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# VISCOELASTIC DAMPER:
# A DAMPER WITH LINEAR OR NONLINEAR MATERIAL?

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## ABSTRACT

Viscoelastic dampers consisting of viscoelastic material (VEM) bonded to steel plates have been tested in many laboratories in the United States, Japan and Taiwan and installed in several large buildings structures to reduce seismic and wind responses (Nielsen, *et al.*, 1994). It is known that the VEM properties vary with the ambient temperature and loading frequency. Consequently, the viscoelastic damper is designed to operate at the ambient temperature and fundamental frequencies of the structure (Chang, *et al.*, 1995). In addition, it has been recognized that the VEM exhibits an *apparent* nonlinear behavior when it is subjected to high strain loading. A linearization technique such as time-averaged treatment is usually used to calculate the VEM shear moduli that represent the mechanical property of the VEM. The VEM moduli calculated in this manner decrease as the strain increases. Since the loading strain in the VEM varies in time, especially for seismic loading, a common question that arises for the designer is what VEM modulus value at which strain level should they use for design and analysis? In addition, there is no standardized linearization methods in calculating the large strain VEM moduli.

This study indicates that in an acrylic-based VEM designated as 3M Brand ISD 110, most of the *apparent* non-linearity can be accounted for by the temperature rise, which results from heat generation in the VEM during dynamic loading. It is then proposed that the VEM in a large range of strain can be characterized in a meaningful way by using small strain modulus data which are linear along with a proper compensation of the temperature rise effects. This finding is important since it can greatly simplify VEM characterization as well as the damper design and analysis procedure for structures.

## KEYWORDS

Viscoelastic damper; energy dissipation device; damping.; nonlinear

## LINEAR VISCOELASTIC THEORY FOR SMALL STRAINS

When a VEM is under a sinusoidal shear stress $\tau(t)$ with a frequency $\omega$, the shear strain $\gamma(t)$ will lag behind the stress by a phase angle $\delta$ as:

$$\tau(t) = \tau_o \sin(\omega t) \qquad \text{and} \qquad \gamma(t) = \gamma_o \sin(\omega t - \delta) \tag{1}$$

where $\tau_o$ and $\gamma_o$ are the stress and strain amplitudes respectively. If the strain is plotted against stress, one will obtain an elliptical hysteresis loop.

Viscoelastic material is often characterized by storage, $G'$, and loss, $G''$, shear moduli to represent the elastic and viscous properties respectively (Lai, 1995). The ratio of the loss to storage modulus is the loss factor, $\eta$, or so-called tangent delta ($\tan\delta$) which is used along with $G'$ to describe the material:

$$\eta = \frac{G''}{G'} = \tan\delta \tag{2}$$

$G'$ and $G''$ are related to the stress and strain amplitudes:

$$G' = \frac{\tau_o}{\gamma_o}\cos\delta \qquad \text{and} \qquad G'' = \frac{\tau_o}{\gamma_o}\sin\delta \tag{3}$$

From Eqs. 1 and 3, the stress-strain relationship becomes (Kasai *et al.*, 1993)

$$\tau(t) = G'\gamma(t) \pm G''(\gamma_o^2 - \gamma^2(t))^{1/2} \tag{4}$$

which is an ellipse.

It is convenient to use complex variables to describe the VEM as

$$G^* = G' + jG'' \qquad \text{and} \qquad |G^*| = \frac{\tau_o}{\gamma_o} = (G'^2 + G''^2)^{1/2} \tag{5}$$

where $j = \sqrt{-1}$.

In structural and building applications, a VE damper typically consists of VEM slabs sandwiched between relatively rigid steel plates. The damper configuration is very simple and its operation is straightforward.

The VE damper can be characterized by the storage, $K'$, and loss, $K''$, stiffness and are related to $G'$ and $G''$ as

$$K' = \frac{G'A}{h}, \qquad K'' = \frac{G''A}{h} \qquad \text{and} \qquad \eta = \frac{K''}{K'} \tag{6}$$

where $A$ is the total shear area and $h$ is the thickness of the VEM slab. An important advantage of the VE damper that the damper is linearly scaleable as shown in Eq. 6. The property of a large damper can be linearly predicted by testing a much smaller damper as long as the testing strain, temperature and frequency are kept the same. $K''$ can be further related to the viscous damping constant as

$$c = \frac{K''}{\omega} = \eta\frac{K'}{\omega} \tag{7}$$

where $\omega$ is the damper operating frequency.

## OBSERVATIONS OF NONLINEAR BEHAVIOR AT LARGE STRAINS

Fig. 1 shows shear stress against time for the 3M Brand ISD110 VEM deformed sinusoidally at 12.5%, 25%, 50% and 100% constant strain amplitudes, 23 °C ambient temperature and 1 Hz. Two observations can be made. First, the performance of the VEM is essentially linear as is indicated by the test that among the four curves, the peak stress in the first cycle is almost linearly proportional to the strain amplitude. Second, the material is time-varying as demonstrated by the peak stress in each curve decaying in time, especially for large strain tests. The decay rate was different for each strain amplitude. Therefore the material is *apparently* nonlinear under the test conditions. This decay in stress may be due to temperature rise in the VEM. This decay is not due to the deterioration of the material because the same decay curve can be reproduced after the VEM cools down to the initial temperature. It can be further postulated based on the present test data that the time-varying behavior contributes to the *apparent* nonlinearity when a time-averaged approach is used to calculate the shear moduli for each strain amplitude.

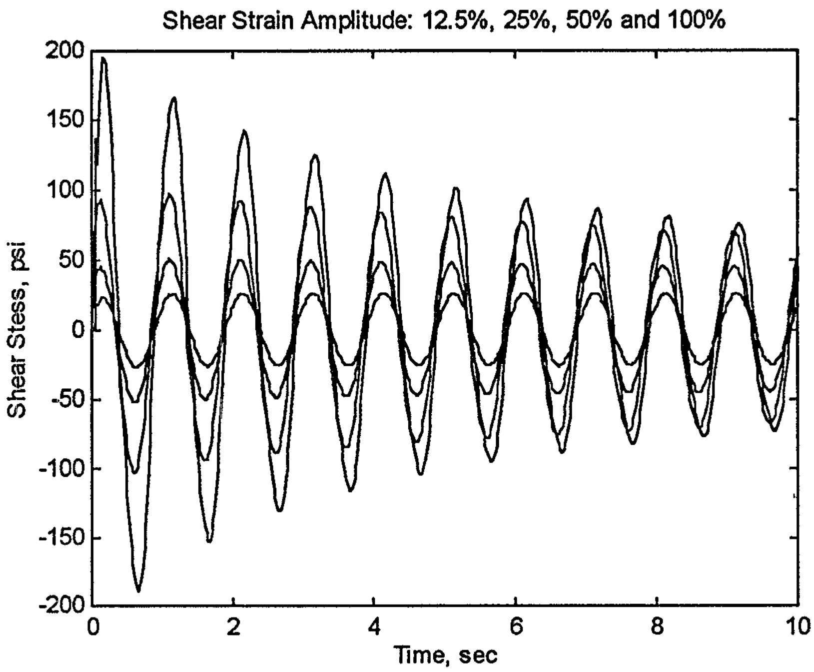


Fig. 1 Damper Shear Stress at 23°C Ambient Temperature, 1 Hz and Various Shear Strain Amplitudes.

## VERIFICATION OF SOURCE OF NONLINEARITY

When the VEM was subjected to a large strain excitation, a portion of the mechanical energy was dissipated, the temperature in the VEM rose as the by-product and the VEM softened. If the temperature rise in the VEM can be "turned" off and the shear stress proportional to the shear strain with no decay in stress with time, then the VEM is *essentially* linear. Unfortunately, it is impossible to "turn" the temperature rise in the VEM off during a test. An indirect test method is proposed as follows: An accurate VEM constitutive model verified by tests is constructed to predict the VEM properties at various strain, loading frequency and ambient temperature values. The temperature rise is then turn off analytically to check whether the VEM is *essentially* linear.

### VEM Constitutive Model

Several VEM constitutive models have been proposed (Koh and Kelly, 1990, Kasai *et al.*, 1993, Tsai, 1993, Shen and Soong, 1995). The fractional derivative model developed by Kasai *et al.*, 1993 was found to be adequate and used in this study. The stress-strain, τ(t)-γ(t) relationship is as follows:

$$\tau(t) + aD^{\alpha}\tau(t) = G[\gamma(t) + bD^{\alpha}\gamma(t)] \qquad (8)$$

where $a$, $b$, $\alpha$ and $G$ are constants to be determined from tests at small strains. Among the four constants, $a$ and $b$ are functions of temperature. Numerical integration is used to evaluate the stress-strain values as:

$$\tau^{(n)} + \frac{a}{(\Delta t)^{\alpha}} \sum_{j=0}^{N} w^{(j)} \tau^{(n-N+j)} = G\left[\gamma^{(n)} \frac{b}{(\Delta t)\alpha} \sum_{j=0}^{N} w^{(j)} \tau^{(n-N+j)}\right] \qquad (9)$$

where $w^{(0)}=[(N-1)^{1-\alpha}-N^{1-\alpha}+(1-\alpha)N^{\alpha}]/\Gamma(2-\alpha)$, $w^{(n-j)}=[(j-1)^{1-\alpha}-2j^{1-\alpha}+(j+1)^{1-\alpha}]/\Gamma(2-\alpha)$, $(1\leq j\leq n-1)$, $w^{(N)}=1/\Gamma(2-\alpha)$ and $\Delta t$ is the time-step size. Eq. 9 was used to solve for $\tau^{(n)}$ for a given $\gamma^{n}$.

The method of reduced variable or so called viscoelastic corresponding states used by polymer chemists (Ferry, 1980) is employed to relate the $G'(\omega)$ values at a temperature $T$ to that at a reference temperature $T_{ref}$ as:

$$G'(\omega)\big|_{T_{ref}} = G'(c_s\omega)\big|_{T} \tag{10}$$

where $c_s(T)$ is the shifting factor and is a function of temperature. A shifting factor shown by Ferry 1980 is used here

$$c_s = e^{-p_1(T-T_{ref})/(p_2+T-T_{ref})} \tag{11}$$

where $p_1$ and $p_2$ are constants depending on a specific VEM.

The constants $a$ and $b$ are then related to the values at the reference temperature as

$$a = a_{ref}c_s^{\alpha} \text{ and } b = b_{ref}c_s^{\alpha} \tag{12}$$

Now all constants, $\alpha$, $G$, $p_1$, $p_2$, $a_{ref}$ and $b_{ref}$ are constants independent of frequency and temperature for a specific reference temperature. The constants for the acrylic based VEM designated as 3M Brand ISD 110 used in this study at 24° C are shown in Table 1. The units for stress is *psi* and temperature is °C.

Table 1 Constants Used in the Model.

| $\alpha$ | $G$ | $p_1$ | $p_2$ | $a_{ref}$ | $b_{ref}$ |
|---|---|---|---|---|---|
| 0.6618 | 18.4064 | 17.8755 | 88.5054 | 0.0213 | 5.7601 |

The storage shear modulus, $G'$, and loss factor, $\eta$ can be written as (Kasai *et al.*, 1093):

$$G' = G\frac{[1+b\omega^{\alpha}\cos(\alpha\pi/2)][1+a\omega^{\alpha}\cos(\alpha\pi/2)]+[ab\omega^{2\alpha}\sin^2(\alpha\pi/2)]}{[1+a\omega^{\alpha}\cos(\alpha\pi/2)]^2+[a\omega^{\alpha}\sin(\alpha\pi/2)]^2} \tag{13}$$

$$\eta = \frac{[-a+b]\omega^{\alpha}\sin(\alpha\pi/2)}{1+[a+b]\omega^{\alpha}\cos(\alpha\pi/2)+a\omega^{2\alpha}} \tag{14}$$

Fig. 2 shows good correlation of the storage modulus, $G'$, and loss factor, $\eta$, between the model and experimental data at 5% shear strain and 15, 24 and 32 °C ambient temperatures.

The model is then used to predict the VEM properties up to 125% strain by including the temperature rise. The temperature in the VEM is computed using the shear stress, strain, density, $\rho$, and specific heat, $s$, of the VEM as:

$$T(t) = T_o + \frac{1}{s\rho}\int_0^t \tau d\gamma \tag{15}$$

where $T_o$ is the initial temperature. In Eq. 15, it is assumed that the heat generated in the VEM is all contained in the VEM and heat loss due to heat conduction is ignored. This assumption applies to the VEM studied since the external loading time to the VEM was short and the thermal conductivity of the VEM was small.

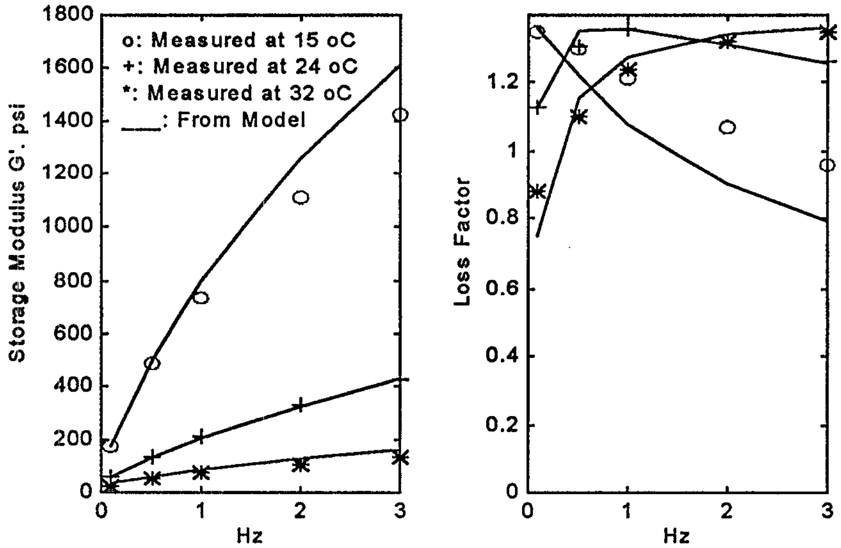


Fig. 2 Correlation of Storage and Loss Factor between the data calculated from model and experimentally measured.

Correlation between Test and Prediction

Cyclic and ramp tests were conducted to verify the predicted results. Force and displacement in each test were recorded simultaneously. Fine thermocouples with response time constant less than 0.1 *sec* were used to measure the ambient temperature and temperature rise in the VEM. The shear area of the VEM was 4.44 $in^2$ and thickness was 0.5". The VEM specific heat was measured as 0.45 *cal/gram °C* and the density was 1.04 $gram/cm^3$.

Cyclic Test. Cyclic tests were conducted at various strain amplitudes, loading frequencies and ambient temperatures as shown in Figs. 3a-3h. The solid lines are measured stress and temperatures. The dashed lines represent the analytical results using the aforementioned fractional derivative model with the initial temperature and strain time history as input. Although 20 cycles in each test were recorded, only 10 cycles are shown here for clarity.

Testing under the wide strain (12.5 to 125%), frequency (0.5 to 4.3Hz) and temperature (22.5 to 32 °C) ranges, correlation between the experimental stress as well as VEM temperature and the analytical results were quite good. For large strain and high frequency tests, the stresses measured from the experiments were usually higher than the analytical results in the latter part of the cycles. This might be due to conduction of a small amount of heat from the VEM into the steel plates during the cycling and the overall VEM becomeing slightly more rigid than was predicted assuming no heat loss from the VEM to the surrounding. Since the computation of the heat conduction for different damper geometry is quite involved, the proposed approach is simple and very useful for short duration excitations such as earthquakes. However, when considering long excitations such as those produced by wind, the heat conduction becomes dominant and should be considered fully.

When the temperature rise was turned off analytically, the stress became a constant amplitude and proportional to the strain for a fixed frequency and temperature. The VEM is then *essentially* linear.

Ramp Test. A series of ramp tests in which the VEM was subjected to a constant speed until failure were conducted at different ramp rates. Figs. 4a and 4b shows the shear stress and associated VEM temperature at 20 %/sec and 200 %/sec ramp speeds, respectively. The VEM failed at about 500% and 400% strain respectively. The failed stress was 250 *psi* for 20%/sec compared to 500 *psi* for 200 %/sec. The failure mechanism was strain control. It is interesting to note that the temperature rose about 2 °C for both the slow and fast strain rates. Although the VEM may be linear, it is also rate and temperature dependent, thus explaining why the stress curves were not a straight line when the VEM was subjected to a constant speed even the temperature rise was turned off.

The model predicted reasonably well the first half of the stress time history up to about 200% strain but under-estimated the latter part since the VEM exhibited the large strain hardening effect and was highly nonlinear. By comparing the predicted the stress-time curves shown in Fig. 4a and Fig. 5a that the temperature rise was "turned off", the temperature rise slightly decreased the shear stress.

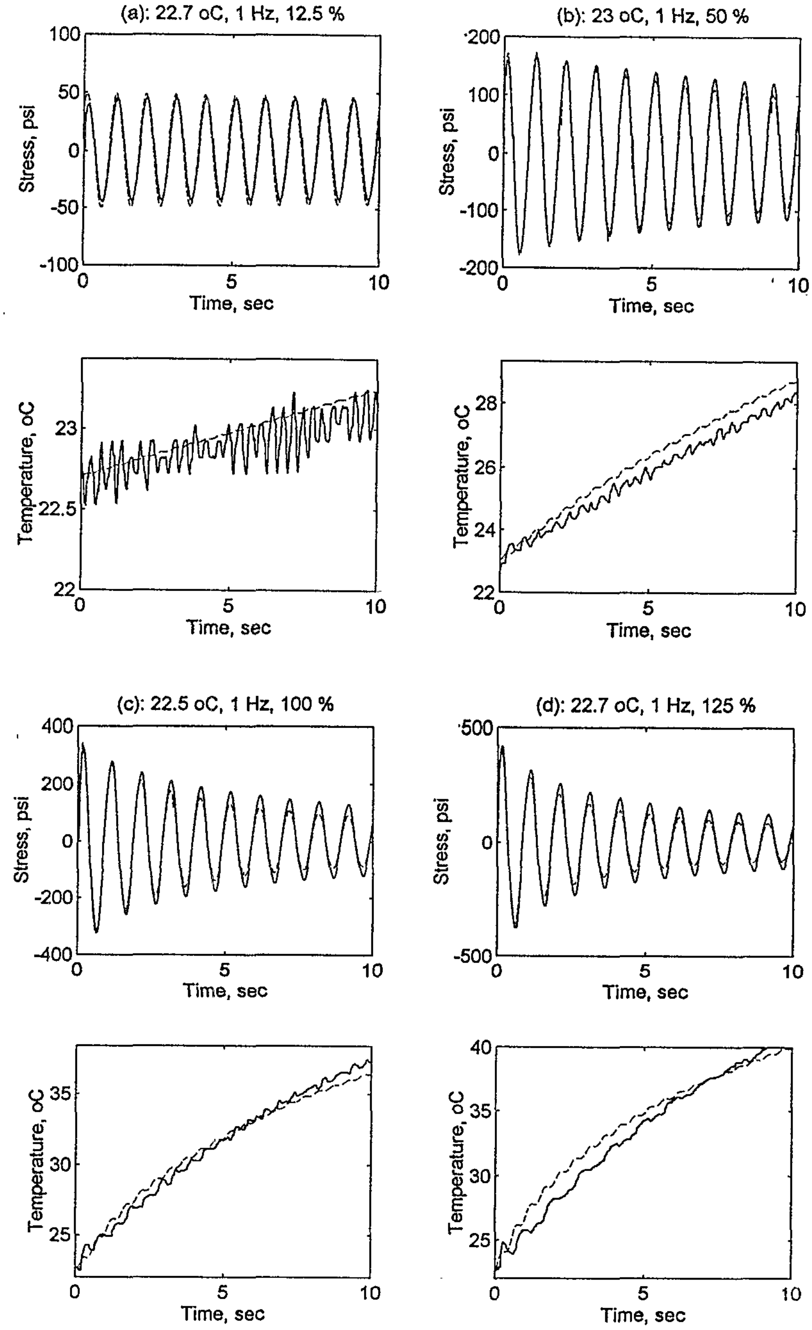


Fig. 3 (a)-(d) Measured (Solid Line) and Analytical (Dashed Line) Stress and VEM Temperature versus Time under Different Strain Amplitude, loading Frequency and Initial Temperature Conditions

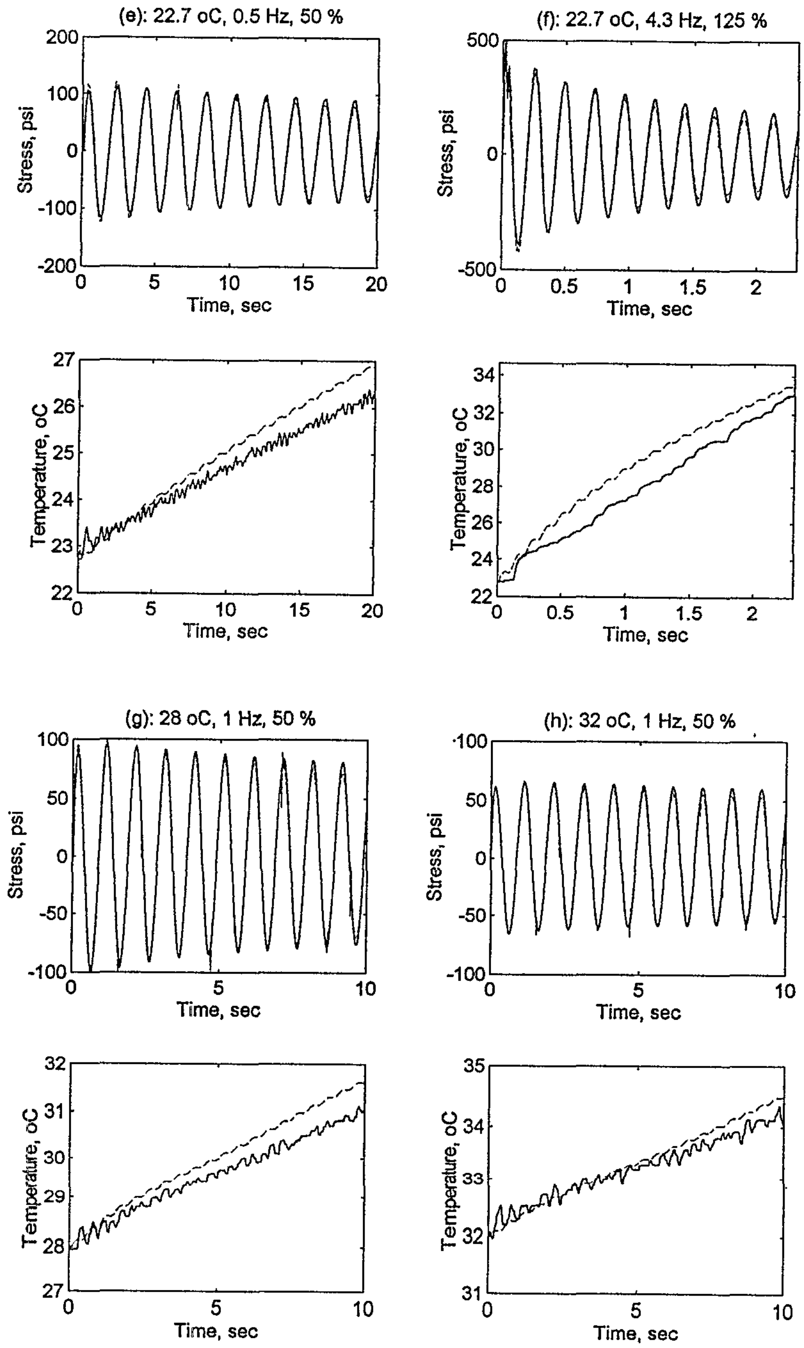


Fig. 3 (e)-(h) Measured (Solid Line) and Analytical (Dashed Line) Stress and VEM Temperature versus Time under Different Strain Amplitude, loading Frequency and Initial Temperature Conditions.

## CONCLUSIONS

The study indicated that the properties of one acrylic based VEM can be *essentially* linear up to 125% shear strain if the temperature rise in the VEM is artificially removed. In other words, the temperature rise appears to be the main source of nonlinearity and predictable by a simple model. Any linear VEM models that work well for small strain can be modified to capture the behavior of the VEM at large strains by including the calculation of the temperature rise in the VEM. Therefore, it appears that the VEM properties can be characterized as a function of two primary parameters, *ambient temperature* and *loading frequency* when the VEM specific heat and density are known.

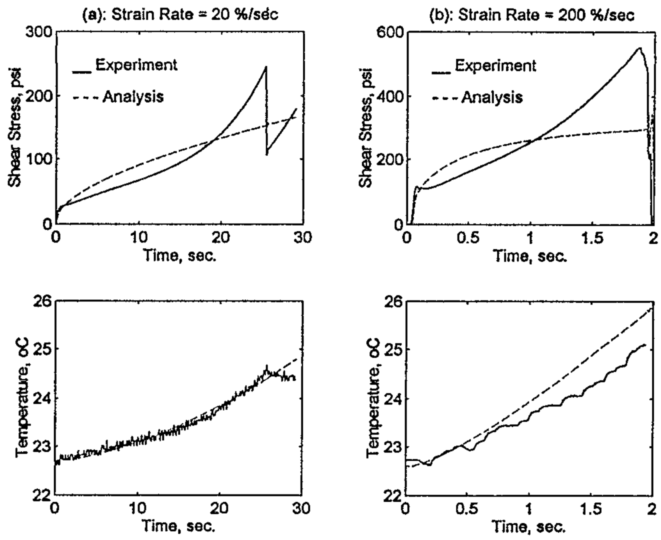


Fig. 4 Ramp Tests with Temperature Rise Consideration.

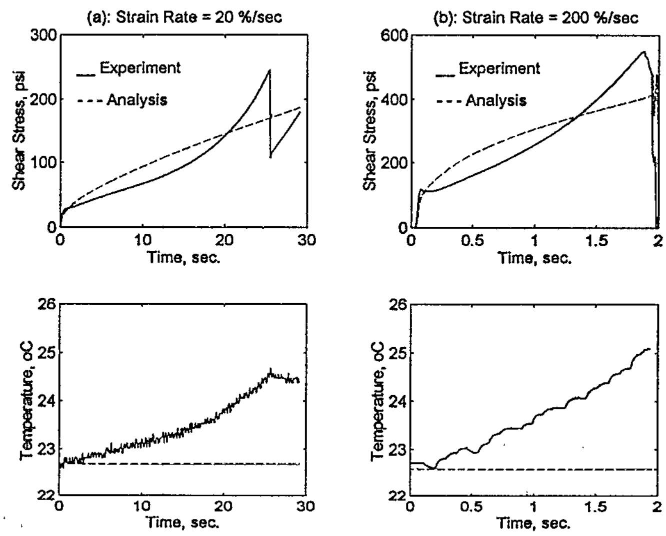


Fig. 5 Ramp Tests without Temperature Rise Consideration.

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