Testing Elastomers for Hyperelastic Material Models in Finite Element Analysis
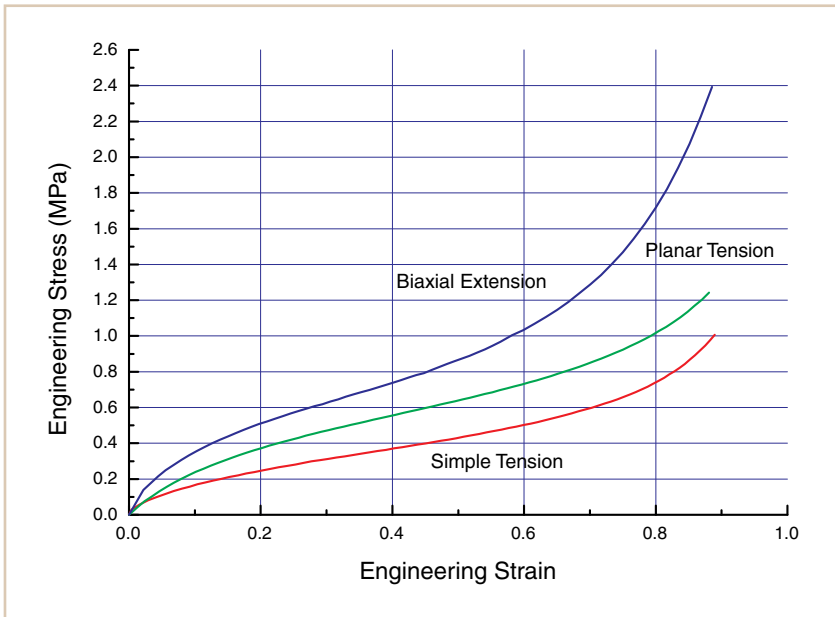

Figure 1, A Typical Final Data Set for Input into a Curve Fitter

By Kurt Miller, Axel Products, Inc.

Introduction

The objective of the testing described herein is to define and to satisfy the input requirements of mathematical material models that exist in structural, nonlinear finite element analysis software

The testing of elastomers for the purpose of defining material models is often misunderstood. The appropriate experiments are not yet clearly defined by national or international standards organizations. This difficulty derives from the complex mathematical models that are required to define the nonlinear and the nearly incompressible attributes of elastomers.

Most of these models are referred to as hyperelastic material models. It is beyond the scope of this article to discuss the details of particular hyperelastic material models. However, most models share common test data input requirements. In general, stress and strain data sets developed by stretching the elastomer in several modes of deformation are required and "fitted" to sufficiently define the variables in the material models. A typical set of 3 stress strain curves appropriate for input into fitting routines are shown in Figure 1. Appropriate experimental loading sequences and realistic strain levels are needed to capture the elastomeric behavior that applies in the analysis.

Testing in Multiple Strain States

The modes of deformation each put the material into a particular state of strain. One objective of testing is to achieve "pure" states of strain such that the stress strain curve represents the elastomer behavior only in the desired state. This testing is not failure oriented. The intention is to model the behavior of the material in the working range of strain and stress. For incompressible elastomers, the basic strain states are simple tension, pure shear, and simple compression. For experimental reasons discussed further on, compression is replaced

Figure 2, Analysis of a Tension Specimen

Axel Products, Inc.

www.axelproducts.com

by equal biaxial extension. For slightly compressible situations or situations where an elastomer is highly constrained, a volumetric compression test may be needed to determine the bulk behavior.

Simple Tension Strain State

Simple tension experiments are very popular for elastomers. There are several standards for the testing of elastomers in tension. However, the experimental requirements for analysis are somewhat different than most standardized test methods. The most significant requirement is that in order to achieve a state of pure tensile strain, the specimen must be much longer in the direction of stretching than in the width and thickness dimensions. The objective is to create an experiment where there is no lateral constraint to specimen thinning. One can perform finite element analysis on the specimen geometry to determine the specimen length to width ratio (Figure 2)[1]. The results of this analysis will show that the specimen needs to be at least 10 times longer than the width or thickness. Since the experiment is not intended to fail the specimen, there is not a need to use a "dogbone" shape specimen. There is also not an absolute specimen size requirement.

Figure 3, A Tension Experiment using a Video Extensometer

The length in this case refers to the specimen length between the instrument clamps. Specimen clamps create an indeterminate state of stress and strain in the region surrounding the clamp in the process of gripping. Therefore, the specimen straining must be measured on the specimen, but away from the clamp, where a pure tension strain state is occurring. A non-contacting strain measuring device such as a video extensometer or laser extensometer is required to achieve this (Figure 3).

Figure 4, Analysis of a Pure Shear Specimen

Figure 5, A Pure Shear Experiment Using a Laser Extensometer

Pure Shear Strain State

The pure shear experiment used for analysis is not what most of us would expect. The experiment appears at first glance to be nothing more than a very wide tensile test. However, because the material is nearly incompressible, a state of pure shear exists in the specimen at a 45 degree angle to the stretching direction[2]. The most significant aspect of the specimen is that it is much shorter in the direction of stretching than the width. The objective is to create an experiment where the specimen is perfectly constrained in the lateral direction such that all specimen thinning occurs in the thickness direction.
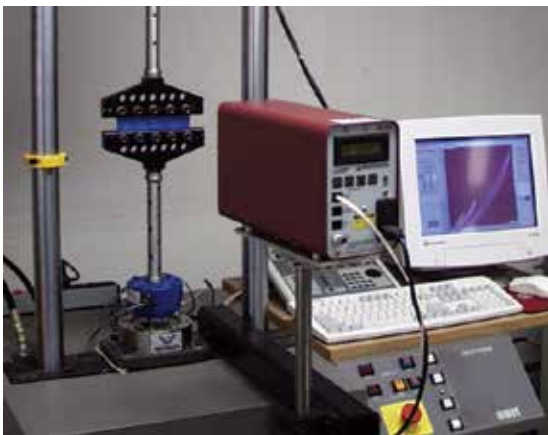
Finite element analysis of the specimen geometry will show that the specimen must be at least 10 times wider than the length in the stretching direction (Figure 4)[3]. This experiment is very sensitive to this ratio. A non-contacting strain measuring device must be used to measure strain away from the clamp edges where the pure strain state is occurring (Figure 5).

Simple Compression Strain State

The compression experiment is also a popular test for elastomers. When testing for analysis, pure states of strain are desired and this is especially difficult to achieve experimentally in compression. Because there is friction between the test specimen and the instrument platens, the specimen is not completely free to expand laterally during compression. Even very small coefficient of friction levels (such as 0.1) between the specimen and the platen can cause substantial shearing strains that alter the stress response to straining (Figure 6). Often, the maximum shear strain exceeds the maximum compression strain! Because the actual friction is not known, the data cannot be corrected.

Figure 6, A Lubricated Compression Specimen Showing Lateral Constraining from Friction at the Surface

Equal Biaxial Strain State

For incompressible or nearly incompressible materials, equal biaxial extension of a specimen creates a state of strain equivalent to pure compression. Although the actual experiment is more complex than the simple compression experiment, a pure state of strain can be achieved which will result in a more accurate material model. The equal biaxial strain state may be achieved by radially stretching a circular disc. Finite element analysis of the specimen is required to determine the appropriate geometry of the clamping points (Figure 7)[4]. Once again, a non-contacting strain measuring device must be used such that strain is measured away from the clamp edges (Figure 8).

Volumetric Compression

Volumetric compression is an experiment where the compressibility of the material is examined. In this experiment, a cylindrical specimen is constrained in a fixture and compressed (Figure 9). The actual displacement during compression is very small and great care must be taken to measure only the specimen compliance and not the stiffness of the instrument itself. The initial slope of the resulting stress strain function is the bulk modulus. This value is typically 2-3 orders of magnitude greater than the shear modulus for elastomers.

Figure 7, Analysis of a Biaxial Specimen

Creating a Consistent Data Set

Although the experiments are performed separately and the strain states are different, data from all of the individual experiments is used as a set. This means that the specimens used for each of the experiments must be of the same material. This may seem obvious but if the specimens are specially molded to accommodate the differing instrument clamps for different experiments, it is possible that the material processing parameters may cause material variations
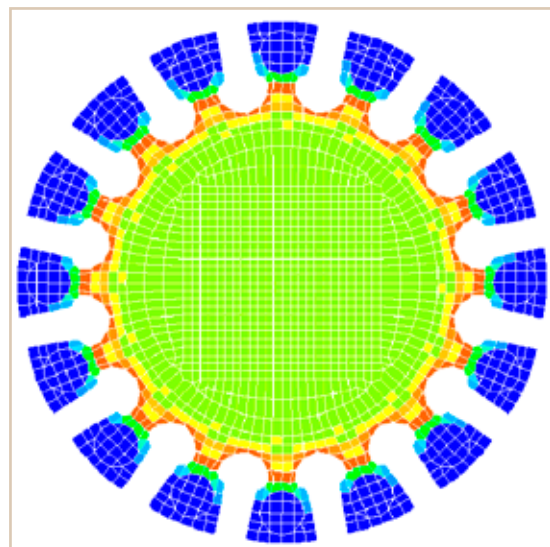

Figure 8, A Biaxial Extension Experiment using a Laser Extensometer (Out of the Image)

Figure 9, A Volumetric Compression Fixture with Specimens

Using Slow Cyclic Loadings to Create Stress Strain Curves

The structural properties of elastomers change significantly during the first several times that the material experiences straining. This behavior is commonly referred to as the Mullins effect[5]. If an elastomer is loaded to a particular strain level followed by complete unloading to zero stress several times, the change in structural properties from cycle to cycle as measured by the stress strain function will diminish. When the stress strain function no longer changes significantly, the material may be considered to be stable for strain levels below that particular strain maximum.

If the elastomer is then taken to a new higher strain maximum, the structural properties will again change significantly. This behavior is documented throughout the literature[6]. One example of this behavior is shown in Figure 10 where a filled natural rubber is strained to 40% strain for 10 repetitions followed by straining to 100% for 10 repetitions. Another example is shown in Figures 11,12, and 13 where a thermoplastic elastomer is strained to 20% strain for 10 repetitions followed by straining to 50% for 10 repetitions.

Observations

Several observations can be made regarding this behavior which are true to a varying degree for all elastomers.

1. The stress strain function for the 1st time an elastomer is strained is never again repeated. It is a unique event.
2. The stress strain function does stabilize after between 3 and 20 repetitions for most elastomers.
3. The stress strain function will again change significantly if the material experiences strains greater than the previous stabilized level. In general, the stress strain function is sensitive to the maximum strain ever experienced.
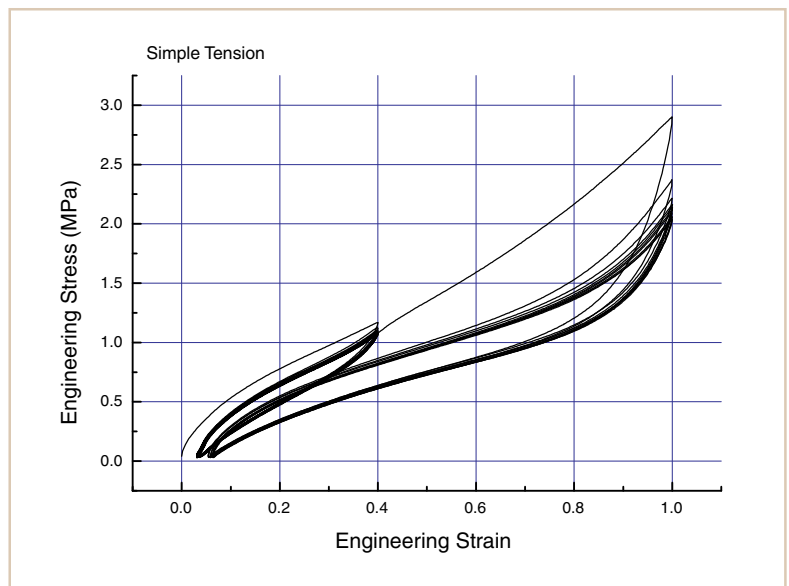

Figure 10, Cyclic Loading of Filled Natural Rubber

from test to test. While it is reasonable to assume that variation exists in the production environment and that we can never really get the exact same material properties every time, it is not acceptable to have this same variation within the data set. The data represents a "snapshot" in time. If even slight variation exists between experiments, a physically impossible material model may be developed in the analysis software. The best way to avoid this problem is to cut the specimens for simple tension, pure shear, and equal biaxial extension experiments from the same slab of material.

The loading conditions, strain levels, and straining rates should also be developed with consideration for the inter-relationship between tests.

4. The stress strain function of the material while increasing strain is different than the stress strain function of the material while decreasing strain.

5. After the initial straining the material does not return to zero strain at zero stress. There is some degree of permanent deformation.

Limitations of Hyperelastic Material Models

Most material models in commercially available finite element analysis codes allow the analyst to describe only a subset of the structural properties of elastomers. This discussion revolves around hyperelastic material models such as the Mooney-Rivlin and Ogden formulations and relates to those issues which effect testing.

1. The stress strain functions in the model are stable. They do not change with repetitive loading. The material model does not differentiate between a 1st time strain and a 100th time straining of the part under analysis.

2. There is no provision to alter the stress strain description in the material model based on the maximum strains experienced.

3. The stress strain function is fully reversible so that increasing strains and decreasing strains use the same stress strain function. Loading and unloading the part under analysis is the same.

4. The models treat the material as perfectly elastic meaning that there is no provision for permanent strain deformation. Zero stress is always zero strain.

The Need for Judgement

Because the models use a simple reversible stress strain input, one must input a stress strain function that is relevant to the loading situation expected in the application. Naturally, this may be difficult because the very purpose of the analysis is to learn about the stress strain condition in the part. However, there are a few guidelines that may be considered.

1. If the focus of the analysis is to examine the first time straining of an elastomeric part, then use the first time stress strain curves from material tests. This might be the case when examining the stresses experienced when installing a part for the first time.

2. If the focus of the analysis is to understand the typical structural condition of a part in service, use stress strain curves derived by cycling a material until it is stable and extracting the stabilized increasing strain curve.

3. If the focus of the analysis is to understand the unloading performance of a part in service by examining the minimum stress conditions, extract a stabilized decreasing strain curve.

4. Perform experiments at strain levels that are reasonable for the application. Large strains that greatly exceed those that the part will experience will alter the material properties such that they are unrealistic for the application of interest.

5. Stabilize the material at 2 or more different levels to cover a broader range of performance and to measure just how sensitive the structural properties are to maximum strain levels.

Stress Relaxation

Slow cyclic loadings alone may not be sufficient to characterize an elastomer. If an elastomer is stretched to a particular strain and held, the stress in the elastomer will decrease over time[7]. This consequence is referred to as stress relaxation. This reduction in stress can be a significant fraction of the initial stress. For many elastomers, the normalized shape of the stress-time function is relatively insensitive to the absolute strain level and to the strain state. This
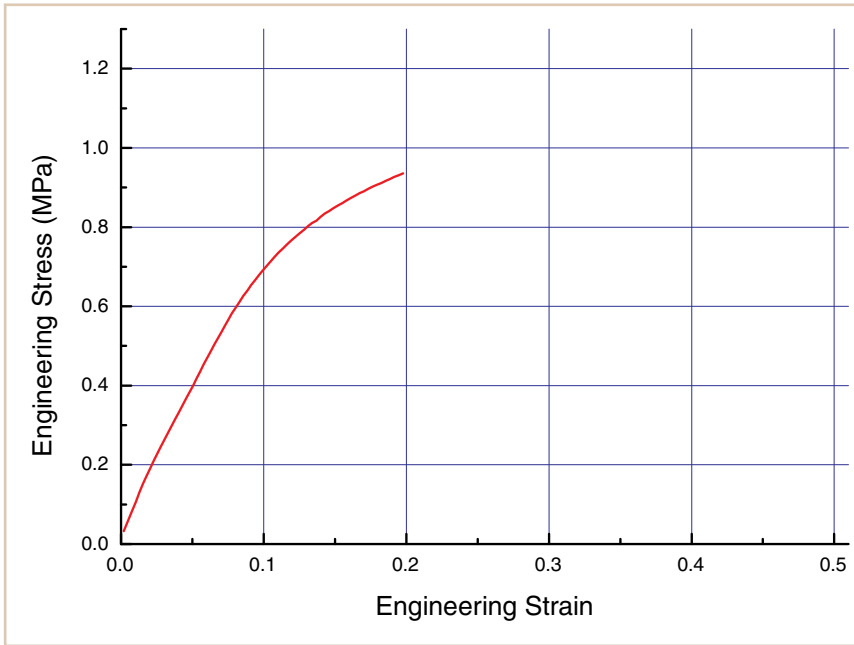
Figure 11, 1st Loading of a Thermoplastic Elastomer

behavior, called viscoelastic, is typically modeled separately from the hyperelastic behavior.

A simple loading experiment where a specimen is stretched to a set strain and allowed to relax may be performed to provide sufficient data to model this behavior. The material data is typically fitted using a Prony Series expansion. The accuracy with which this may be fitted is sensitive to the number of decades of time data. This means that the relaxation data from .1 second to 1 second is just as valuable to the fit as the relaxation data from 1 second to 10 seconds and so on. As such, proper data collection early in the experiment can provide several decades of time data without running the experiment over several days.

There are many other loading patterns used to develop stress strain curves for input into the fitting routines of analysis software. Sets of relaxation curves may be used to create stabilized data sets, dynamic vibrations may be superimposed on relaxation data[8], and all of the loading patterns above can be performed across a broad range of temperatures.
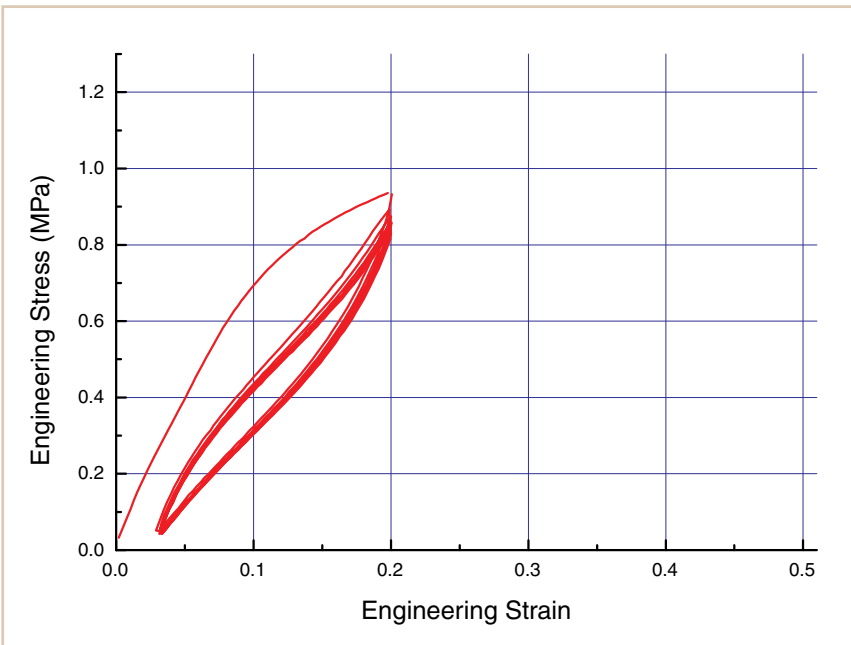
Data Reduction Considerations

Figure 12, Multiple Strain Cycles of a Thermoplastic Elastomer

The stress strain experimental data may need to be modified for input into curve fitters. Most curve fitters use engineering strain and engineering stress input files. If the first time stress strain curves are used, the data reduction is straightforward. The only modification needed might be to reduce the number of data points so that the curve fitter can handle the data set.

If a stabilized loading is going to be used, then several steps are needed. First, a piece of the data needs to be cut from a larger data set. In addition to reducing the number of data points in the data set, corrections need to be made because the stress strain "slice" has a nonzero initial strain. The strain zero needs to be shifted, the strain needs to be corrected for a new larger starting gage length, and the stress needs to be modified for a new cross sectional area.

Summary

Physical testing of elastomers for the purpose of fitting material models in finite element analysis requires experiments in multiple states of strain under carefully considered loading conditions. The material models themselves have limitations and these limitations must also be considered. Fortunately, the actual shapes of the test specimens can be examined and verified using analysis.

References:

1. Dalrymple, T. Experimental Elastomer Analysis Course Notes, Ann Arbor, Michigan, January, 1998.

2. Timoshenko, S.P. Theory of Elasticity (3rd Ed.), McGraw-Hill, New York, NY, 1970.

3. Wolf, D. and Miller, K. "Experimental Elastomer Analysis", Presented at a meeting of the Rubber Division, American Chemical Society, Orlando, Florida, September 21-24, 1999.

4. Day, J. "A Method for Equibiaxial Stretching of Elastomeric Sheets", HKS Michigan Update Seminar and Users' Meeting, Novi, Michigan, November 16, 1999.

5. Mullins, L. "Softening of Rubber by Deformation," Rubber Chemistry and Technology, Vol. 42, pp. 339-362, 1969.

6. Gent, A.N. Engineering with Rubber, Oxford University Press, New York, NY, 1992.

7. Ferry, J.D. Viscoelastic Properties of Polymers (2nd Ed.), John Wiley & Sons, New York, NY, 1970.

8. Morman, Jr., K. N. and Nagtegaal, J. C. Finite Element Analysis of Sinusoidal Small-Amplitude Vibrations in Deformed Viscoelastic Solids. Part I. Theoretical Development, International Journal for Numerical Methods in Engineering, Vol. 19, pp.1079-1103 (1983)
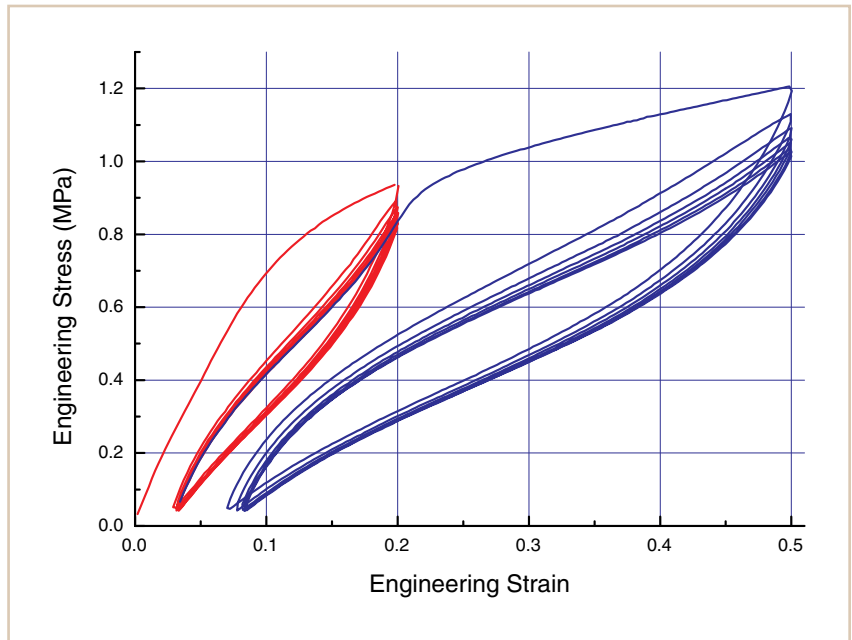
Figure 13, Multiple Strain Cycles of a Thermoplastic Elastomer at 2 Maximum Strain Levels

For more information, visit www.axelproducts.com.

Axel Products provides physical testing services for engineers and analysts. The focus is on the characterization of nonlinear materials such as elastomers and plastics.

Axel Products, Inc.

2255 S Industrial
Ann Arbor MI 48104
Tel: 734 994 8308
Fax: 734 994 8309
info@axelproducts.com

axel
physical testing services