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MECHANICAL TESTS FOR VALIDATION OF SEISMIC ISOLATION ELASTOMER CONSTITUTIVE MODELS

R. F. Kulak, and T. H. Hughes
Reactor Engineering Division
Argonne National Laboratory
Argonne, Illinois

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ABSTRACT

High damping laminated elastomeric bearings are becoming the preferred device for isolating large buildings and structures, such as nuclear power plants. The key component of these bearings is a filled natural rubber elastomer. This material exhibits nonlinear behavior within the normal design range. The material damping cannot be classified as either viscous or hysteritic, but it seems to fall somewhere in between. This paper describes a series of tests that can be used to characterize the mechanical response of these elastomers. The tests are designed to determine the behavior of the elastomer in the time scale of the earthquake, which is typically from 30 to 60 seconds. The test results provide data for use in determining the material parameters associated with nonlinear constitutive models.

INTRODUCTION

Seismic base isolation is accepted by civil engineers as a viable strategy for protecting structures from earthquake damage. The main benefits are: (1) the elimination of damage to the civil structure, (2) the reduction in damage to contents, and (3) the ability to save lives. In contrast, the traditional methods for seismic design (i.e. seismic hardening) may leave the structure standing. However, the internal contents may be severely damaged and the occupants may be subjected to injuries or loss of life. The traditional approach may lead to a long loss of time and costly repairs.

On a worldwide basis, the use of seismic base isolation has been increasing rapidly for such critical facilities as computer centers, medical centers, and emergency control facilities. The Western United States has several buildings that employ seismic isolators. On a global domain, Japan has been the most aggressive in adapting isolation to their structures. Now, more than fifty buildings use or plan to use seismic isolation. Currently there are two French designed nuclear power plants; one is located in Cruas-Meysee, France and the other in Koeberg, South Africa. From the various devices proposed for seismic isolators, the laminated elastomer bearing is emerging as the preferred device for large buildings/ structures (i.e., no more than eight stories in height). The laminated bearing is constructed from alternating thin layers of elastomer and metallic plates (shims). The elastomer is usually a carbon filled natural rubber that exhibits damping when subjected to shear. Recently, some blends of natural and synthetic rubbers have appeared.

The first part of this paper looks at several constitutive models that are available for modelling the nonlinear elastic and hysteretic behavior of the elastomer. Next several definitions for shear stiffness and damping ratio are examined. This is followed by a discussion of mechanical characterization testing of the elastomer. Before candidate elastomers can be used in seismic isolation bearings, their response to design-range loads and beyond design-range loads must be determined. Specimen testing should be divided into two categories. In the first category, measurements of the mechanical properties that are specified in the Technical Specifications are made. Thus, this class of testing is for quality assurance of the elastomer produced by the rubber compounder. The second category of tests are performed to determine the response of the elastomer under earthquake-type loading conditions.

CONSTITUTIVE MODELS

The constitutive model used to represent the elastomer in the bearing is perhaps the most important ingredient to a successful analysis. Bearing elastomers are typically nonlinear hysteretic materials. However, for preliminary studies it is often economical to perform nonlinear elastic analysis. Most currently used finite element programs use a strain-energy function, W, based upon Mooney-Rivilin (1940) and Blatz-Ko (1962) formulations. For example, the compressible form for the Mooney-Rivilin model is given by

$$W = K_1(J_1 - 3) + K_2(J_2 - 3) + 1/2\ \kappa\ (J_3 - 1)^2 2 \qquad (1)$$

where J_1, J_2 and J_3 are modified stretch invariants and κ is the bulk modulus. The above forms of the strain-energy function are derived on the basis of uniaxial and biaxial tests. Also, it is known that they are only valid for stretch ratios in the range of 1.1 to 2.2. Thus, the use of these forms beyond the design range is questionable. The laminated elastomeric bearing will be subjected to a combination of compressive and shear forces during a seismic event.

Several constitutive models have been proposed to simulate the behavior of elastomeric materials. Koh and Kelly (1985) use a fractional derivative representation, and Simo and Taylor (1985) use a viscoelastic model with damage effects. In the Simo-Taylor model, the deviatoric viscoplastic stress tensor, S_{ij}, is given by

$$S_{ij} = \int_{-\infty}^{t} [G_\infty + (G_o - G_\infty) e^{-(t-s)/\nu}] \dot{\pi}_{ij}(s) ds \qquad (2)$$

where K is the bulk modulus, J the determinant of the deformation gradient, δ_{ij} the identity tensor, G_∞ and G_o the long term and short term shear moduli, respectively, t is the time, and ν is the relaxation time constant. The strain history function is expressed by

$$\pi_{ij}(s) = \left[\beta - (1-\beta) \frac{1-e^{\psi_s/\alpha}}{\psi_s/\alpha} \right] \text{dev } \bar{C}_{ij}(s) \qquad (3)$$

where α and β are material parameters, ψ is the damage parameter, and $\bar{C}_{ij}$ is the volume preserving right Cauchy strain tensor. Equations 1 and 2 identify six material parameters that must be obtained from specimen tests, namely: K, G_o, G_∞, α, ν, and β.

SHEAR STIFFNESS

A key mechanical property that determines the fundamental horizontal frequency of a base isolated system is the shear stiffness of the isolator. Because of the relatively high shear modulus of the steel, it is the shear modulus of the elastomer that determines the shear stiffness of the bearing. However, there are several different forms being used to define this quantity. One form is the storage modulus, G', which is given by

$$G' = \frac{\tau(\gamma^{+}_{max}) - \tau(\gamma^{-}_{max})}{\gamma^{+}_{max} - \gamma^{-}_{max}} \qquad (4)$$

where γ^+_{max} and γ^-_{max} are the maximum positive and negative shear strains, respectively, that occur during a complete hysteresis loop, and $\tau(\gamma^+_{max})$ is defined to be the shear strain at γ^+_{max}.

Another form that is popular is the so-called effective shear modulus, G_{eff}, given by

$$G_{eff} = \frac{\Delta\tau}{\Delta\gamma} = \frac{\tau^+_{max} - \tau^-_{max}}{\gamma^+_{max} - \gamma^-_{max}} \tag{5}$$

where τ^+_{max} and τ^-_{max} are the maximum positive and negative shear stress, respectively. Note, for rounded loops, typical at the lower strain levels, Eqs. 5 and 6 give values that can differ by about 12 percent. For pointed tip loops, which occur at higher strains, the values calculated by both equations are nearly the same. Since the value of the stiffness is used in the computation of the damping factor, the choice of the stiffness form will affect the value of that quantity. Note, the values needed for Eq. 5 can be determined with greater accuracy.

It is necessary that the form chosen for the shear modulus be explicitly spelled out in the technical specifications for the rubber compound. Otherwise, the compounder may take the liberty to choose his definition and produce an elastomer with unacceptable engineering properties.

DAMPING RATIO

Another quantity used to characterize elastomers is the damping ratio, ζ. Here again there is not a unique method for determining its value from experimental data. For example, a popular formula for the damping ratio is

$$\zeta = \frac{U_D}{4\pi G'\gamma^2_{max}} \; ; \quad U_D = \oint_0^{2\pi/\omega} \tau\dot{\gamma}dt \; ; \quad G' = \frac{\tau(\gamma_{max})}{\gamma_{max}} \tag{6}$$

where U_D is the energy dissipated per cycle (i.e., the area within the hysteresis loop), G' the storage modulus, γ the shear strain, and τ the shear stress. Note, the storage modulus is defined to be the stress at the maximum strain. The above definition is obtained from a linear viscoelastic model and works well for those materials. It also provides reasonable values for elastomers at strain levels below 100 percent, the range where the hysterisis loops are elliptical. However, at higher levels the loops are no longer elliptical and Eq. 7 gives misleading results. To obtain more reasonable values for the damping ratio, the following definition can be used

$$\bar{\xi} = \frac{U_D}{2\pi U_S} \quad ; \quad U_s = \int_0^{\gamma_m} \bar{\tau} d\gamma \tag{7}$$

Here $\bar{\tau}$ defines the average value of the hysteresis loop at a fixed strain level. Thus, the $\bar{\tau}$ curve bisects the hysteresis loop and represents a pseudo elastic response curve. It should be noted that for linear viscoelastic materials, the $\bar{\tau}$ curve approximates the storage modulus line.

TESTING ENVIRONMENT

The elastomer testing facility at Argonne National Laboratory is set up for high precision dynamic testing of small coupon specimens. The laboratory contains two Instron universal testing machines of the 8500 series. These machines have digital electronic controls using the latest technology for dynamic testing. Both machines have identical 55 kip load frames and interchangeable load cells and holding fixtures. One of the machines has a 22 kip electro-mechanical actuator for quasistatic testing and the other machine has a 5 kip hydraulic actuator with a 6 gallon-per-minute hydraulic power supply for dynamic testing. Both machines are connected to 386DX computers that can be programmed for test control, data acquisition and data processing. At present the hydraulic machine is set up to perform shear tests on three bar specimens (Fig. 1) either of a stress relaxation type or cyclic testing up to 375% strain using a 5 mm thick specimen. Frequencies up to 100 Hz can be handled at very low strain levels. Two sample points on the system performance limiting curve would be 5 mm cyclic amplitude at 10 Hz and 40 mm at 1 Hz. A temperature cabinet is available and will be installed so these shear tests can be performed over a temperature range of -100°F to 400°F. Work is currently underway to develop the capability to perform biaxial shear-compression tests. In this case the hydraulic machine will apply the compressive loads and the electronics from the other machine will control an actuator/load cell combination that will apply the shear loading.

Small samples of the elastomer were tested in shear to obtain the mechanical data required to characterize the elastomers and to validate the constitutive model. The PC computer program used to interface with the operator and analyze the data was written specifically for this type of elastomer testing by one of the authors.

of increasing strain levels followed by a series of decreasing strain levels. The specimen was subjected to six cycles of an increasing strain sequence (±5, ±10, ±20, ±50, ±100, ±150 percent) immediately followed by six cycles of a decreasing strain sequence (±100, ±50, ±20, ±10, ±5 percent). Table 1 gives the values for stiffness during the increasing strain sequence, decreasing strain sequence, and the average of the two. It was noticed that the stiffness at a specific strain level is always less during the down sequence than during the up sequence. Also, the percent difference is greater at the lower strain levels.

Table 1. Difference in Secant Modulus Between the Up Sequence and Down Sequence

Strain (%)	Up	Down	Average
5	343	312	327
10	266	248	257
20	207	196	201
50	146	140	143
100	116	112	114
150	121	121	121

The next test was performed to determine the variation in stiffness and damping with frequency. The specimens were tested at the following frequencies: 0.01, 0.1, 0.5, 0.8, 1, 5, and 10 Hz. The maximum strain at each frequency was limited by the performance envelope of the testing machine. For example, the 5 percent strain tests were performed at all frequencies, and the 150 percent strain tests were performed only up to 1.0 Hz. Figures 5 and 6 show the frequency dependence of the stiffness and damping. It is noted that for the seismic isolation system design frequency range (0.4 to 1.0 Hz), the variations in stiffness and damping are small. Also, these variations indicate that the material damping is close to being hysteretic.

Relaxation tests were performed to determine the elastomer's behavior under constant strain. A shear strain was applied to the specimen and held for 36 seconds. The resulting stress relaxation is shown in Fig. 7. It is seen that the stress drops rapidly from its initial value. Figure 8 shows the effect that "scragging" has on the relaxation behavior.

ACKNOWLEDGMENTS

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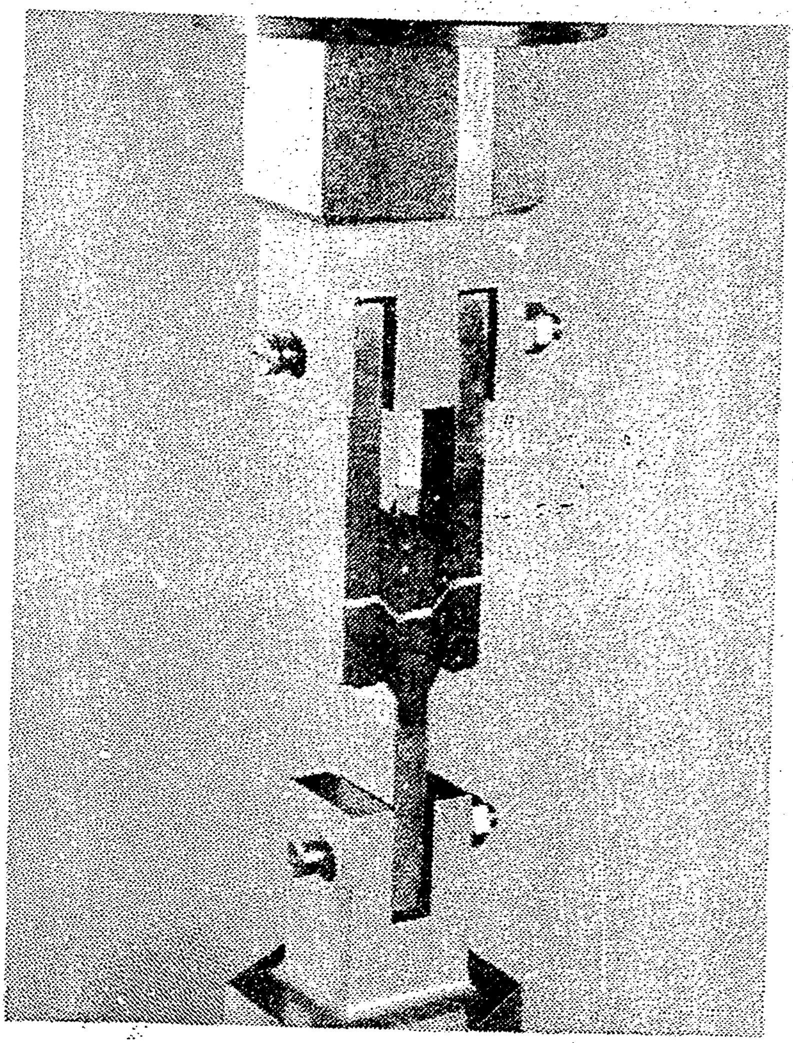

Fig. 1. Three-Bar Shear Specimen

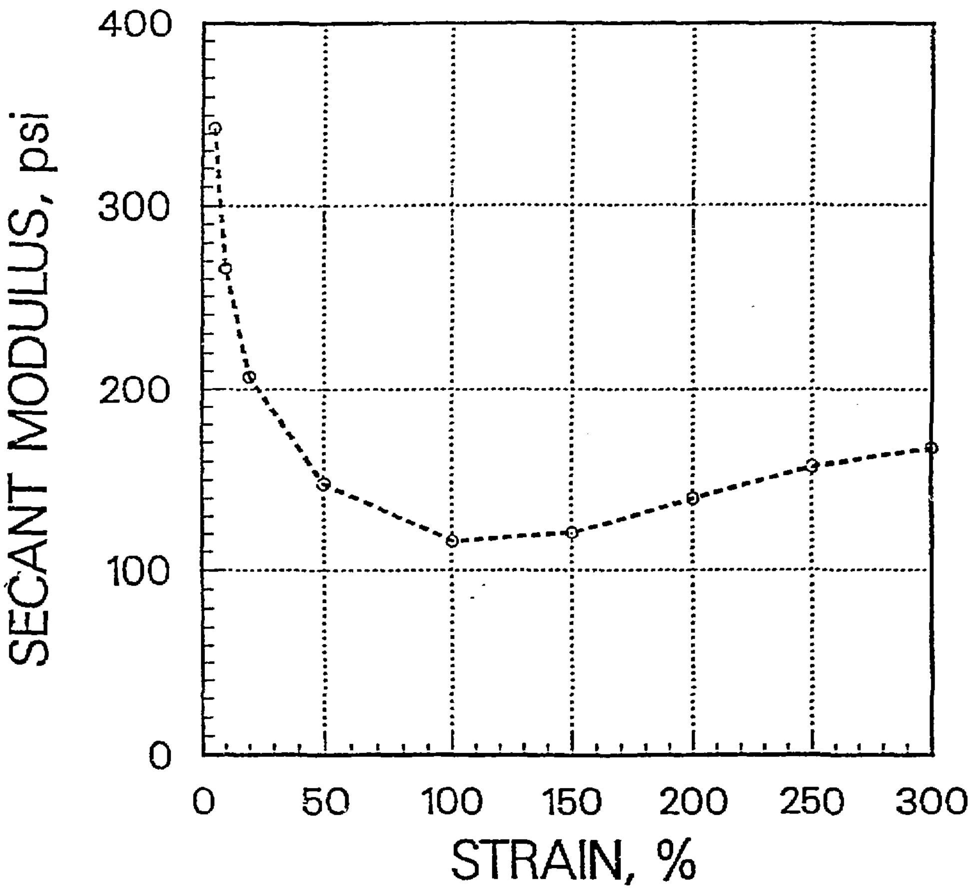

Fig. 2. Variation in Stiffness with Shear Strain

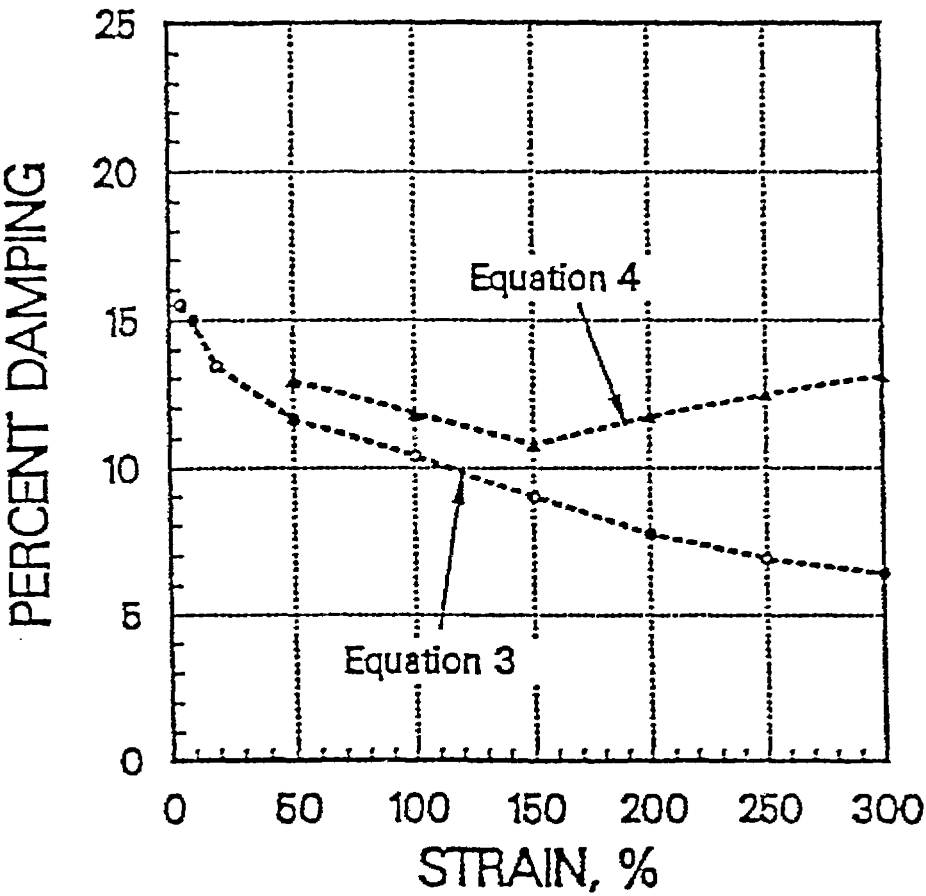

Fig. 3. Variation in Damping with Shear Strain

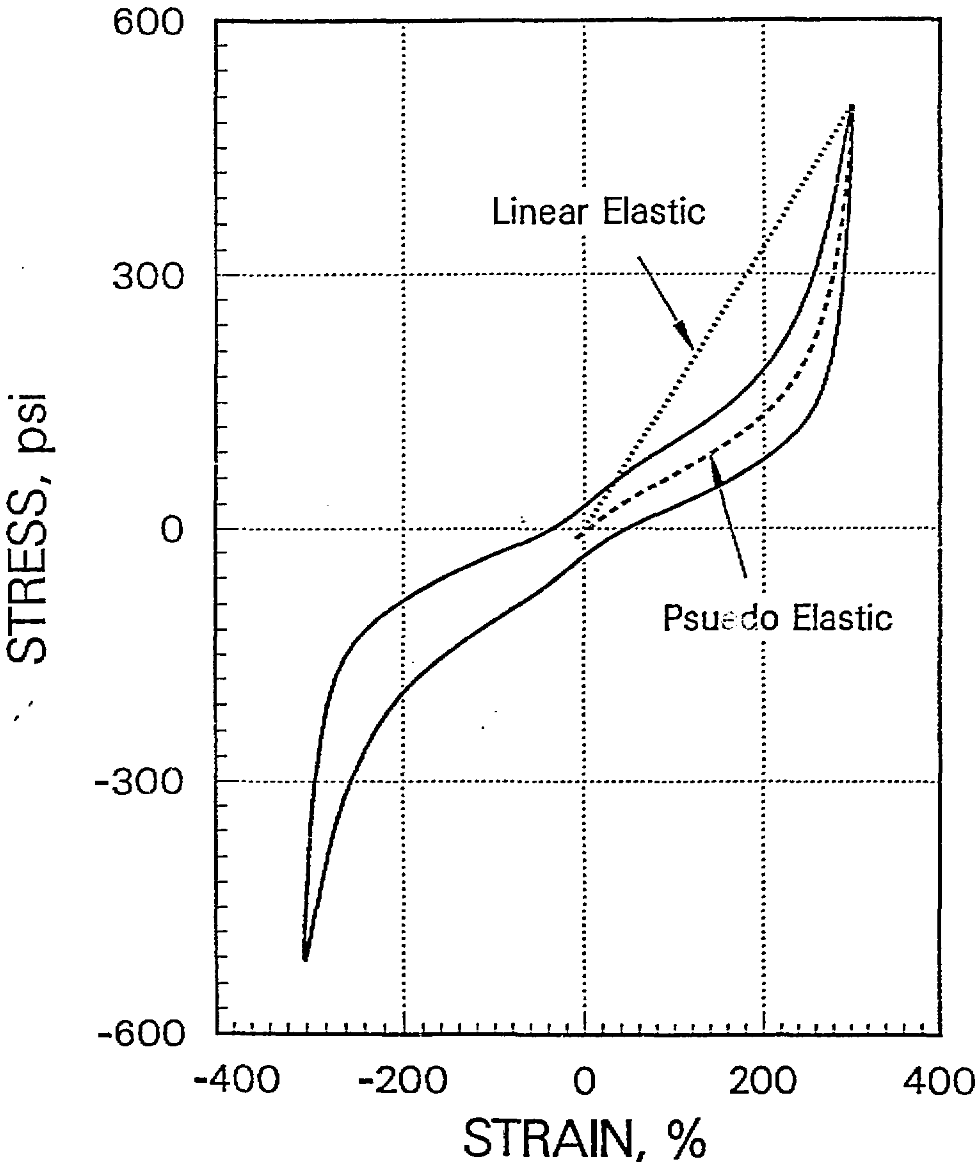

Fig. 4. Hysteresis Loop for 300 Percent Shear Strain

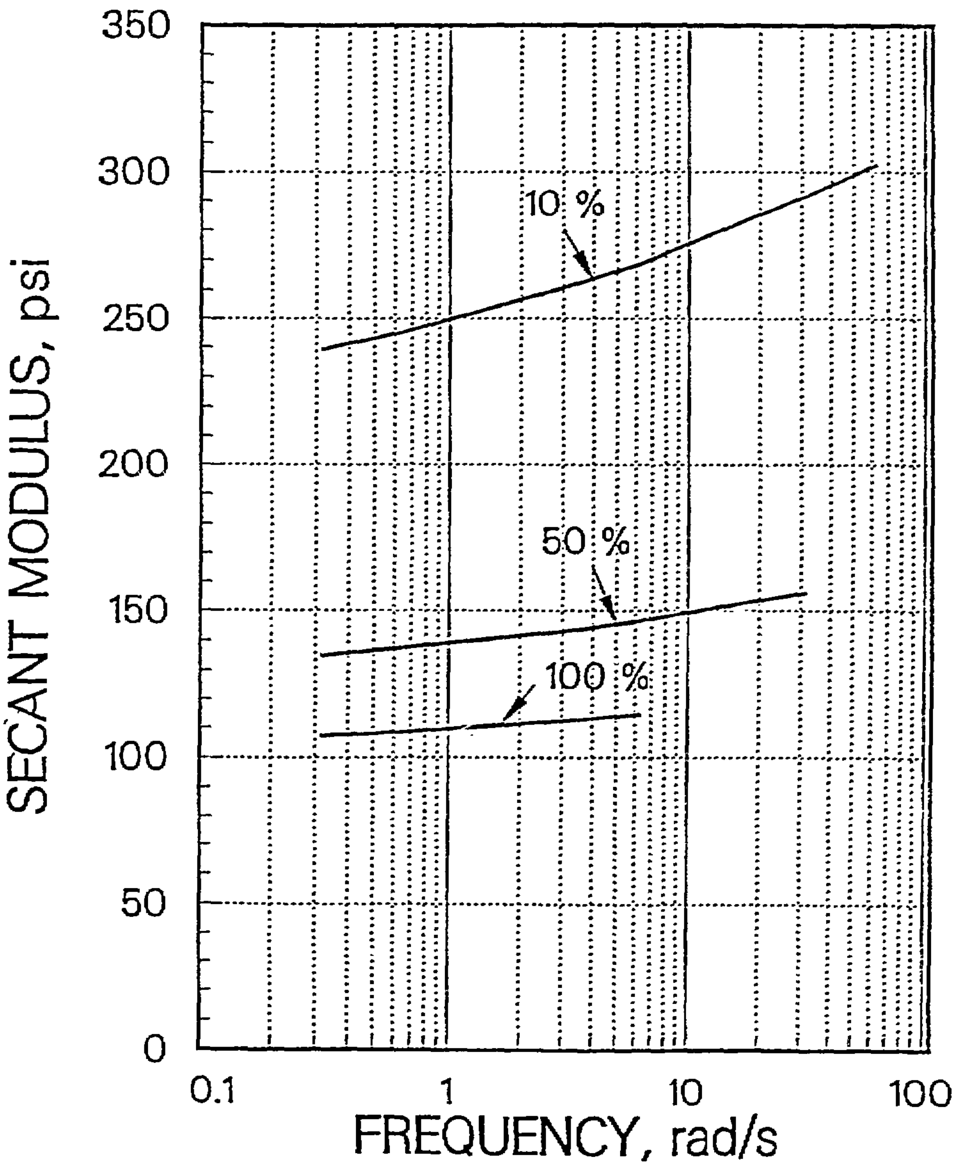

Fig. 5. Variation in Stiffness with Frequency and Strain Level

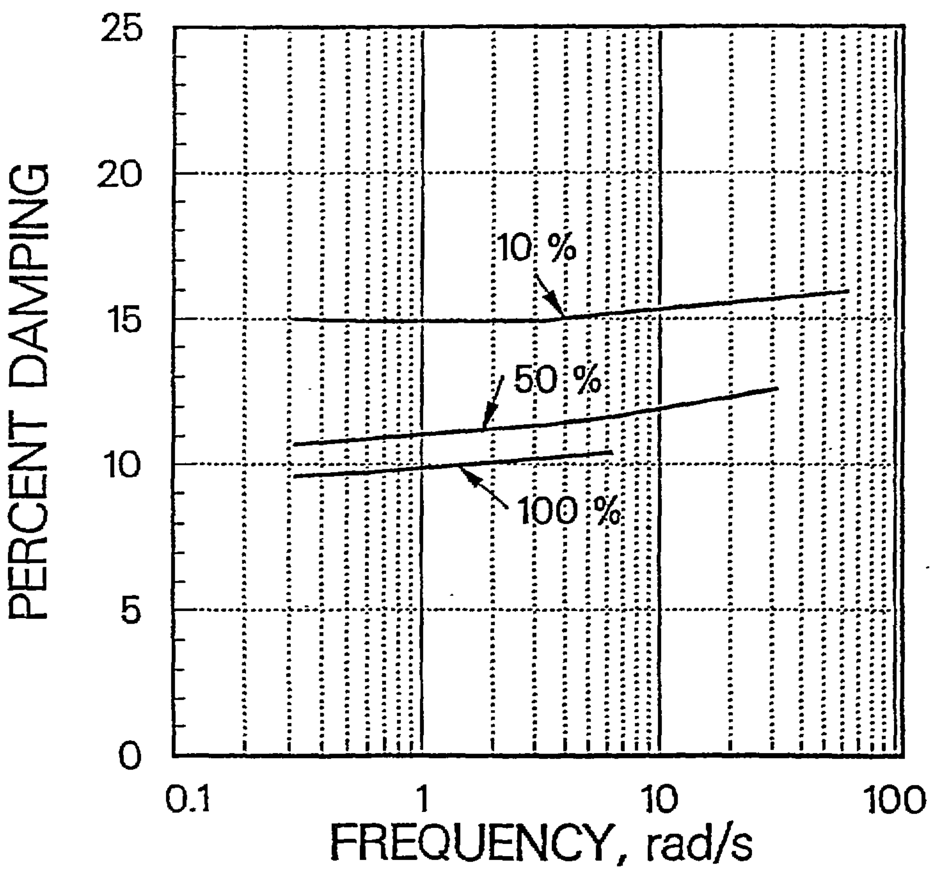

Fig. 6. Variation in Damping with Frequency and Strain Level

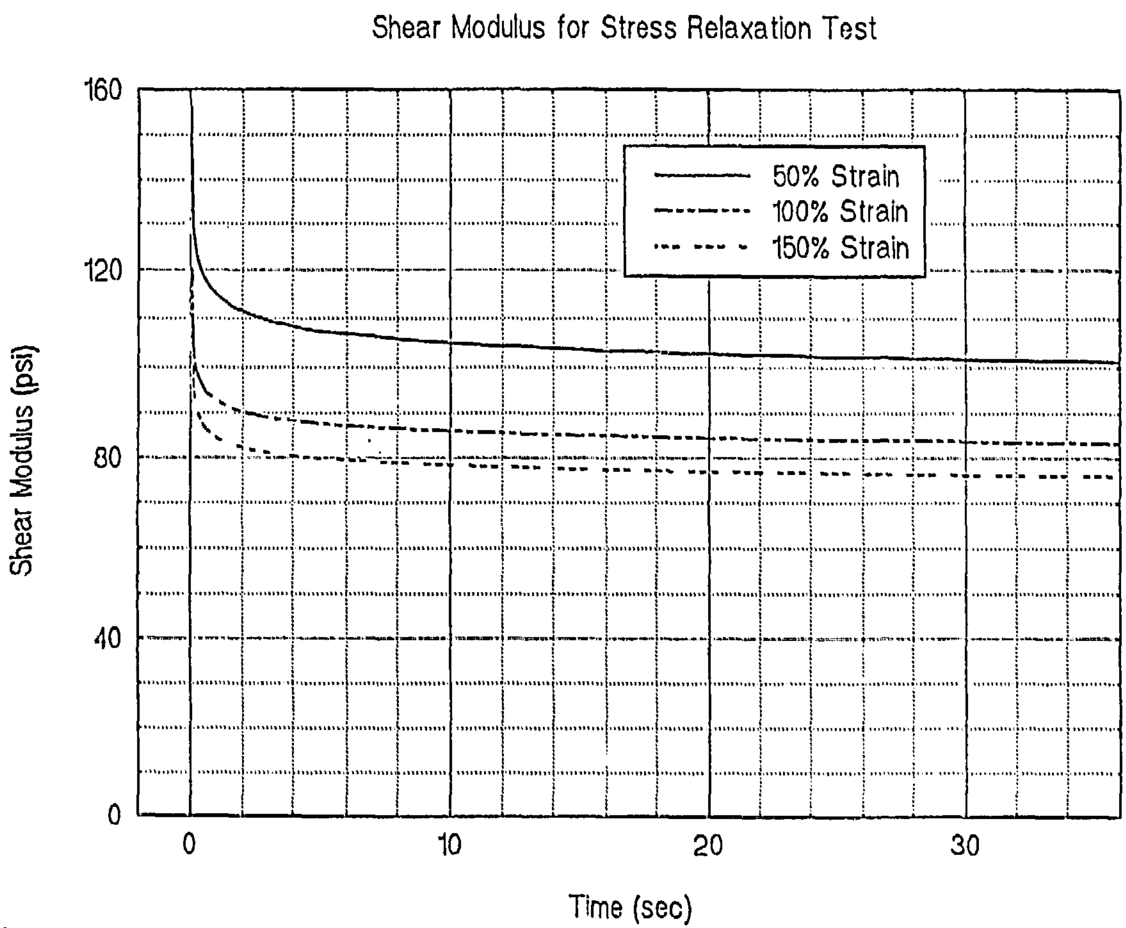

Fig. 7. Stress Relaxation at 50, 100, and 150 Percent Shear Strain

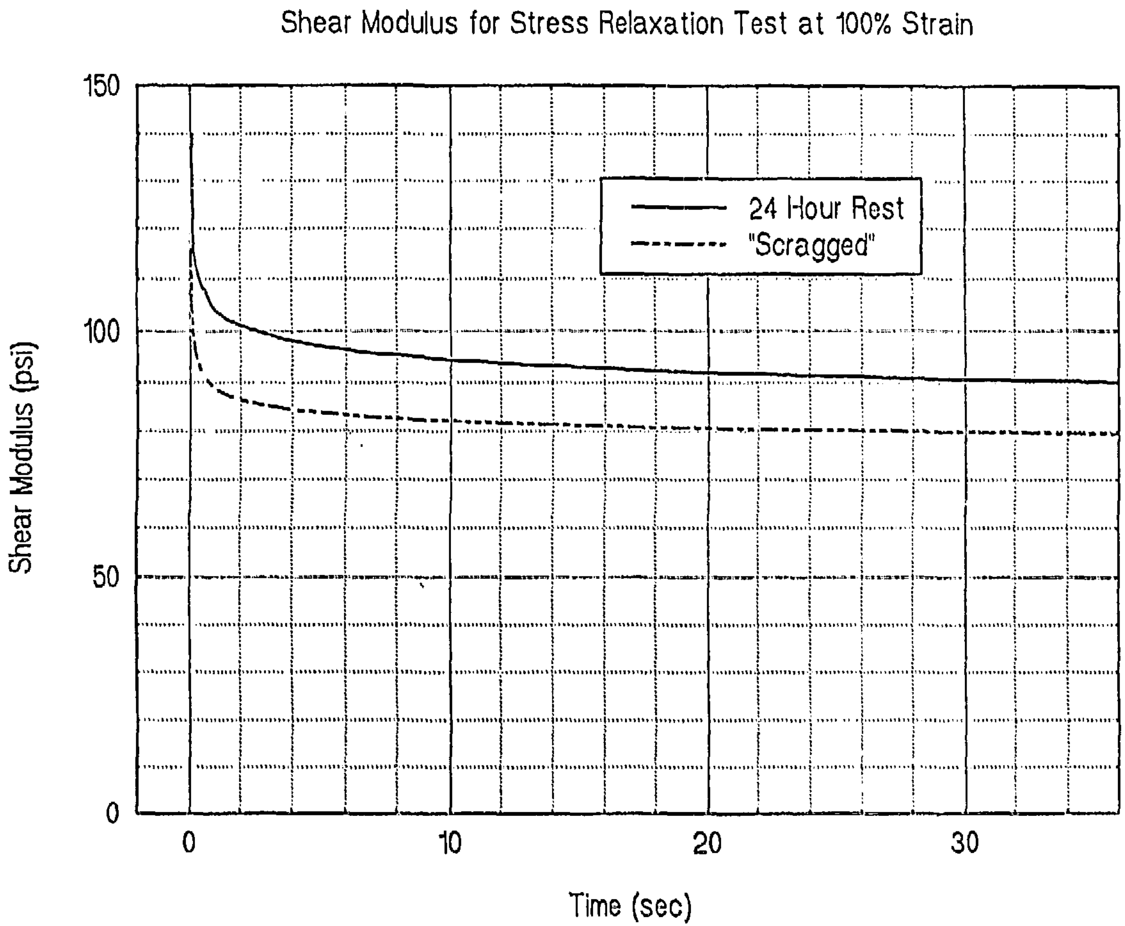

Fig. 8. Effect of Scragging on Stress Relaxation at 100 Percent Shear Strain