Dependence, Hyperelastic, Viscoelastic, Hysteresis

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1 Introduction

Many papers have been written about the testing of elastomers for purposes of creating hyperelastic material models for use with FEA (finite element analysis). The hyperelastic material model represents the material's nonlinear elasticity, but no time-dependence. There is also good documentation on using stress relaxation testing to create a Prony series linear viscoelastic representation. The Abaqus/CAE pre-processing software contains a curve-fitting calibration utility for such purposes. A common application of stress relaxation testing and Prony series viscoelastic modeling is for sealing applications with a time-frame of interest over many hours, days and weeks. In recent years there is more interest in modeling elastomer time-dependence in short-duration, harsh, transient dynamics events. The general scope of this work is to demonstrate the process of material testing, material model calibration, and Finite Element (FE) simulation needed to evaluate and correlate a transient dynamic event.

The authors have collaborated to investigate and define a testing and material model calibration process for simulation of short-duration transient dynamics events. In any practical application the testing required and FE calibration required would look like this.

- Material and Component Tests
    - Quasi – Static
    - Dynamic (Constant Strain Rate, Stress Relaxation)

- Material Model Calibration
    - Quasi – Static : Hyperelastic
    - Dynamic : Linear Viscoelastic, Prony Series

Since the hyperelastic part of this process is already well documented, we will focus our attention only on the testing and calibration of the viscoelastic portion of the material model.

A common set of test data often used to understand a material's strain-rate dependence is a family of constant strain-rate uniaxial tests. A typical set, or family, of curves is shown in Figures 1 and 2. Figure 1 shows only the load curves while Figure 2 shows the load and unload behavior. The figures are from uniaxial tension testing of material samples. While this test data is common and relatively easy to perform, there is no curve fitting or calibration utility for using it within the Abaqus suite of tools. The idea that we had was to perform stress relaxation testing and focus on very early time response during this test. Could we use early-time stress relaxation data and the existing curve fitting capabilities in Abaqus/CAE to create valid hyperelastic + viscoelastic material models? We have developed a test and calibration methodology that successfully replicates the strain-rate dependence seen in a family of constant strain-rate tests.

All of the testing and simulation work uses engineering (nominal) stress and strain measures. Abaqus/CAE uses engineering stress and strain values for calibration of hyperelastic material models.

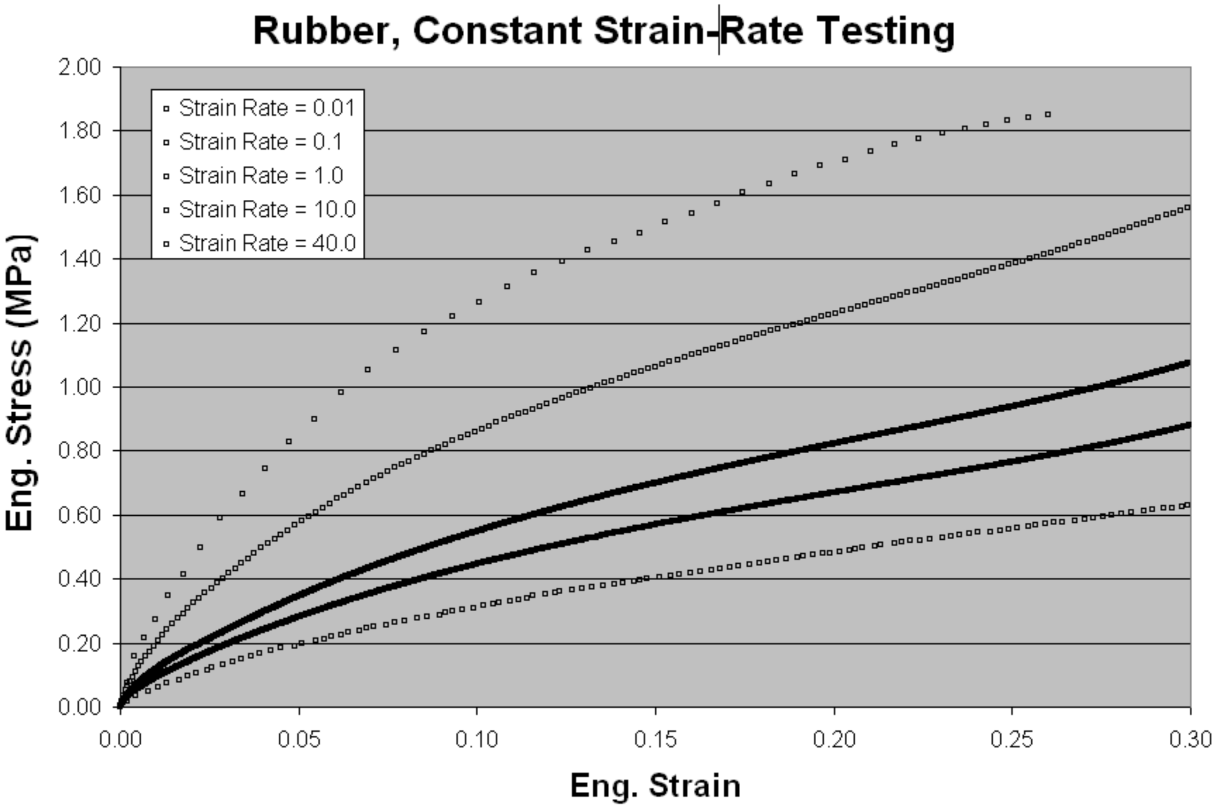

Figure 1. Typical family of constant strain-rate curves, loading only.

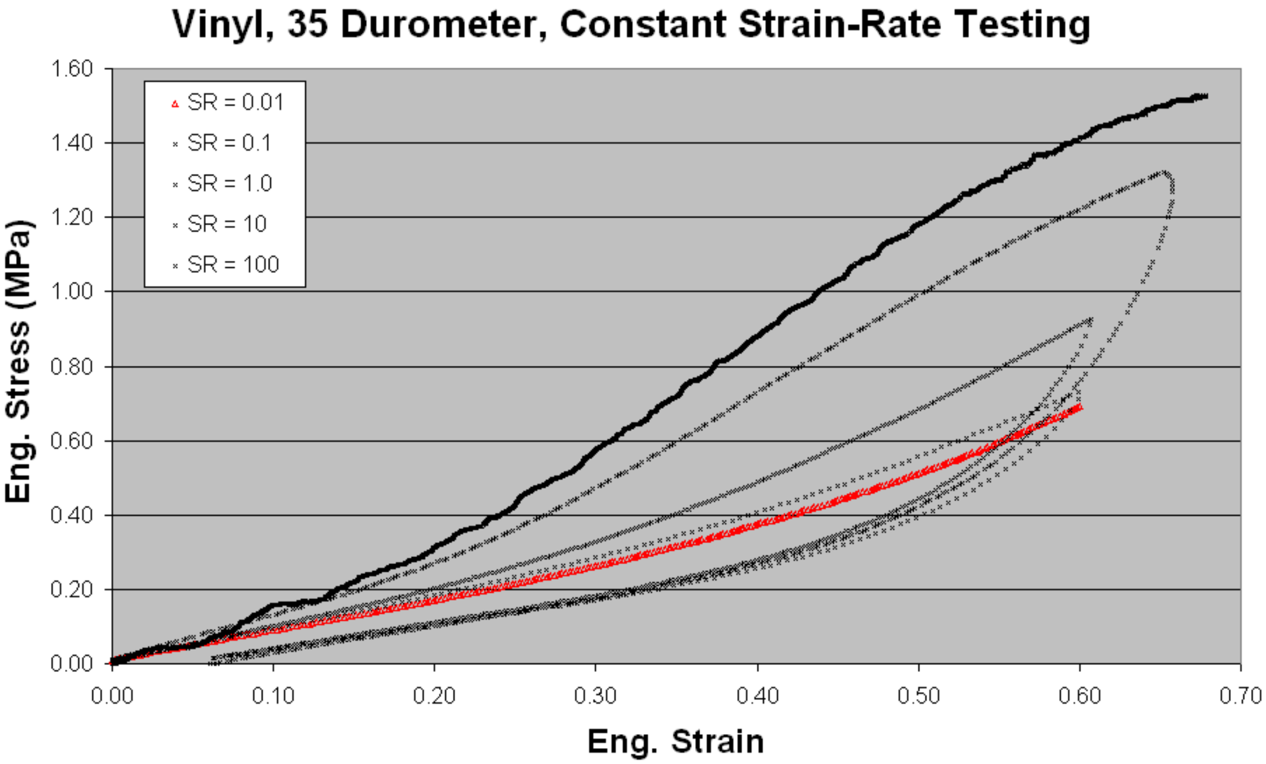

Figure 2. Typical family of constant strain-rate curves, load / unload.

2 Hyperelastic Material Model Calibration

While we do not need to go into the details of calibrating the hyperelastic material model, it may be useful to show the end results. Samples of the material were exercised through ten load and unload cycles to damage the samples. A single test curve representing the uniaxial tension and uniaxial compression quasi-static test raw data was used to calibrate the deviatoric part of the hyperelastic model. Test data from a confined compression test was used to calibrate the dilatational part of the hyperelastic model.

The material available for characterization was limited because it was extracted from a manufactured product. Sections of rubber were manually cut from the product and sliced into small sheets with irregular contours. As such, the types of experiments and the attainable strain states that could be experimentally achieved were restricted.

The uniaxial tension and compression test data was used to calibrate deviatoric Yeoh model coefficients; the Yeoh model response to uniaxial deformation is compared against the test data in **Figure 3**. The dilatational part of the Yeoh model (the three D coefficients) were calibrated from the volumetric test data. **Figure 4** show the correlation of the volumetric simulation result with the volumetric test data. The calibrated Yeoh coefficients give very good correlation with quasi-static test results.

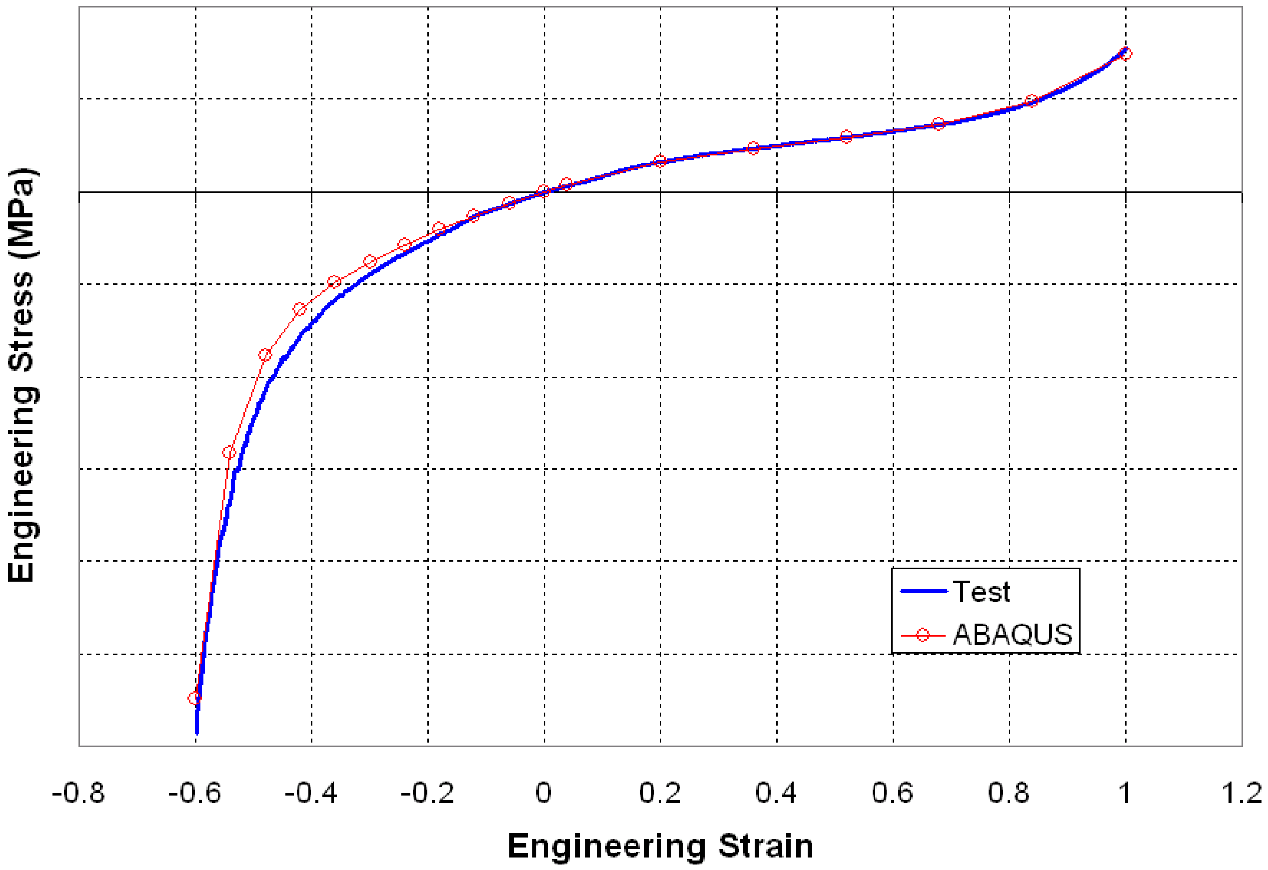

Figure 3. Correlation of the uniaxial tension and compression simulation results.

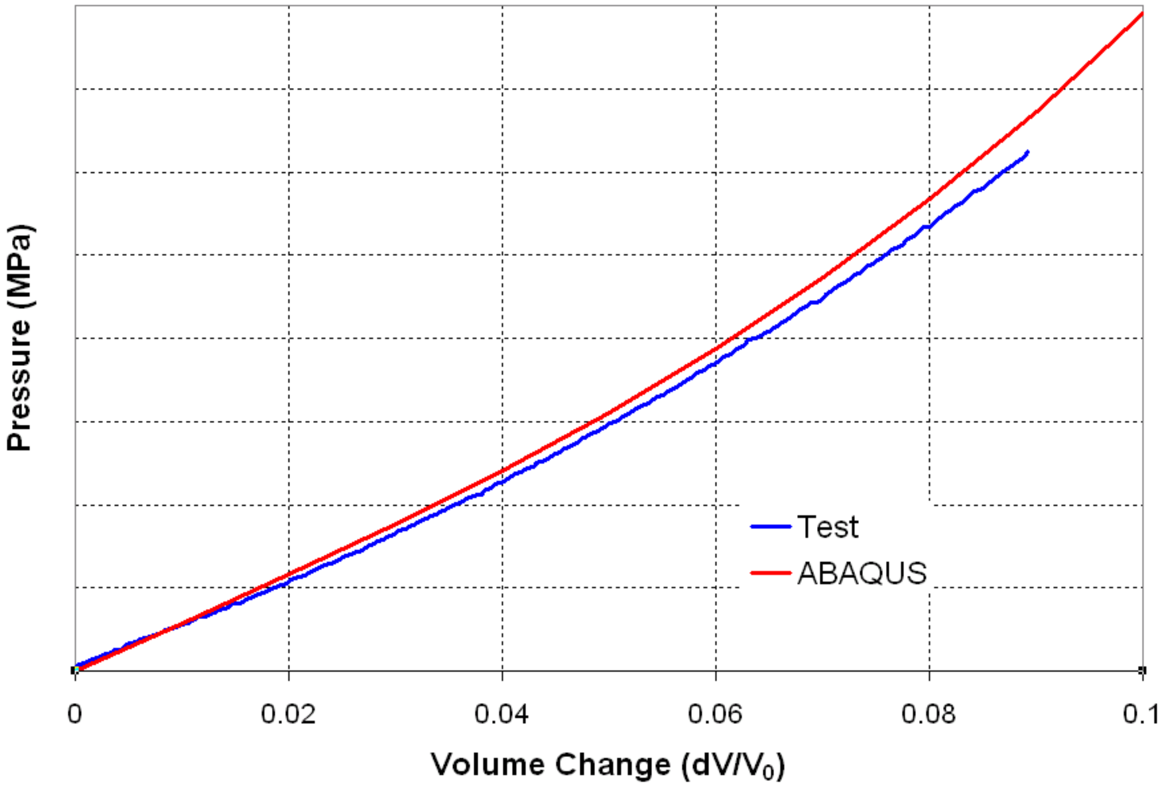

Figure 4. Correlation of the volumetric simulation result.

3 Dynamic Testing

3.1 Overview

The earlier quasi-static testing enabled the creation of a hyperelastic (nonlinear elastic) material model in Abaqus as shown in the previous section. As material is loaded at higher velocities the elastomer material reacts with a varying response depending on the strain rate. Dynamic testing was proposed to enable the creation of a viscoelastic portion of the overall elastomer material model. The hyperelastic + viscoelastic material model will represent the nonlinear elastic and strain-rate dependencies of the overall material behavior. Two types of dynamic testing were carried out: stress relaxation testing, and uniaxial tension testing at four constant strain rates. We use the stress relaxation testing and uniaxial testing at four strain rates together to define the viscoelastic material model. We will discuss the details of the stress relaxation testing and the uniaxial testing at four strain rates. Following that, we will discuss the material model calibration process.

We want to use both stress relaxation testing and constant strain-rate testing to build a Prony series viscoelastic material model for several reasons. First, the stress relaxation testing is relatively easy to perform and there are existing curve-fitting tools built into the Abaqus/CAE software that allow for quick definition of the Prony series coefficients. Also, we have previous experience that the Prony series defined from stress relaxation information will replicate the family of constant strain-rate deformations reasonably well (in terms of capturing the rate-dependence of the loading curves). We anticipate, at most, small modifications of the Prony series coefficients derived from the stress relaxation data will be needed to best match the rate-dependence shown in the family of constant strain-rate tests.

3.2 Stress Relaxation Testing and Linear Viscoelastic Material Calibration

The stress relaxation test is a relatively simple test that gives us a good deal of information about the time dependence of the material's behavior. The stress relaxation test imposes a constant displacement (strain) on a material specimen and measures the change in force (stress) over time. The idealized stress relaxation test is shown below in **Figure 5**. This test is performed on uniaxial tension specimens. This test measures the time dependence of the shear modulus, given that solid elastomers exhibit very little time dependence of the volumetric, or dilatational, response.

The idealization in **Figure 5** is that the strain is instantaneously imposed at time zero. Actually, there is always a finite time over which the strain is ramped from zero to its constant value. For our purposes we wanted to apply the strain as quickly as possible since we were interested in the stress relaxation at very early times. The dynamic events we are interested in modeling occur over a short time frame, thus we are interested in using the stress relaxation test to measure the time dependence of the material behavior over a relatively short period – a fraction of a second. After discussion with Axel Products, we decided to load the material specimen as quickly as possible, trying to ramp the applied strain to its constant value at a strain rate of approximately 50 /sec. This idealized strain loading with a 50 /sec strain rate is shown below in **Figure 6**. The actual loading rate of the test will be shown in a later section.

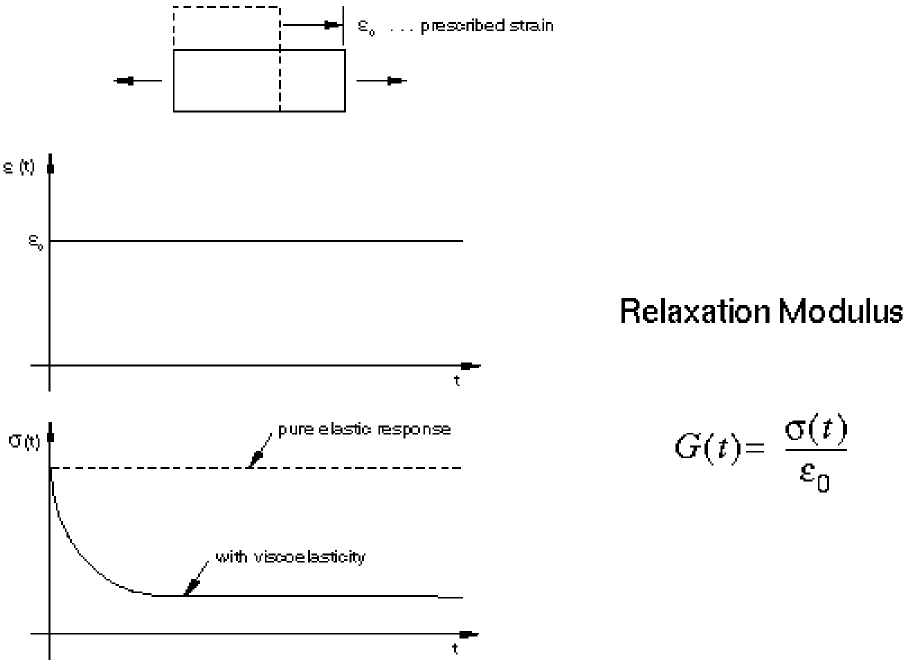

Figure 5. Stress Relaxation Test.

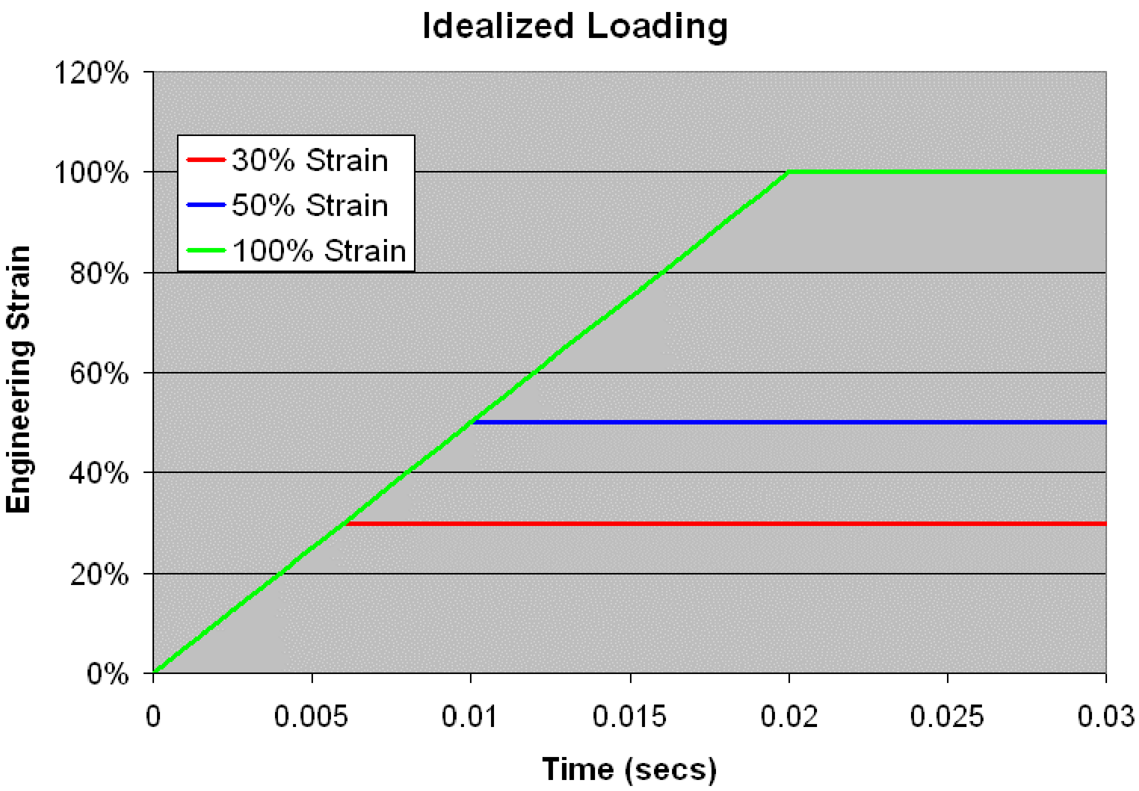

Figure 6. Strain Loadings for the Stress Relaxation Test

The difficulty would be that at such speeds of loading there would likely be some overshoot of the actuator due to inertia. The data capture interval will be every 0.001 seconds (1 millisecond). We decided to stop the stress relaxation test at a total time of 100 seconds. This would give us at least four decades of time information for the time-dependence of the material.

One of the reasons stress relaxation data is so useful is that curve fitting procedures exist in Abaqus/CAE to fit a set of linear viscoelastic Prony series coefficients. Part of this work is to explore how well we can capture very early time information in the stress relaxation test and how well the Prony series model derived from it can be used to represent the material behavior in the uniaxial tension testing at various constant strain-rates.

Stress Relaxation Testing Procedure

The objective of a stress relaxation experiment is to instantaneously subject a material to a step change in strain and observe the stress response. The stress response in time is stress relaxation. In the laboratory, the strain cannot be instantly imposed so instead the strain is increased at a controlled constant rate of straining until the target strain is achieved whereas an instantaneous stop is attempted. In the case upon which this paper is based, the short time stress response if of interest. This means that high measurement fidelity is desired in a small amount of time after the target strain is achieved. The testing was done in simple tension with a test specimen approximately 2 mm by 4 mm cross section and 25 mm long. The test specimen was extracted from a manufactured part.

Prior to measuring the relaxation response of the elastomer, the elastomer is cycled at a slow straining rate of 0.01 /sec between a near zero stress and a strain of 1.0 to reduce the effects of softening in the elastomer and to create a condition in the material similar to that of the material in service.

After a specimen recovery period, the specimen is strained at a straining rate of 50 /sec to an initial target strain of 0.10 and allowed to relax for 110 seconds. The test specimen is then unloaded to near zero stress and allowed to recover for 300 seconds. The test specimen is again loaded to subsequently higher strain levels at 50 /sec for 110 seconds each time and allowed to recover after each strain level until strain levels of 0.10 though 1.0 in increments of 0.10 was accomplished. The result is a family of relaxation curves at increasing levels of strain as shown in **Figure 8**.

The testing was performed on a Instron Model 8800 Series servo-hydraulic test instrument. The test instrument is fitted with a crosshead mounted 10 kN low mass high fidelity actuator and a high response servo-valve. The test frame is a custom frame featuring a very high mass base and low mass tripod style upper crosshead. The system is designed to provide low force, high fidelity waveforms. The force on the test specimen was measured using a high stiffness 200 N full scale capacity load cell. The load cell is mounted to the instrument base to reduce accelerations transmitted into the load cell.

The strain in the test specimen is measured using a non-contacting laser extensometer during the 0.01 /sec testing. A relationship between strain in the gripped test specimen and actuator travel was established and actuator travel was used for subsequent determination of strain at high strain rates.

The test rate of 50 /sec used during the relaxation loadings requires the actuator to move at approximately 1200 mm/s based on the exact effective gage length. At this loading rate the actuator can stop quickly but not perfectly. Although the stopping error which presents in the form an overshoot strain of approximately 0.05 to 0.02, the effect on the stress at small times is significant and must be corrected as shown in **Figure 10**.

Stress Relaxation Test Results

Axel Products carried out the stress relaxation testing at 10% strain to 100% strain in intervals of 10% strain. We will extract from this data at 30%, 50%, 80% and 100% for post-processing. The strain and stress data was captured every millisecond, and the stress relaxation was monitored for a total time of 100 seconds. The strain rate for each of these strain loadings is about 50 /sec. **Figure 7** shows the raw data strain loading results (strain versus time). One can compare this to **Figure 6**. The point at which each of these loadings begins is not perfectly aligned in the raw data. One of the first data post-processing tasks is to perform a time shift on the raw data to align the start point of the test data capture. Also, as we anticipated, there is a small amount of overshoot in reaching the constant strain target for each test.

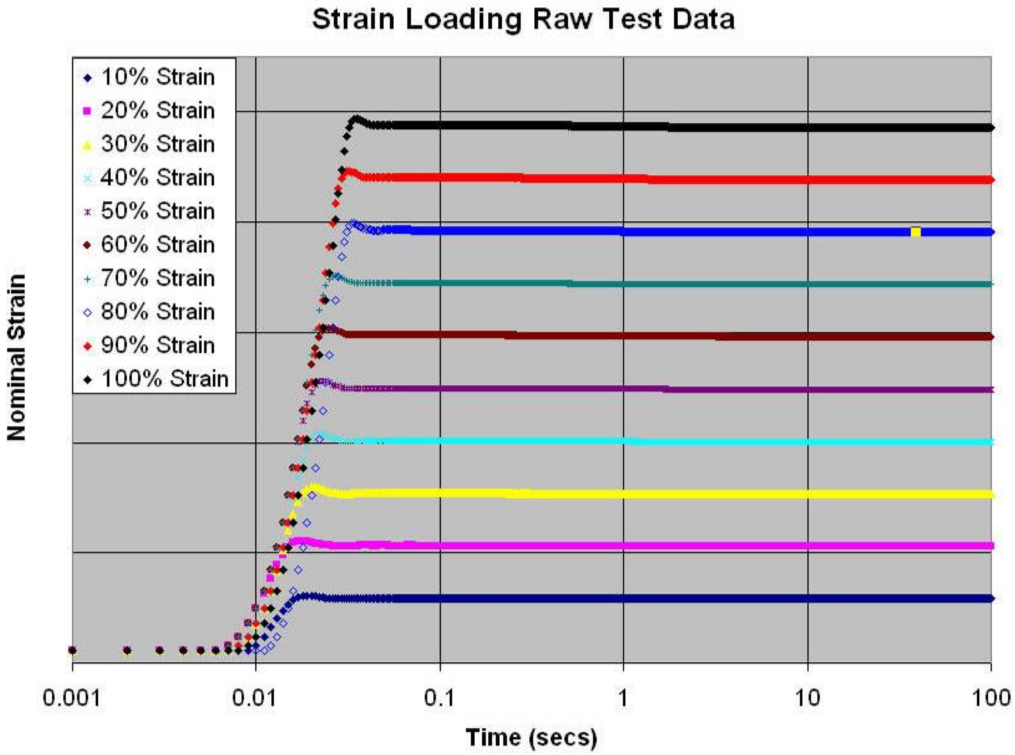

Figure 7. Stress relaxation raw data for strain loading.

The raw test data for the stress response is shown in **Figure 8**. Just as there was an overshoot in the strain target of each loading, there is a corresponding overshoot in the initial stress value.

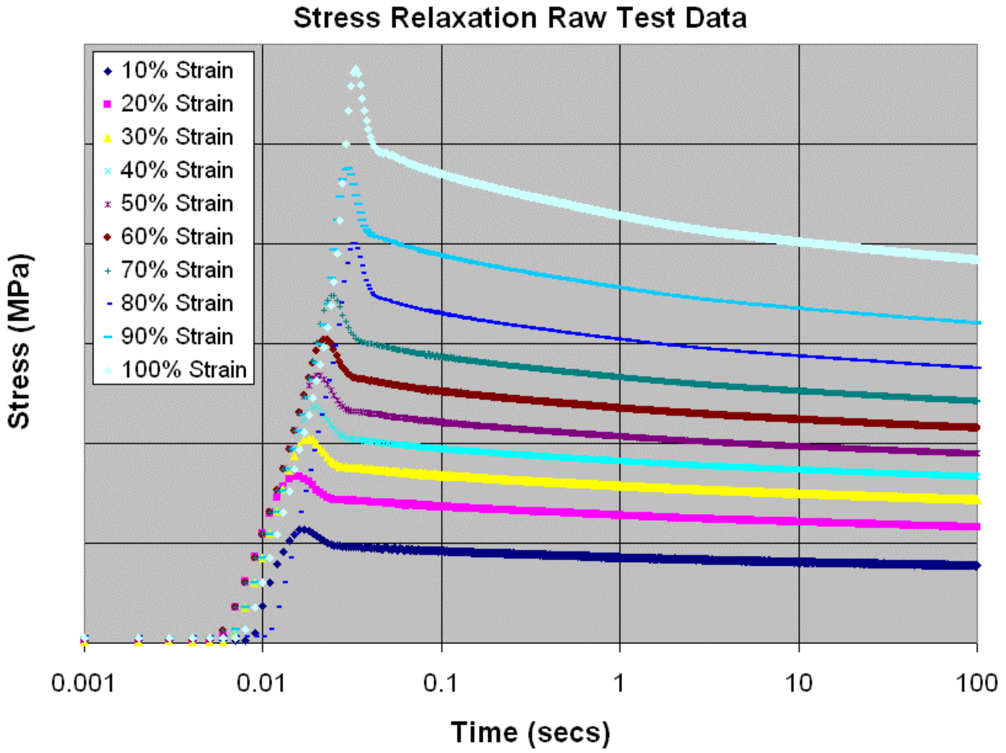

Figure 8. Stress Relaxation raw data for the stress response

Linear Viscoelastic Material Calibration

We have used additional steps in post-processing the raw test data into a form that we will use to calculate a set of Prony series viscoelastic coefficients. We have corrected for the alignment of the start of the test and we have back-extrapolated a stress value at the beginning of the test to compensate for the overshoot condition. The time-shifted test data is shown in **Figure 9**. We do not need all of this test data for our Prony series curve fitting. For further post-processing of the test data, we will focus on the 30%, 50%, 80% and 100% test data. An equation is used to back-extrapolate a stress value at a time of 0.01 seconds. For this process we ignore data in the range of the overshoot. Beginning with test data after the overshoot, the next 30 data points are used to back-extrapolate a stress value at a time of 0.01 seconds. This result is shown in **Figure 10**. The curves labeled 30_Mod, etc show the back-extrapolated data.

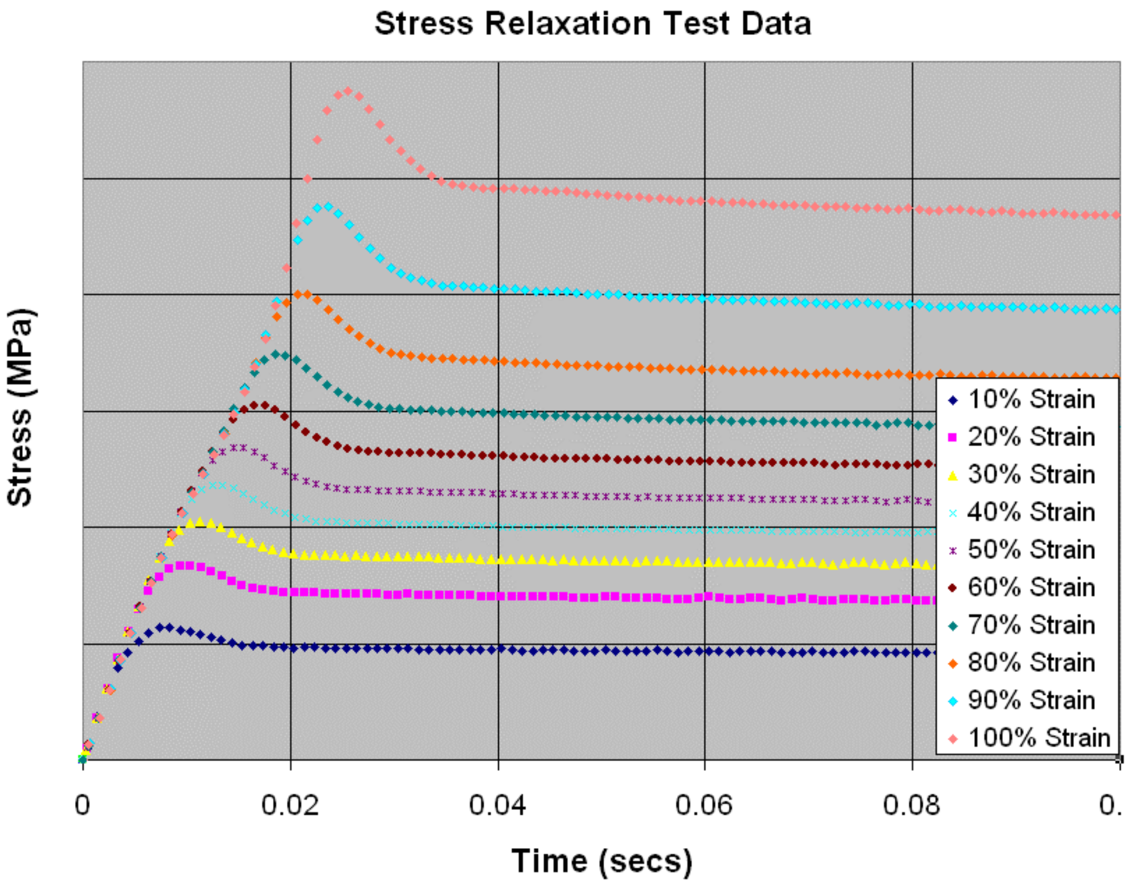

Figure 9. Time-shifted Stress Relaxation Test Data

One thing we always want to do when looking at stress relaxation data is to normalize the data from various loadings and compare. This is a way to determine how linear viscoelastic the material behavior is. If the overlaid normalized curves lie on top of each other, the material is deemed to be linear viscoelastic. If the curves vary, then there is some nonlinear viscoelastic behavior present. In the end, we must pick only one of the stress relaxation curves to form the basis for our Prony series curve fit. In **Figure 11** we show the normalized curves from the 30%, 50%, 80% and 100% strain loadings. While not perfectly linear viscoelastic, there is not a great deal of variation in the relaxation from the different loadings. We chose the 80% strain loading stress relaxation curve for calculating the Prony series coefficients.

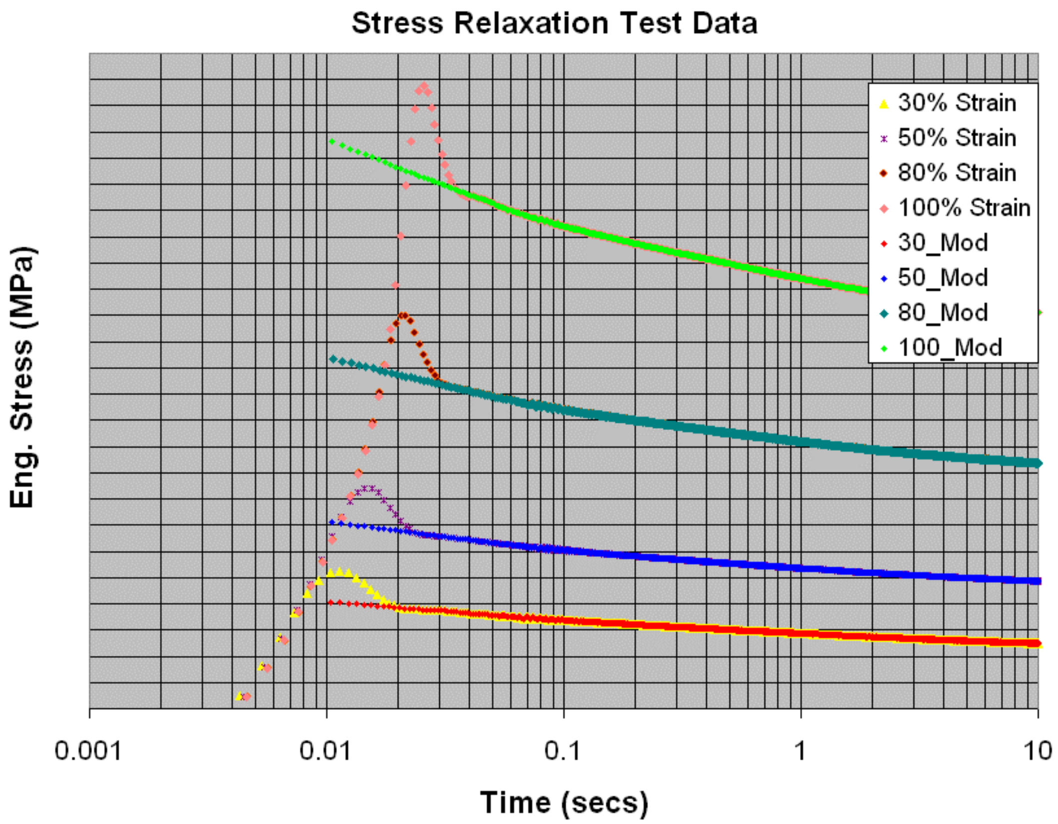

Figure 10. Back-Extrapolated Stress Relaxation Data

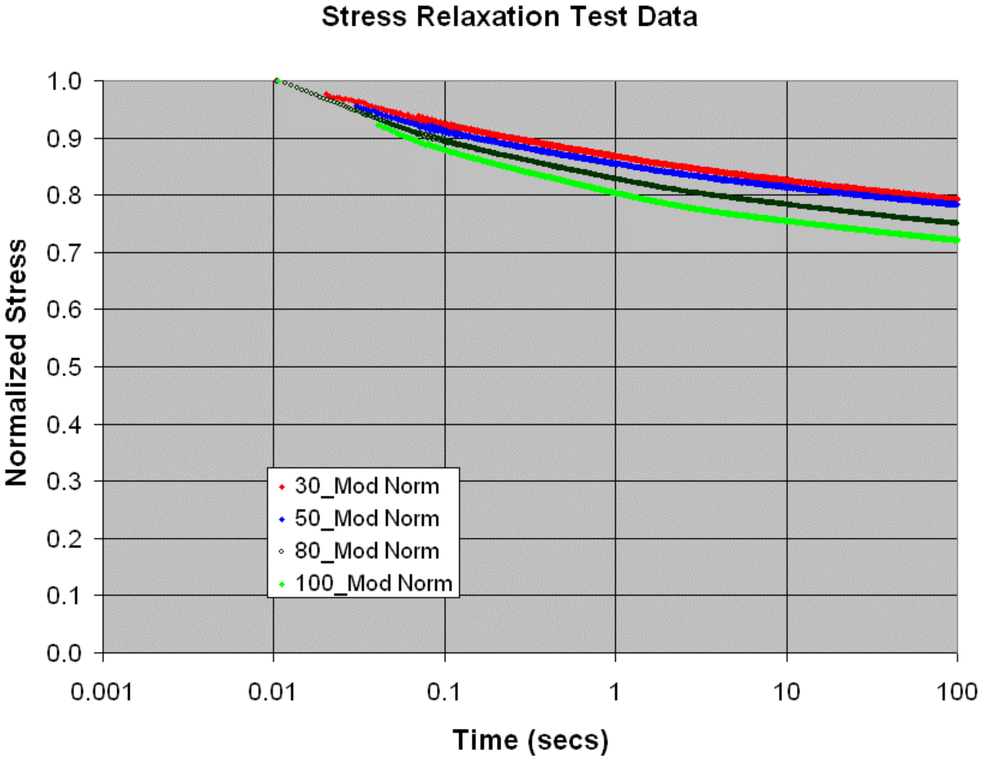

Figure 11. Normalized Stress Relaxation Data

Before using the 80% data for curve fitting, we have performed one additional back-extrapolation. We know that for the higher strain-rates near 50 /sec we would like to have some stress relaxation data in the time range of 0.001 to 0.01. The absence of this data will cause the Prony series to exhibit very little or no rate-dependence in the range of strain rates from 1-50 /sec. **Figure 12** shows this additional back-extrapolation for the 80% stress relaxation data (dark green curve labeled 80_Mod). We will also normalize this test data for curve fitting our Prony series coefficients. We have used this set of data in Abaqus/CAE to calculate the Prony series. The ERRTOL value used in the Abaqus viscoelastic curve fitting was set to 0.001, which resulted in a five-term Prony series.

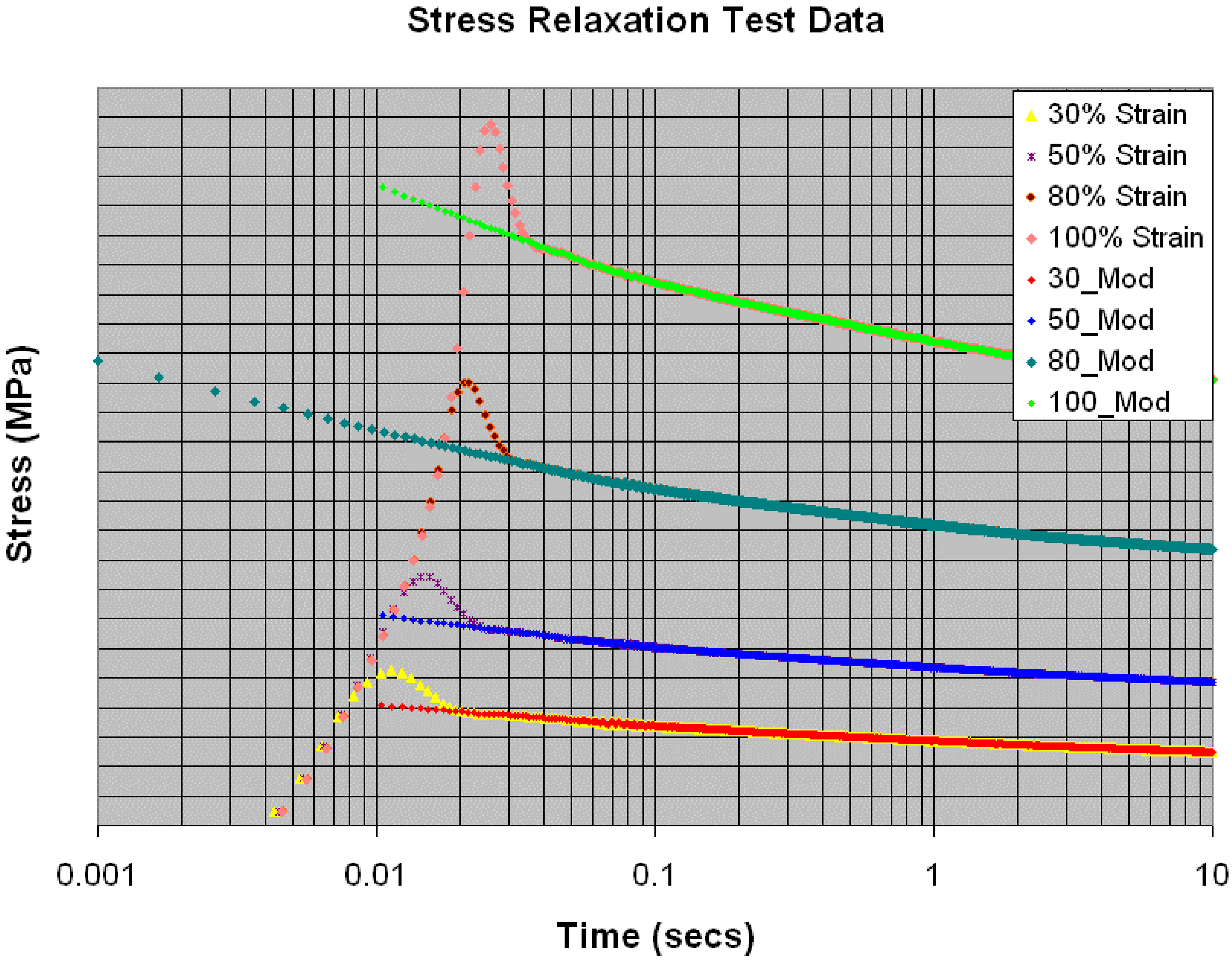

Figure 12. Back-extrapolation of the 80% data to 1 millisecond

It is commonly understood that for solid elastomers the volumetric behavior exhibits very little or no time-dependence. Thus we are only defining a Prony series for the shear behavior of the material. Curve fitting, or calibration, in the Abaqus/CAE software yielded a five-term Prony series set of coefficients

This five-term Prony series results in a stress relaxation function that very nicely matches the test data used in the curve fitting. The Prony viscoelastic representation is compared against the test data in **Figure 13**. The Prony series function is nearly flat in the 100 – 1000 second range. This allows us to take the Yeoh model defined from testing performed at 0.01 /sec and consider it to be the "long term" elastic response.

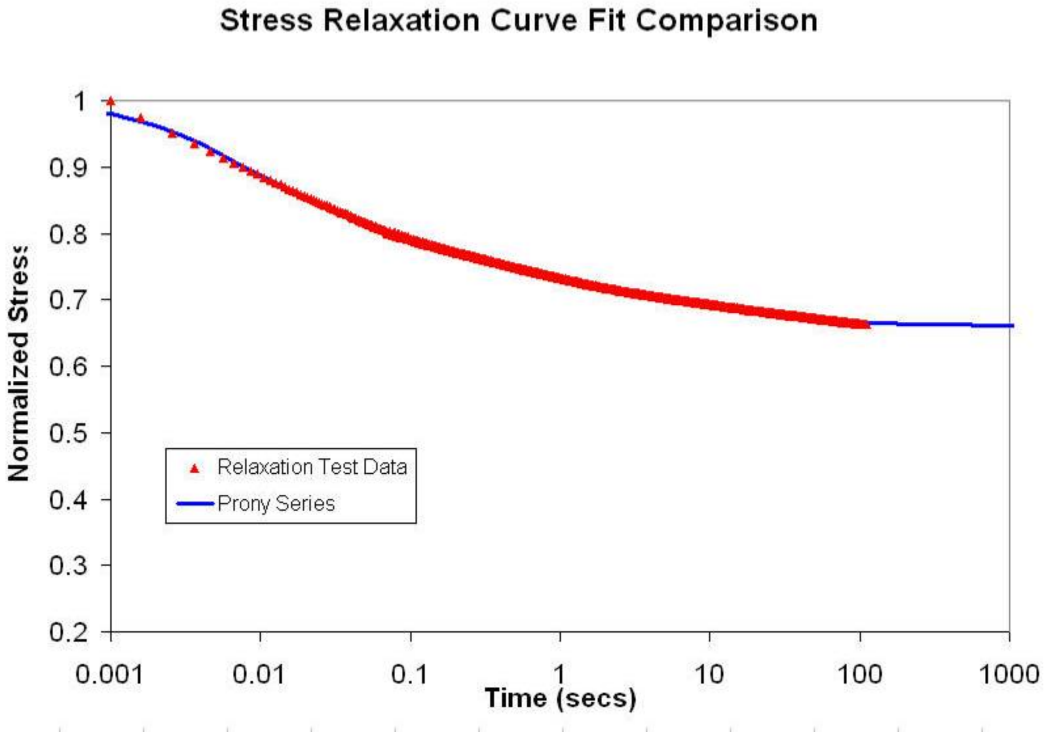

Figure 13. Comparison of the Prony Series function to the Test Data

3.3 Dynamic Uniaxial Tension Testing

In this section we show the test results for the family of constant strain-rate tests. We will also compare the linear viscoelastic (Prony series) material model response to this excitation. The earlier quasi-static testing was performed at a strain-rate of 0.01 /sec. The high strain-rate testing was performed at 0.1, 1.0, 10 and 50 strain/second rates. All of this testing was performed at room temperature. The loading in each test is a triangular waveform – a linear ramp up to a peak strain followed by a linear ramp down until the specimen is unloaded. The target peak strain was 100% strain.

Dynamic Uniaxial Tension Testing Procedure

The objective of the uniaxial testing procedure is to examine the effects of the rate of straining during a load-unload triangle waveform. At slow strain rates this can be accomplished very exactly; at the higher strain rates, the instantaneous change from loading to unloading becomes less exact.

In this case, the testing was done in simple tension with a test specimen approximately 2 mm by 4 mm cross section and 25 mm long. The test specimen was extracted from a manufactured part.

Prior to measuring the relaxation response of the elastomer, the elastomer is cycled at a slow straining rate of 0.01 s-1 between a near zero stress and a strain of 1.0 to reduce the effects of softening in the elastomer and to create a condition in the material similar to that of the material in service.

After a specimen recovery period, the specimen is strained at a straining rate of 0.1 s-1 to a target strain of 1.0 and unloaded to zero stress at the same rate of straining. The test specimen is then allowed to recover at zero stress for 300 seconds. The test specimen is again loaded to a target strain of 1.0 and unloaded to zero stress followed by a 300 second recovery for strain rates of 1.0, 10 and 50 s-1. The result is a family of curves at increasing straining rates as shown in Figure 14.

The same measuring techniques and instrumentation was used in the dynamic uniaxial testing as in the stress relaxation testing.

Dynamic Uniaxial Tension Test Results

The family of constant strain-rate raw test data is shown below in **Figure 14**.

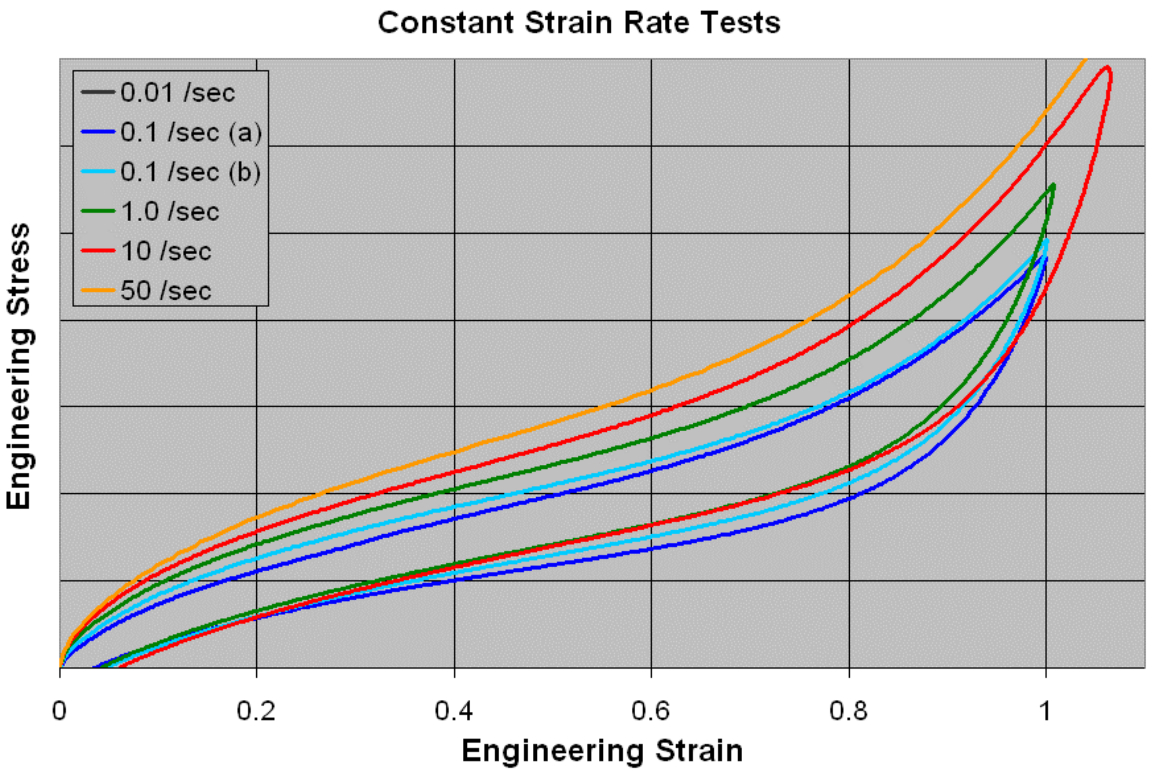

Figure 14. Family of constant strain-rate dynamic testing, load / unload (100% Strain).

The loading portion of the test data will be very useful in comparing to the simulation results. This subset of the dynamic test data is shown in **Figure 15**. The Y-axis scales for **Figure 14** and **Figure 15** are the same.

Comparison with Linear Viscoelastic Material Model Response

The comparison of the dynamic load curves with the Abaqus linear viscoelastic material model is shown in **Figure 16**. The Abaqus material model responses are shown in yellow. This linear viscoelastic material model matches the rate-dependence very well. There is no need to modify the Prony coefficients determined using the stress relaxation test data.

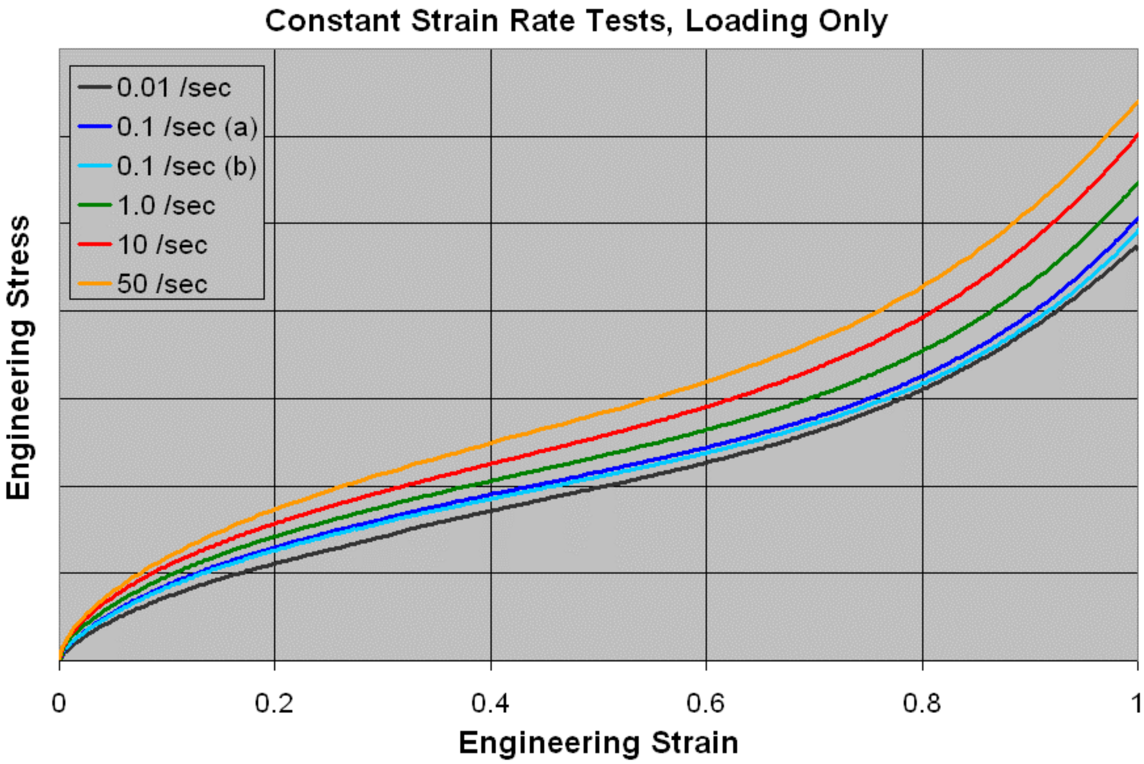

Figure 15. Family of constant strain-rate dynamic testing, loading subset

We would like to show one more comparison, this time focusing on the size of the hysteresis loop during the load/unload cycle. This comparison is best done by comparing **Figure 14** to **Figure 17**. **Figure 17** contains only the linear viscoelastic material model response to a load/unload cycle of deformation. By comparing these two figures, one can see that the linear viscoelastic material model does a poor job in capturing the true size of the hysteresis loops. This is consistent with our prior experience. But recall from **Figure 16** that the linear viscoelastic material model does a very good job in capturing the rate-dependence of the loading curves. This material model should be very useful for simulations in which we want to capture the loading behavior of a component and capture peak load conditions.

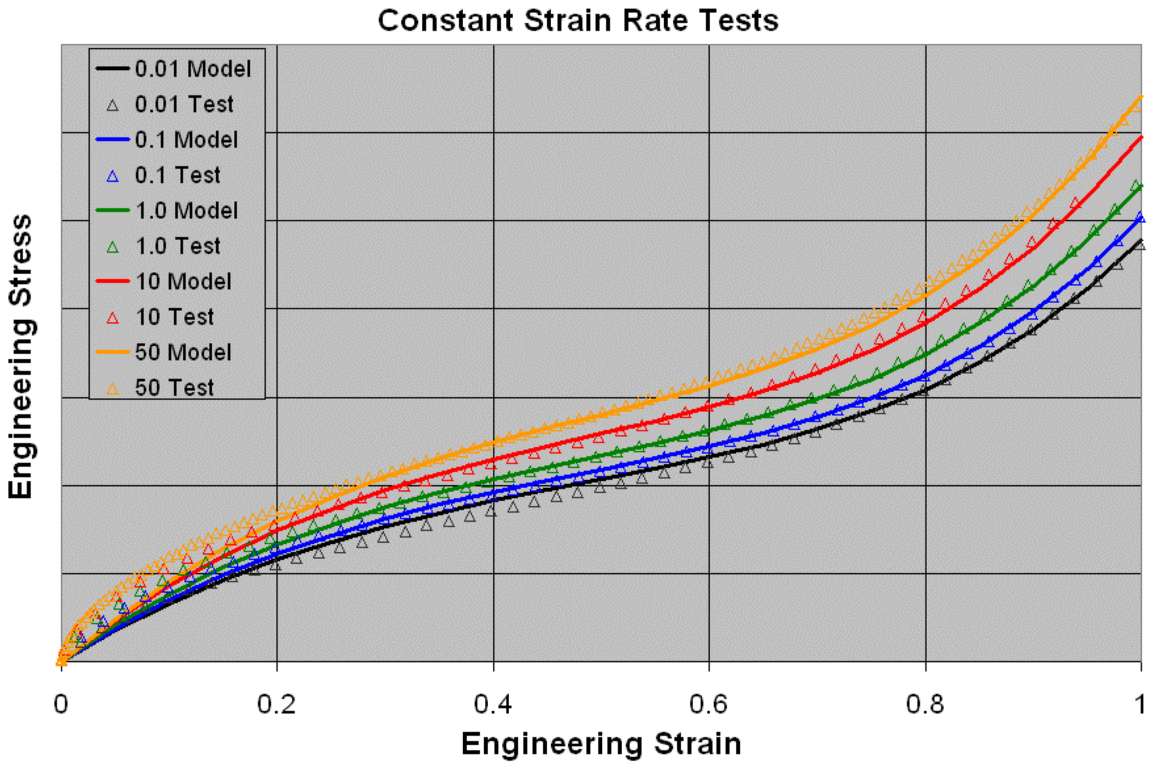

Figure 16. Comparison of test data and simulation response

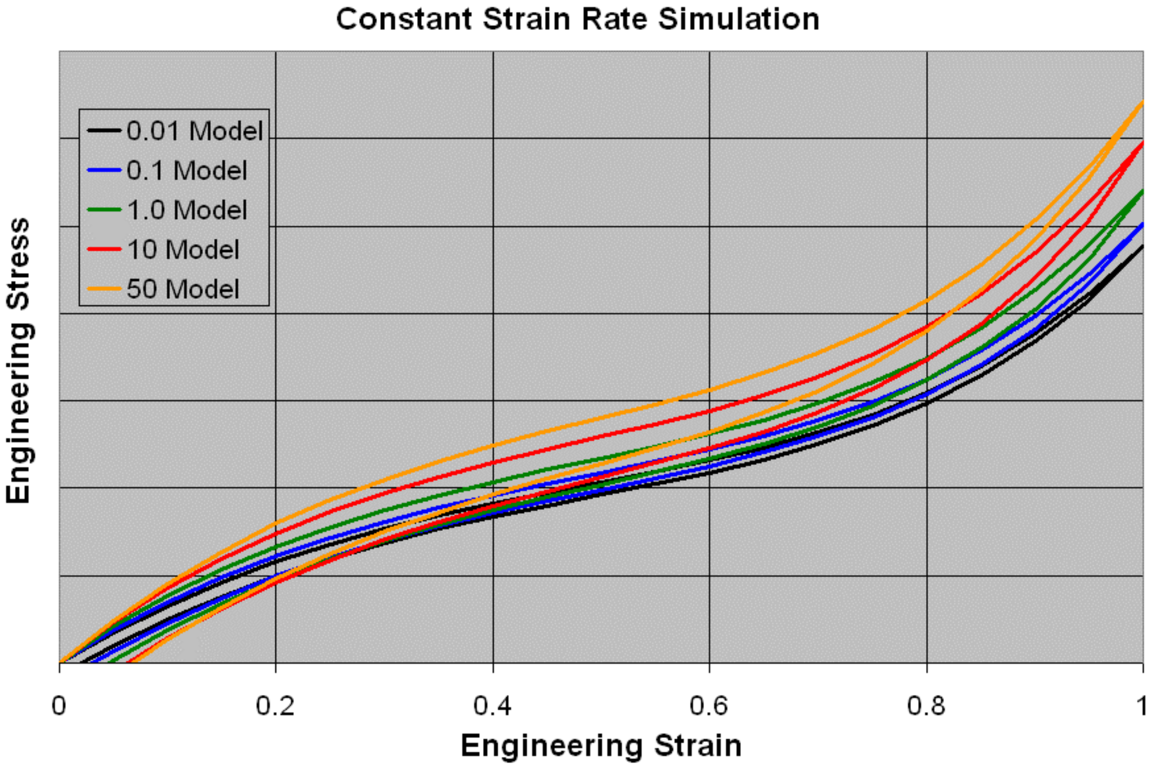

Figure 17. Prony series material model response to load / unload cycle

4 Conclusions

Material tests were performed for defining the quasi-static hyperelastic portion of an Abaqus material model. Stress relaxation testing was performed to calibrate the Prony series linear viscoelastic portion of the material model. The Prony series material model was calibrated using standard procedures built into the Abaqus/CAE software. The material model calibration showed an excellent correlation with the stress relaxation data.

Uniaxial tension testing was used to produce a family of constant strain-rate test data. This data was not used in the calibration process for the Abaqus viscoelastic material model. The material model calibrated from stress relaxation data did an excellent job in reproducing the family of constant strain-rate curves – for the loading portion. Thus, the combined usage of the hyperelastic and linear viscoelastic material models can be used for the transient dynamic event analysis, especially when interested in peak load conditions.

The Prony series material model however, does a poor job of replicating the hysteresis loop seen in a load / unload cycle of deformation. This material model will not accurately capture the energy dissipated in load / unload transient dynamic events.