Testing and Analysis

Cyclic Loadings RevC, April 2001

Using Slow Cyclic Loadings to Create Stress Strain Curves for Input into Hyperelastic Curve Fitting Routines

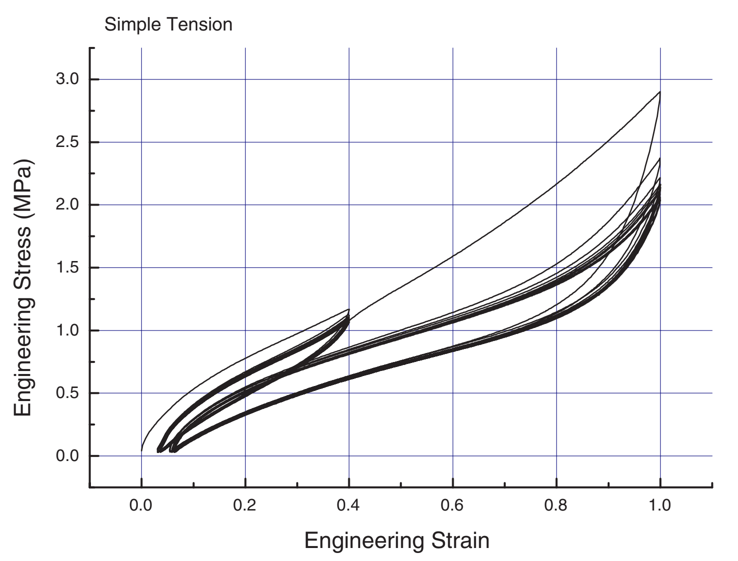

Figure 1: Cyclic Loading of Natural Rubber

Introduction

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 Mullin's effect[1]. If an elastomer is loaded to a set 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 set strain maximum.

If the elastomer is taken to a new higher strain maximum, the structural properties will again change significantly. This behavior is documented throughout the literature.[2] One example of this behavior is shown in Figure 1 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 Figure 4 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 the behavior in Figure 1 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 experienced.
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.

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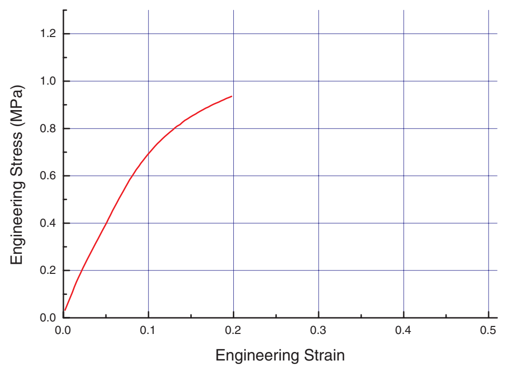


Figure 2: 1st Straining of a Thermoplastic Elastomer

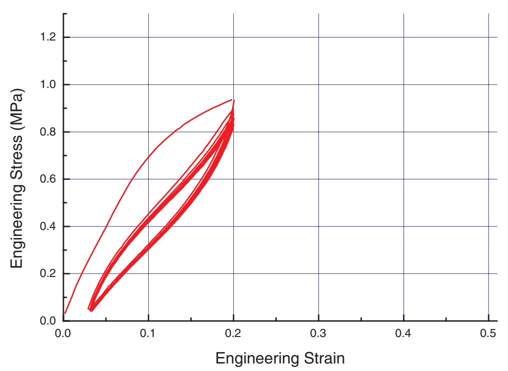


Figure 3: Multiple Strain Cycles of a Thermoplastic Elastomer

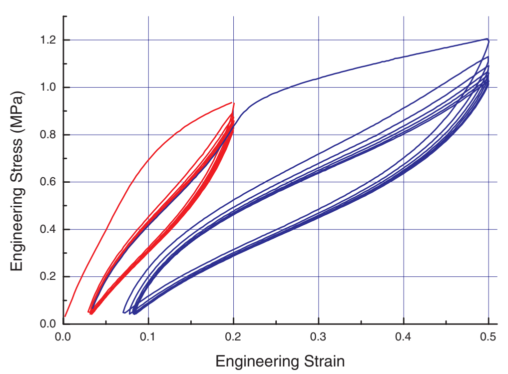


Figure 4: Multiple Strain Cycles of a Thermoplastic Elastomer at 2 Maximum Strain Levels

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.

These models generally require the fitting of experimental stress strain curves, preferably in multiple states of strain. For reasons beyond the scope of this document, simple tension, planar tension (pure shear) and biaxial extension are the most desirable experimental states of strain.

Limitations related to testing are as follows:

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 to 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 a couple different levels to cover a broader range of performance and to measure just how sensitive the structural properties are to maximum strain levels.

Data Reduction Considerations

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 might be to reduce the number of data points so the curve fitter can handle the data set.

If a stabilized loading is going to be used, then a piece of the data needs to be cut from a larger data set. In addition to reduce the number of data points in the data set, corrections need to be made because the stress strain "slice" has non zero initial stress and strain points. The following alterations need to occur:

1. Slice out the selected loading path.
2. Subtract and note the offset strain.
3. Divide all strain values by (1 + Offset Strain) to account for the "new" larger stabilized gage length.
4. Multiply all stress values by (1+ offset strain) to account for "new" smaller stabilized cross sectional area.
5. The first stress value should be very near zero but shift the stress values this small amount so that zero strain has exactly zero stress.
6. Decimate the file by evenly eliminating points so that the total file size is manageable by the particular curve fitting software.

File Name and Content Conventions

The data file name conventions used are as follows:

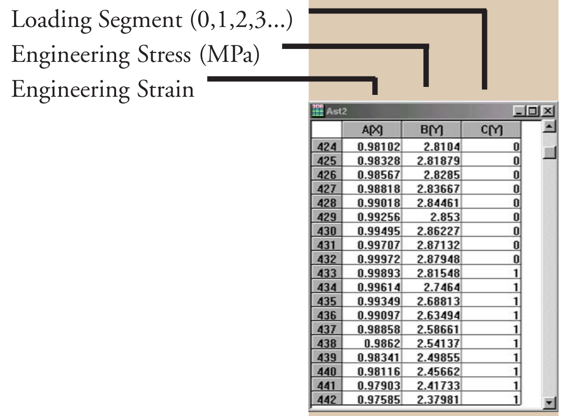
MaterialName
_StrainState_Temperature_SpecimenRepetionNumber_LoadingSegment

For example:

File name 215eb23C1S18 is material 215, eb represents the equal biaxial state of strain, 23C is the test temperature, 1 represents the 1st specimen repetition for this experiment, S18 represents the 18th loading segment from the experiment.

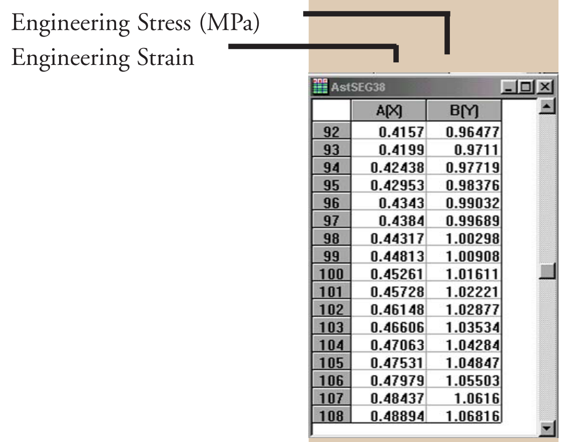
Strain States include eb:equal biaxial, pt:planar tension (pure shear), st:simple tension and vc:volumetric compression

A typical data file from the experiment is shown in Figure 5. The extracted data set from a particular loading is shown in Figure 6. Figure 7 shows the original experimental loading as well as extracted and reduced stress strain curves for the stabilized loadings to 40%



	A(X)	B(Y)	C(Y)
424	0.98102	2.8104	0
425	0.98328	2.81879	0
426	0.98567	2.8285	0
427	0.98818	2.83667	0
428	0.99018	2.84461	0
429	0.99256	2.853	0
430	0.99495	2.86227	0
431	0.99707	2.87132	0
432	0.99972	2.87948	0
433	0.99893	2.81548	1
434	0.99614	2.7464	1
435	0.99349	2.68813	1
436	0.99097	2.63494	1
437	0.98858	2.58661	1
438	0.9862	2.54137	1
439	0.98341	2.49855	1
440	0.98116	2.45662	1
441	0.97903	2.41733	1
442	0.97585	2.37981	1

Figure 5: Experimental Data Format



	A(X)	B(Y)
92	0.4157	0.96477
93	0.4199	0.9711
94	0.42438	0.97719
95	0.42953	0.98376
96	0.4343	0.99032
97	0.4384	0.99689
98	0.44317	1.00298
99	0.44813	1.00908
100	0.45261	1.01611
101	0.45728	1.02221
102	0.46148	1.02877
103	0.46606	1.03534
104	0.47063	1.04284
105	0.47531	1.04847
106	0.47979	1.05503
107	0.48437	1.0616
108	0.48894	1.06816

Figure 6: Reduced Extracted Data Format

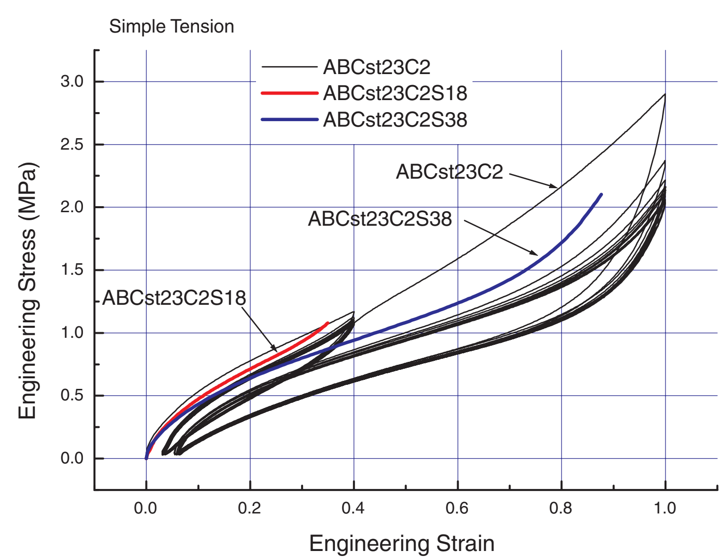


Figure 7: Cyclic Loading of Natural Rubber with Reduced Extracted Data Overlaid

and 100%.

Relaxation and Vibrations

An elastomer subjected to a constant strain will relax. This means that the stress will decay over time. The slow cyclic straining discussed herein will not predict this behavior. Separate experiments to measure this behavior are necessary[2].

Elastomers often experience high frequency vibrations superimposed on quasi-static loads. The examination of this dynmaic behavior also requires additional experiments[3].

Strain States

Although the primary purpose of this document is to discuss a particular loading approach to testing, images of common strain states are shown in Figure 8, Figure 9,

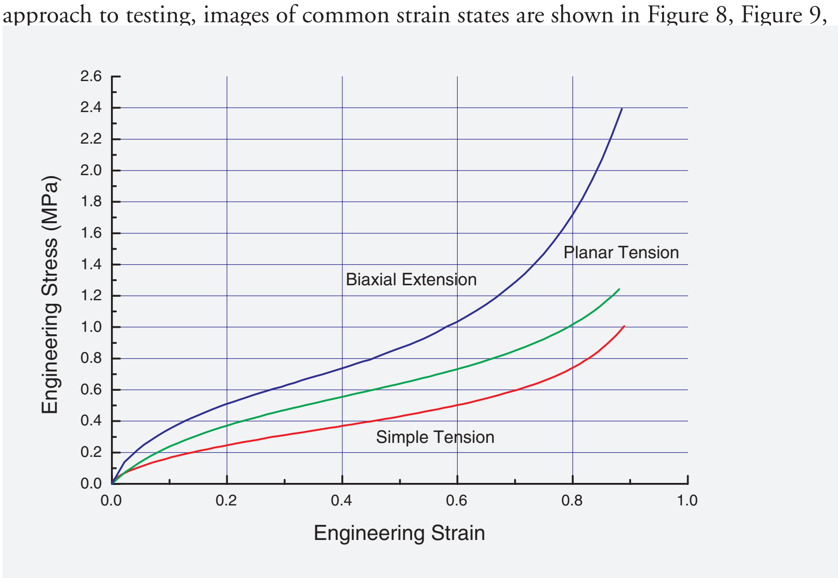


Figure 11: 3 Reduced Data Sets Prepared for Analysis

fitting software is shown in Figure 11.

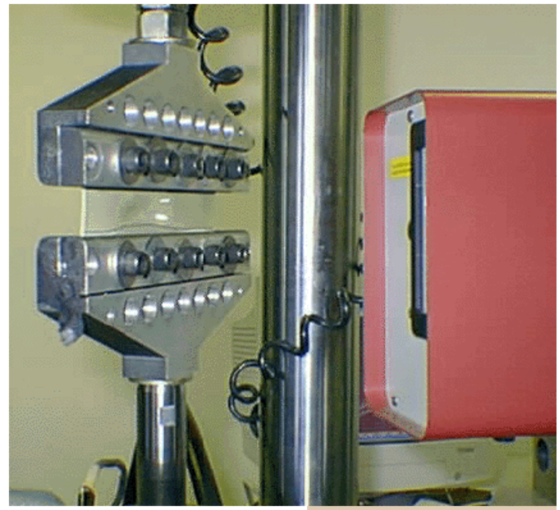


Figure 8: Planar Tension Test with Laser Extensometer

Figure 9: Biaxial Extension

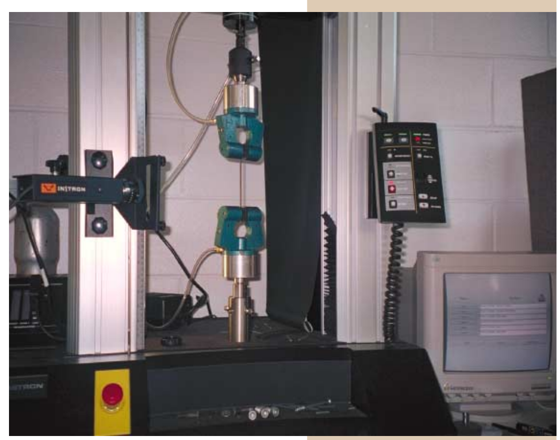


Figure 10: Simple Tension Test with Video Extensometer

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1. Mullins, L. "Softening of Rubber by Deformation," Rubber Chemistry and Technology, Vol. 42, pp. 339-362, 1969.
2. Gent, A.N., Engineering with Rubber, Oxford University Press, New York, NY, 1992.
3. Ferry, J.D. Viscoelastic Properties of Polymers (2nd Ed.), John Wiley & Sons, New York, NY, 1970.
4. Mormon, K.N. and J.C. Nagtegaal. "Finite Element Analysis of Sinusoidal Small-Amplitude Vibrations in Deformed Viscoelastic Solids," Int. J. Numerical Methods in Engineering, Vol. 19, No.7, pp. 1079-1103, 1983.

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