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HEAT GENERATION EFFECTS ON VISCOELASTIC DAMPERS IN STRUCTURES

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ABSTRACT

The first part of this paper is concerned with the response of viscoelastic dampers subjected to transient temperature conditions caused by heat generation during cyclic deformation. Simple tools for modeling viscoelastic materials are discussed and verified using experimental data obtained in a test program on shear dampers using the polymer Scotchdamp 109 of The 3M Company conducted at the Laboratory of the Civil Engineering Department of the University of California at Berkeley. The second part of this study is a numerical investigation of the effects of heat generation on the response of structures with supplemental viscoelastic dampers with the aim of defining design guidelines for structures incorporating this type of dissipater.

KEYWORDS

Damping, energy dissipation, nonlinear viscoelasticity, damper design, experimental research.

INTRODUCTION

Applications of acrylic-polymer dampers in retrofit and new construction has been accompanied by extensive experimental research on their mechanical behavior (Mahmoodi, 1969; Aiken and Kelly, 1990; Soong and Lai, 1991; Chang *et al.*, 1992; Kasai *et al.*, 1993; Blondet, 1993; Nielsen *et al.*, 1994). Due to the high sensitivity of the mechanical properties of this type of material to variations in temperature, modeling this dependence and assessing its effects on the dynamic response of structures with supplemental viscoelastic (VE) dampers is of significant relevance in developing design guidelines for this type of energy dissipater.

Consider the following linear model of the shear force in a VE damper

$$F(\varpi) = \frac{A}{h}(G_s(\varpi) + jG_l(\varpi))V(\varpi) \tag{1}$$

where $A =$ shear area of the damper, $h =$ thickness of the VE pad, $G_s(\varpi) =$ storage *modulus* of the VE material, $G_l(\varpi) =$ loss *modulus*, $j =$ imaginary unit, and $V(\varpi) =$ Fourier transform of the damper deformation, $v(t)$. At constant temperature and subjected to sinusoidal deformation of amplitude γ_o, the dissipation of energy per cycle per unit volume is $\pi|G_l(\varpi)|\gamma_o^2$. This energy, in the form of heat, causes a rise in the temperature of the material proportional to the square of the deformation amplitude.

For an arbitrary deformation signal, the total dissipated energy per unit volume is

$$W = \frac{1}{2\pi}\int_{-\infty}^{\infty} G_l(\varpi)\varpi|\Gamma(\varpi)|^2\, d\varpi \tag{2}$$

where $\Gamma(\varpi)$ is the Fourier transform of the shear deformation $\gamma(t) = v(t)/h$. Designs of VE dampers with variations in h, maintaining constant the ratio A/h, lead to lower or higher strains levels in the VE material and, consequently, lower or higher dissipation per volume of material. This implies that h plays an important role in the temperature problem because h controls the strain demand on the damper.

The design of VE dampers requires then the definition of design strain levels that guarantee appropriate behavior of the dampers during operation. These strain levels will depend on the mechanical properties of the VE material, the damper geometry, the frequency content of the deformation signals, the duration of the excitation process, and the thermal conductivity and radiation properties of the damper.

This work describes an experimental program conducted at the University of California at Berkeley to obtain data on the response of VE dampers during transient temperature conditions so that the merits of modeling tools could be assessed. A second purpose of this investigation is to determine the effects of temperature on the response of structures incorporating VE dampers so as to draw recommendations and guidelines for the design of this type of dissipater.

EXPERIMENTAL PROGRAM

Experimental Setup

Six small dampers manufactured by The 3M Company using the Scotchdamp^{TM} Polymer 109 were used in the experimental program. They had identical nominal geometry with two $0.5in$ thick layers, and cross sectional areas of $1.5in \times 1.5in$.

The dampers were tested in a Universal Testing Machine built by MTS Systems Corporation. The actuator, commanded by a 5 GPM servovalve, had a capacity of $35kips$ and a stroke of $6in$. The servolvalve was commanded by an MTS 436 Control Unit which in turn, was digitally controlled using a personal computer with data acquisition and control software. The load in the damper was measured using a tension and compression load cell (Model 3174 Lebow, EATON Corp.) with a nominal capacity of $10kips$. An electrical oven with a digital temperature controller was used to heat the specimens to the desired initial temperatures. An LVDT was used to measure the deformation of the damper; this signal was used as feedback in the controller. Thermocouples (TC) were installed in the specimens tested and temperature readings were accurate to $\pm 0.1^\circ C$. The TC junction diameter was 0.003 in; this especially thin junction was used to reduce the time constant (thermal inertia) of the TC. Room temperature was measured with a thermometer.

The tests conducted in the dampers consisted in imposed deformation signals at various initial temperatures. The command signals utilized were sine signals of frequencies between $0.1Hz$ and $4Hz$, sine sweeps, steps, and broad-band signals. During the tests, deformation, force, material temperature and ambient temperature were recorded. In addition, several tests were conducted to characterize the cooling process of the damper with the damper undeformed. This was aimed at obtaining a simple first-order differential model for the temperature of the damper to be used in the analytical phase of this research. Only a small fraction of the data analyzed is presented herein. A detailed analysis of the data is presented elsewhere (Inaudi *et al.*, 1996).

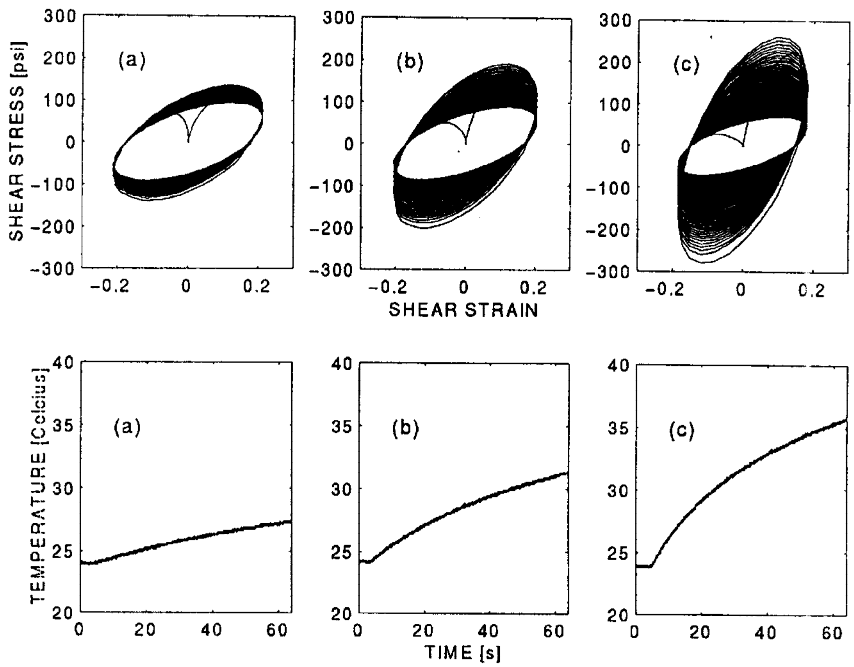

Fig. 1. Hysteresis loops and material-temperature histories obtained in tests of sinusoidal deformation: (a) $0.5Hz$, (b) $1Hz$, (c) $2Hz$.

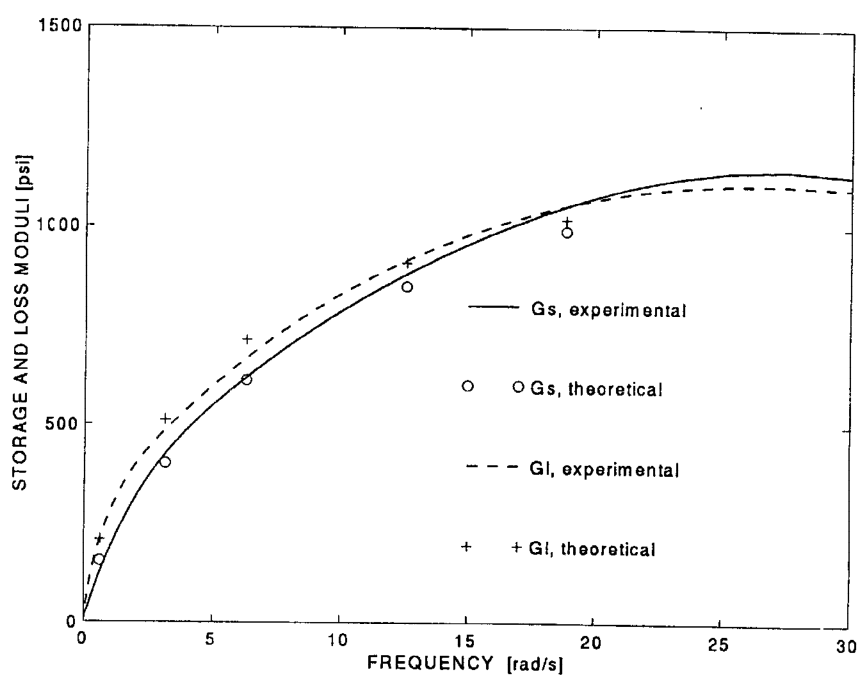

Fig. 2. Experimental and theoretical storage and loss *moduli* for polymer Scotchdamp 109 at a reference temperature of $21\,^{\circ}C$.

Results

Figure 1 shows stress-strain curves measured during three sinusoidal-deformation tests of equal amplitude and different frequencies ($0.5Hz$, $1Hz$, and $2Hz$) and their corresponding temperature histories $\theta(t)$ during the sixty seconds of testing. As illustrated in the figures, the higher the deformation frequency, the higher the temperature increase in the VE material and, the higher the deterioration of the mechanical properties for the same test duration. While a temperature increase of $3^{\circ}C$ causes only a minor decrease in the energy dissipation per cycle (Fig. 1a), an increase of $12^{\circ}C$ causes a very significant reduction in the energy dissipation per cycle (Fig. 1c).

The cooling process of the VE material during periods with no deformation after heating produced by cyclic deformation of the damper was investigated during the tests. Data of the material-temperature decay from various initial temperatures were obtained. It was observed that the rate of the temperature decay depends on the initial temperature of the VE material and, modeled as a simple exponential decay

$$\dot{\theta}(t) = -\frac{1}{\gamma_{\theta}}(\theta(t) - \theta_{amb}), \tag{3}$$

where θ_{amb} = ambient temperature, yields cooling times γ_{θ} of about $2000s$ for $\theta(t)-\theta_{amb} \approx 1^{\circ}C$, $1000s$ for $\theta(t)-\theta_{amb} \approx 10^{\circ}C$, and $700s$ for $\theta(t)-\theta_{amb} \approx 20^{\circ}C$, for the dampers tested. In general, the rate of cooling of a VE damper will depend on its geometry, and is a complex process because it depends on the initial temperature distribution which in turn depends on the stress history. An important aspect verified during testing is that the time constant of this process is significantly longer than the duration of earthquake signals.

MODEL OF VISCOELASTIC MATERIAL INCORPORATING TEMPERATURE

A model using a chain of Maxwell elements in parallel with temperature-dependent properties is described in this section. The dynamics of the material temperature is modeled using a first-order differential equation which accounts for heat generation in the VE material and energy losses due to conductivity and radiation. The model of the damper is implemented numerically to assess the effects of temperature variations on the performance of structures incorporating VE dampers.

Models Considered in the Literature

A widely used concept in linear viscoelasticity is the time-temperature superposition principle, which states that the following relationship holds for the complex *modulus* $G(\varpi,\theta) = G(\varpi\alpha(\theta),\theta_{ref})$, where θ is the temperature of the material, θ_{ref} = a reference temperature, and $\alpha(\theta)$ = shift factor. In the time domain, these relationships imply $E(t,\theta) = E(t/\alpha(\theta),\theta_{ref})$, where E is the relaxation function of the material and $t/\alpha(\theta)$ is called the reduced time. Materials exhibiting this property are called thermorheologically simple.

For transient temperature conditions, Morland and Lee (1960) proposed the use of an integral expression of the reduced time. More recently, a Kasai *et al.* (1993) and Aprile (1995) have proposed evolutionary models in which the shear stress is expressed as:

$$\sigma(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} G(\varpi,\theta(t))\Gamma(\varpi)e^{j\varpi t}d\varpi \tag{4}$$

where the evolutionary complex *modulus* $G(\varpi,\theta(t))$ is modeled using fractional derivative operators and the temperature dynamics is modeled neglecting heat losses due to radiation and conduction in the damper and approximating the energy dissipation rate by the instantaneous power, which leads to

$$\theta(t) - \theta(t_o) \approx \frac{1}{c_{\theta}}\int_{t_o}^{t}\sigma(t')\dot{\gamma}(t')dt' \tag{5}$$

where c_θ = thermal inertia of the VE material, and t_o = initial time.

A model of this kind incorporates the dependence of the mechanical properties of the VE material on temperature, but makes an approximation in the dynamics of the material temperature because of the difference between the energy dissipation rate and the input energy rate (Inaudi and Kelly, 1996) and the neglect of conduction and radiation heat losses of the material. In addition, these models use fractional derivatives which require step-by-step solutions in the frequency domain (Aprile, 1995) or memory variables to approximate the integro-differential equations in the time domain (Kasai *et al.*, 1993) in the case of transient temperature.

Maxwell Chains with Temperature-Dependent Parameters

A Maxwell chain with temperature-dependent relaxation times is used to model VE materials in this section. In an attempt to improve the temperature model shown in Eq. (5), and still keeping a simple model for the temperature dynamics without accounting for strain localization and variations of the temperature field in the VE pad, yet at the same time, accounting for radiation and conduction heat losses from the damper, a simple one dimensional differential model for the temperature of the VE material is proposed. The main motivations behind this approach are computational advantages over fractional-derivative models, simpler parameter identification procedure for the model parameters (a linear least-square problem), and exact estimation of the energy dissipation rate.

The force $f(t)$ in the proposed model for the damper satisfies

$$f(t) = A\sum_{1}^{N_e} z_i(t) + k_o v(t) \tag{6}$$

where A = shear area of the damper, k_o = static stiffness, and the N_e state variables $z_i(t)$ satisfy

$$\dot{z}_i(t) = -\frac{1}{\tau_i(\theta)} z_i(t) + \beta_i \dot{\gamma}(t) \tag{7}$$

where $\tau_i(\theta)$ = relaxation time of the i-th Maxwell element, β_i = elastic *modulus* of the i-th Maxwell element, and $\dot{\gamma}(t) = \dot{v}(t)/h$. Utilizing a thermorheologically-simple model for the Maxwell chain, we have

$$\tau_i(\theta) = \tau_i(\theta_{ref})\alpha(\theta) \tag{8}$$

In this work, we use the following expression for the shift factor (Kasai *et al.*, 1993)

$$\alpha(\theta) = (\theta_{ref}/\theta)^p \tag{9}$$

Using the database of polymer Scotchdamp 109 and for a reference temperature of $21^\circ C$, the shift factor is curve fitted to the experimental data to obtain $p = 5.61$. The model parameters β_i are obtained using least squares by selecting a set of $\tau_i(\theta_{ref})$ and minimizing the square differences in the storage and loss *moduli* between the model and the experimental values.

The temperature dynamics is modeled as

$$\dot{x}(t) = -\frac{1}{\gamma_\theta} x(t) + \frac{1}{c_\theta}\dot{W}(t) \tag{10}$$

where $x(t) = \theta(t) - \theta_{amb}$, γ_θ = cooling time constant due to conduction and radiation losses, c_θ = thermal inertia of the VE material, and $\dot{W}(t)$ = energy dissipation rate per unit mass which for this model, can be written as

$$\dot{W}(t) = \sum_{i=1}^{N_e} \frac{z_i^2(t)}{\tau_i(\theta(t))\beta_i} \tag{11}$$

Equations (7) and (10) are coupled differential equations that model the stress and temperature dynamics in a model with $N_e + 1$ internal variables, $z_i(t)$ and $x(t)$.

Comparison with Experimental Data

Comparisons were made between the recorded experimental data and the model predictions. This was done using deformation signals recorded during tests and simulating the proposed model subjected to these deformation signals. The numerical integration scheme utilized used a predictor-corrector scheme on a partition of the differential equations based on the fact that the temperature dynamics has a large time constant. Analytical predictions with and without temperature transients were compared with recorded responses and very satisfactory correlation was obtained incorporating Maxwell chains with 5 to 10 elements in parallel.

Figure 2 shows the model prediction of the storage and loss *moduli* at $21^{o}C$ obtained using 10 Maxwell elements with relaxation times at the reference temperature between $0.001s$ and $1000s$. Better fit to the experimental data can be obtained using a larger number of Maxwell elements in parallel at the cost of increasing the order of the model.

Figure 3 shows a comparison of experimental and simulated damper force in the case of a sweep deformation signal of $40s$ in duration obtained using the Maxwell model shown in Fig. 2. The ambient temperature of this test was $24^{\circ}C$, $\gamma_{\theta} = 1000s$, and $c_{\theta} = 0.0051^{\circ}Cin^2 / lb$. As shown in Figs. 3a and 3b very satisfactory correlation is obtained in the estimation of the damper force. Figure 3c shows the material temperature recorded in the tests and that obtained in the simulation; again very good correlation is obtained.

EFFECTS OF TEMPERATURE IN DEFORMATION SPECTRA

A study of the effects of temperature variations on the response of single-degree-of-freedom (SDOF) oscillators incorporating VE dampers was carried out using numerical simulation. The model studied was

$$m\ddot{y}(t) + m\omega^2 y(t) + f(t) = -m\ddot{u}_g(t) \tag{12}$$

where $m =$ mass, $\omega =$ undamped natural frequency, $\ddot{u}_g(t) =$ ground acceleration, and $f(t) =$ force in the VE damper modeled according to Eq. (6). The parameters A and h of the damper were selected such that the model had a specified equivalent damping $\xi = (AG_l(\omega)/h)/2(AG_s(\omega)/h + m\omega^2)$ at the ambient temperature, and a specified estimated maximum shear strain $\hat{\gamma}_{\max} = D(\omega,\xi)/h$ for the ground motion considered, where $D(\omega,\xi) =$ displacement response spectra of a Kelvin SDOF oscillator with parameters ω and ξ , for the ground motion considered.

Figure 4 shows deformation spectra and material temperature spectra for SDOF oscillators with equivalent damping $\xi = 0.05, 0.10, 0.15, 0.20$ and estimated maximum shear strains of $\hat{\gamma}_{\max} = 0.20$ in figures (a) and $\hat{\gamma}_{\max} = 0.50$ in figures (b). The initial temperature and ambient temperature were assumed as $21^{\circ}C$. As shown in the bottom figures, the temperature increase in the VE material decreases with an increase in the equivalent damping constant (Inaudi *et al.*, 1993; Inaudi and Kelly, 1996), and does not exceed $4^{\circ}C$ in the case of $\hat{\gamma}_{\max} = 0.20$ (low design shear-strain values), while it reaches almost $30^{\circ}C$ in the case of $\hat{\gamma}_{\max} = 0.50$ and $\xi = 0.05$. As shown in the top figures, these temperature variations have a detrimental effect on the deformation of the oscillator which increases as the temperature rise in the damper increases. It is observed that the temperature increase decreases with the undamped natural period of the structure because, although the estimated strain levels are the same for the complete period range, the number of deformation cycles increases with the natural frequency of the structure and, consequently, higher total energy dissipation should be expected in the case of structures with larger frequencies. Similar conclusions can be reached analyzing other earthquake signals (Inaudi and Kelly, 1996).

These type of response spectra can be utilized to recommend allowable design shear strain values for VE dampers and are being currently studied by the writers.

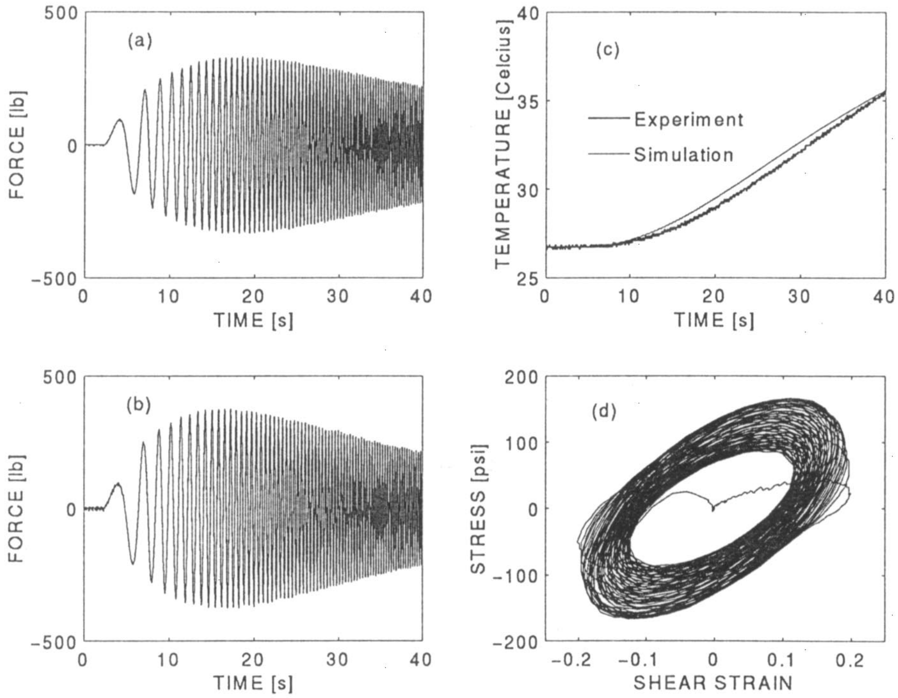

Fig. 3. Comparison of experimental and simulation results during a sweep deformation test (ambient temperature = $24^{\circ}C$): (a) Force recorded during experiment, (b) Force obtained by simulation, (c) Material temperature in experiment and simulation, (d) Hysteresis loops obtained in the simulation.

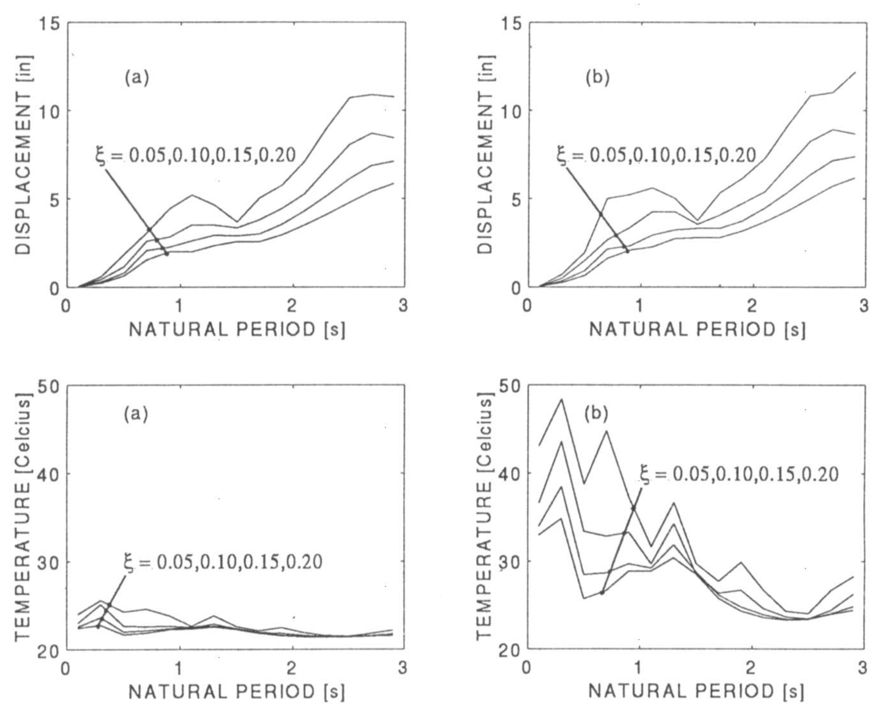

Fig. 4. Displacement spectra and material temperature spectra: (a) Design shear strain = 0.20, (b) Design shear strain = 0.50.

CONCLUSIONS

A simple and efficient model for VE dampers in structures subjected to earthquake or wind-type excitations which accounts for temperature variations due to heat generation in the material and radiation and conductivity losses was presented. Good correlation was obtained when comparing analytical predictions and experimental data. The effects of heat generation on the response of SDOF structures with supplemental VE dampers were evaluated using numerical simulation. Based on these results, design recommendations regarding design strain levels for VE dampers can be developed. On the basis of results obtained in this research, a maximum value of $\hat{\gamma}_{max} = 0.15$ is recommended when linear analysis is to be used in the estimation of the response of the structure, that is if transient temperature effects are to be neglected. Nonlinear analysis is recommended for cases in which $\hat{\gamma}_{max} > 0.15$, that is when temperature can have significant effect on the structural response.

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