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NUMERICAL ANALYSIS OF A FULL-SCALE VISCOELASTIC DAMPER SUBJECTED TO LONG-DURATION HARMONIC LOADING

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Viscoelastic damper, Long-duration loading,
Temperature Rise, Heat transfer analysis

1. Introduction

1.1 VE Damper Behavior under Long-Duration Loading

In the advent of the advancing construction technologies, buildings are becoming taller and lighter. As such, tall buildings are becoming more susceptible to long-duration wind loadings. One effective way of controlling wind-induced vibration is the employment of viscoelastic (VE) dampers which are made by sandwiching thin slabs of VE materials between steel plates (e.g., Fig. 1).

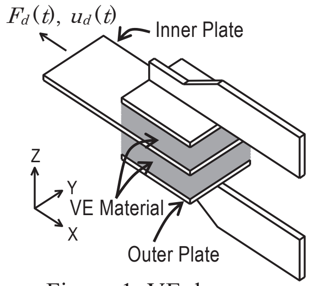

Figure 1. VE damper

Through shear deformation, VE damper dissipates kinetic energy and converts significant portion of this energy into small amount of heat which is then dispersed to the surrounding air mainly by the laminating steel plates. Although the amount of temperature rise per cycle of harmonic loading is relatively small, for long-duration loading such as wind, heat significantly accumulates within the VE material due to its low thermal conductivity κ (about 1/200 that of steel). Consequently, the dynamic properties (i.e., stiffness and damping) of the VE damper decreases with the increase of its temperature[1].

1.2 Short-Duration and Long-Duration Models

In 1993 and 1997, Kasai et al. proposed models for VE damper subjected to short-duration (such as typical earthquake) and long-duration loadings, respectively. Both these models are based on the viscoelastic constitutive rule using the fractional time-derivatives of stress τ and strain γ. The short-duration model (Figure 2(a)) showed the effect of temperature increase due to the dissipated energy, and it considers uniform distributions of temperature θ and strain γ[2]. The long-duration model, herein known as 1D-LD Model, combines the VE constitutive rule and one-dimensional (1D) heat transfer analysis, and considers varying distributions of temperature and strain[3] (Figure 2(b)).

To simulate the real three-dimensional heat transfer, in 2006, Kasai et al.[4] proposed a technique of combining elastic-static analysis and three-dimensional transient-state heat transfer analysis using 3D finite element method (herein known as 3D-FEM model).

1.3 Objective

Although the aforementioned studies[2-4] showed good predictions, the devices analyzed were only a simple lap shear VE damper with two-layers (Figure 1). In engineering practice nowadays, full-scale multi-layered VE dampers are used. It is therefore the objective of this current study to carry-out a 3D-FEM analysis of a full-scale VE damper using the idea proposed by Kasai et al. in 2006[4].

2. Full-Scale Multi-Layered VE Damper Test

2.1 Damper Specimen

The full-scale multi-layered VE damper analyzed in this study is from the graduate study of Sugiyama[5]. Figure 3 shows the test setup. The main part of the VE damper was inside an enclosure to control the ambient temperature θ_c.

Figure 4 shows the longitudinal section of the VE damper. The 6 laminated VE slabs were ISD-111 type, each having a

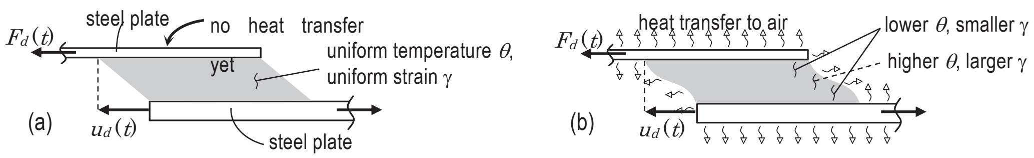

Figure 2. (a) Short-duration model and (b) long-duration model

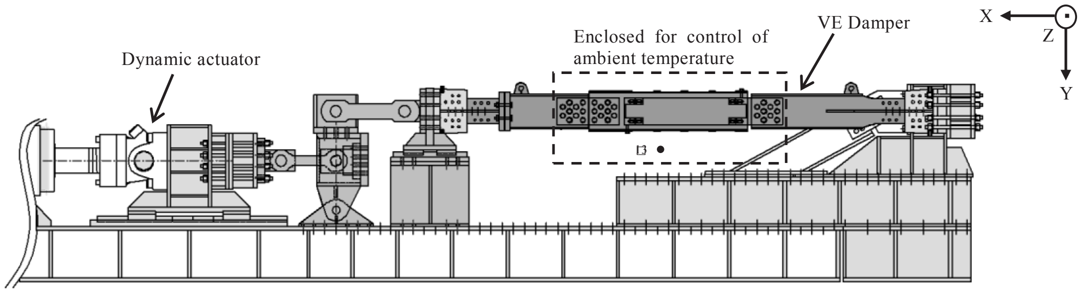

Figure 3. Test setup for viscoelastic damper

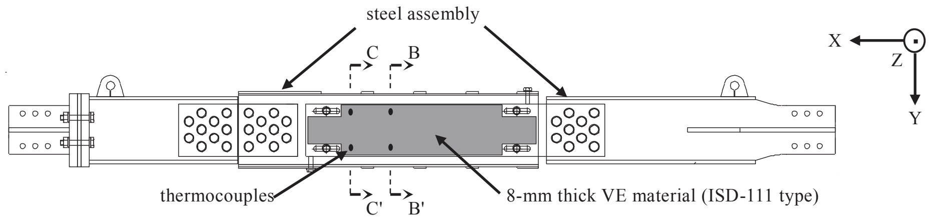

Figure 4. VE damper detail

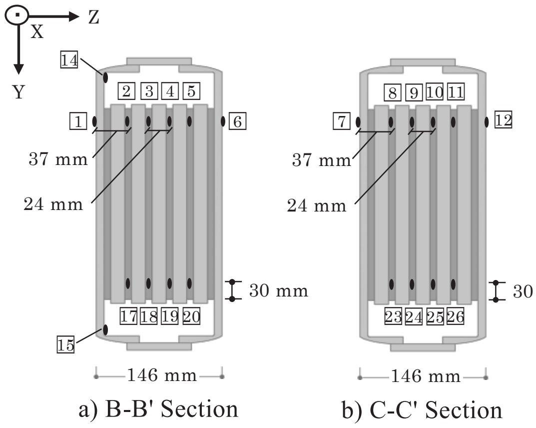

Figure 5. Temperature measurement position

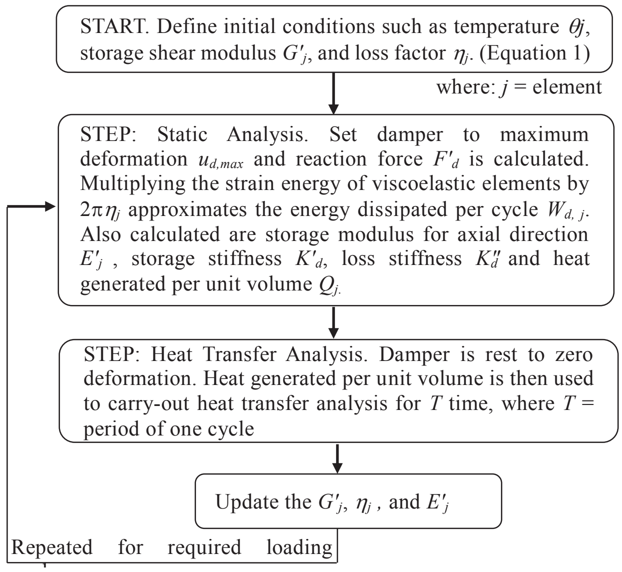

Figure 6. Flow of the 3D-FEM Analysis

thickness of 8 mm. As provided by the manufacturer for ISD-111, the shear modulus G = 3.92 N/cm^2, fractional derivative order α = 0.558, at reference temperature θ_{ref} = 20.0°C, a_{ref} = 0.0056 and b_{ref} = 2.10 and p_1 = 14.06 an p_2 = 97.32. The total shear area A_s = 912,000 mm^2. Thermocouples were placed in various locations of Sections B-B' and C-C' to measure the temperature at 1-min interval (Figure 5).

2.2 Loading Condition

The full-scale VE damper was subjected to a harmonic displacement of peak value ±5.66 mm (±70.75% shear strain) at a frequency of 0.277 Hz. Duration of loading was 27,796 seconds. Ambient temperature inside the enclosure was set to be at 26°C. Outside the enclosure, the ambient temperature was observed to be 22°C

3. Static Analysis of VE Damper with 3D-Finite Element Heat Transfer Analysis

Figure 6 shows the overview of the 3D-FEM analysis proposed by Kasai et al.[4]. A finite element analysis software ABAQUS® Ver2017 was used as a tool in implementing this technique. After the calculation of the temperature θ_j at the end of every loading cycle, the storage shear modulus G'_j and loss factor η_j (Equation 1) are updated. A subroutine in FORTRAN® was linked to ABAQUS® in order to calculate the G'_j and η_j.

$$G'_j = G\frac{1+a_jb_j\omega^{2\alpha}+\left(a_j+b_j\right)\omega^{\alpha}\cos(\alpha\pi/2)}{1+a_j^2\omega^{2\alpha}+2a_j\omega^{\alpha}\cos(\alpha\pi/2)} \tag{1a}$$

$$\eta_j = \frac{\left(-a_j+b_j\right)\omega^{\alpha}\sin(\alpha\pi/2)}{1+a_jb_j\omega^{2\alpha}+\left(a_j+b_j\right)\omega^{\alpha}\cos(\alpha\pi/2)} \tag{1b}$$

where ω = circular frequency (rad/s) and parameter a_j and b_j are

$$a_j = a_{ref}\,\lambda_j^{\alpha},\quad b_j = b_{ref}\,\lambda_j^{\alpha},\quad \lambda_j = \exp\left[-p_1\left(\theta_j-\theta_{ref}\right)/\left(p_2+\theta_j-\theta_{ref}\right)\right].$$

Energy dissipated per cycle $W_{d,j}$, storage modulus for axial direction E'_j, storage stiffness K'_d, loss stiffness K''_d, and heat generated per unit volume Q_j are calculated as follows:

$$W_{d,j} = \pi \eta_j V_j \left\{ \sum_{k=1}^{3} E'_j \varepsilon_{kk,j}^2 + G'_j \left(\gamma_{12,j}^2 + \gamma_{23,j}^2 + \gamma_{31,j}^2 \right) \right\} \tag{2}$$

$$E'_j = 2G'_j (1+\nu) \tag{3}$$

$$K'_d = F'_d / u_{d,\max} \tag{4}$$

$$K''_d = \left(\sum_j W_{d,j} \right) \Big/ \left(\pi u_{d,\max}^2 \right) \tag{5}$$

$$Q_j = W_{d,j} / (V_j\, T) \tag{6}$$

where V_j = volume of element j, $\varepsilon_{mn,j}$ and $\gamma_{mn,j}$ = strains at the center of the element, and ν = Poisson's ratio.

4. Static Analysis of VE Damper with 3D-Finite Element Heat Transfer Analysis

Figure 6(a) the 3D-FEM model of the full-scale VE damper test specimen. Coupled temperature-displacement solid elements in ABAQUS® were used. The mesh size of the VE material in the X- and Y-directions was close to 10 mm and each VE slab was divided into 6 elements in the Z-direction. Since the damper has symmetry in the XY- and XZ-planes, only a quarter portion was used in the analysis.

Table 1 indicates the properties of the steel and VE materials used for heat transfer analysis.

The heat transfer coefficient α_c which describes the convective heat transfer was decided by trial-and-error approach and the value adopted for this study is 2.6 N/s/m/°C.

5. Results

Figure 6(b) shows the temperature distribution at the end of the long-duration harmonic loading (t = 27,796 s). It is seen that the temperature at the mid-portion of the full-scale VE damper significantly increased. From the initial temperature of 26°C, the VE damper reached a maximum temperature is found to be 39.73°C.

Figure 7 compares the predicted temperature θ at the measurement locations (Figure 5) vs. the measured values. Additionally Point 13 is the ambient temperature inside the enclosure. Although there are observable difference between the analysis and test results, the variation is not significantly large. Overall, the temperature is predicted with good accuracy.

Figure 8 compares the storage stiffness K'_d of the analysis and the test results. It shows the 3D-FEM model predicts the change of the dynamic properties of the VE damper with high accuracy. As expected, the storage stiffness decreases as the VE damper is subjected to long-duration loading. From the analysis, the initial value of K'_d is equal to 9.55 kN/mm and dropped to 6.92 kN/mm at the end of the loading.

6. Conclusion

This study applied the 3D-FEM model previously proposed by Kasai et al.[4] to analyze a full-scale multi-layered viscoelastic damper subjected to long-duration harmonic loading. Results have shown that the VE damper behavior was predicted with accuracy. Although there were some slight

Table 1. Material Properties of Steel and VE

	Steel	VE
κ (N/s/°C)	43.128	0.188
s (N·cm/kg/°C)	46.63 x 10^3	19.40 x 10^4
ρ (kg/cm^3)	7.80 x 10^{-3}	1.00 x 10^{-3}

1 N/s/cm/°C = 100 W/m^2/°C

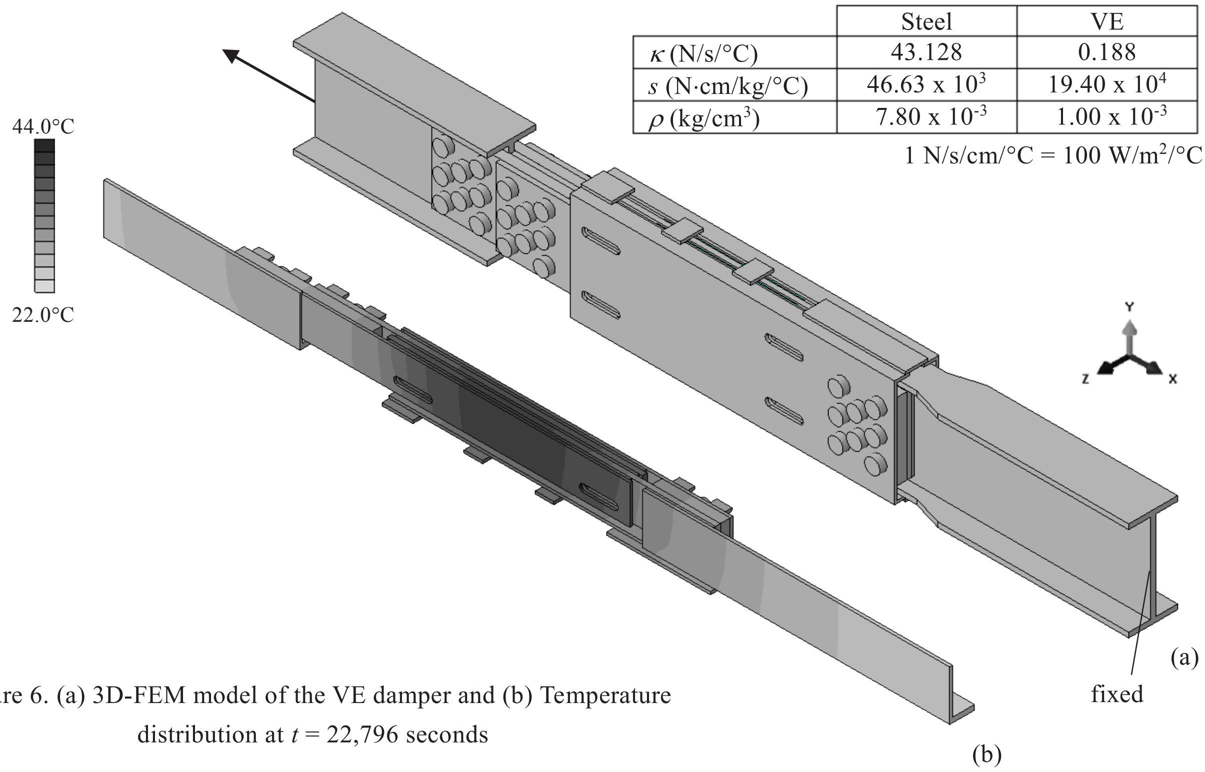

Figure 6. (a) 3D-FEM model of the VE damper and (b) Temperature distribution at t = 22,796 seconds

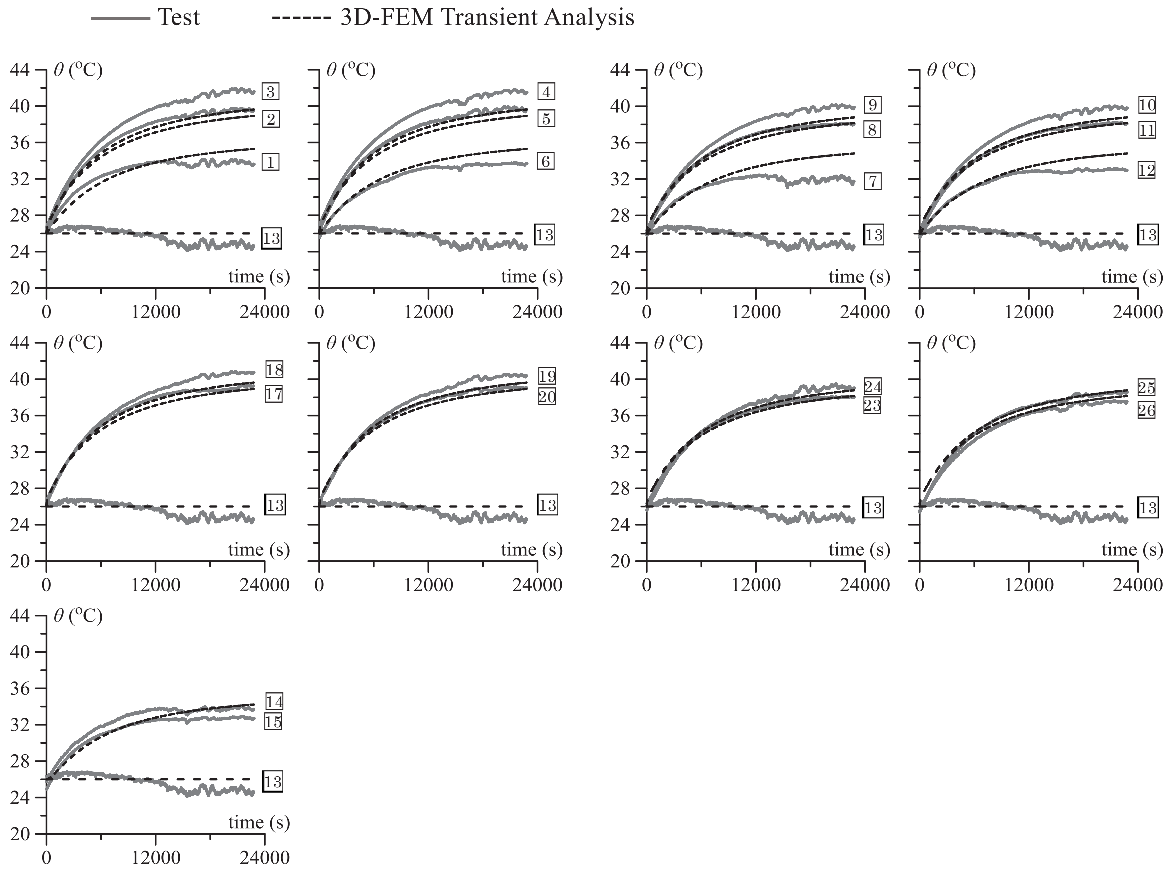

Figure 7. Temperature: Test vs. 3D-FEM Analysis

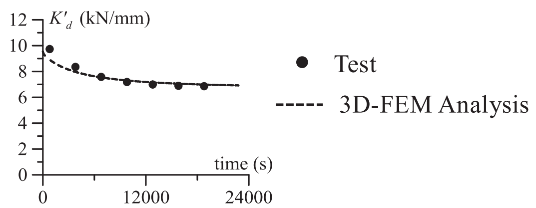

Figure 8. Storage Stiffness: Test vs. 3D-FEM Analysis

difference between the predicted temperature and the measured temperature, the variations is still within the acceptable range. Especially since storage stiffness, which is among the major concern of the engineering practice, is predicted accurately.

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