

論文 / 著書情報
Article / Book Information

論題(和文)	
Title(English)	Study of Full-Scale Multi-Layered Viscoelastic Dampers under Long-Duration Harmonic Loading (Part 2: Analytical Investigation using Three-Dimensional Finite Element Model)
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出典(和文)	日本建築学会大会学術講演梗概集, , pp. 749-750
Citation(English)	Summaries of technical papers of annual meeting, , pp. 749-750
発行日 / Pub. date	2019, 9
権利情報	一般社団法人 日本建築学会

Study of Full-Scale Multi-Layered Viscoelastic Dampers under Long-Duration Harmonic Loading (Part 2: Analytical Investigation using Three-Dimensional Finite Element Model)

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Full-Scale Viscoelastic Damper Long-Duration Loadings 3D-FEM Analysis

1. INTRODUCTION

Despite the several experiments conducted in the past¹⁻⁴⁾, there are no analytical investigations carried-out for a full-scale brace-type multi-layered viscoelastic (VE) damper subjected to long-duration loading. To address this matter, this paper analytically investigates one of the past experimental studies cited in Part 1, i.e., from the study of Sugiyama⁴⁾.

The proposed model of Kasai *et al.*⁵⁾ for VE dampers under long-duration loadings which considers heat generation and transfer is used for the analysis.

2. STATIC ANALYSIS OF DAMPER WITH 3D-FINITE ELEMENT HEAT TRANSFER ANALYSES

Figure 1 shows the overview of the technique proposed by Kasai *et al.*⁵⁾ which combines elastic-static analysis and transient-state heat transfer analysis for each harmonic loading cycle. This concept is used to carry-out the three-dimensional finite-element analysis of damper test specimen, thus, referred herein as 3D-FEM model.

The 3D-FEM model simulates the temperature- and frequency sensitivities of VE material. The storage shear modulus G' and the loss factor η of each 3D element of the VE material j at temperature θ are defined as

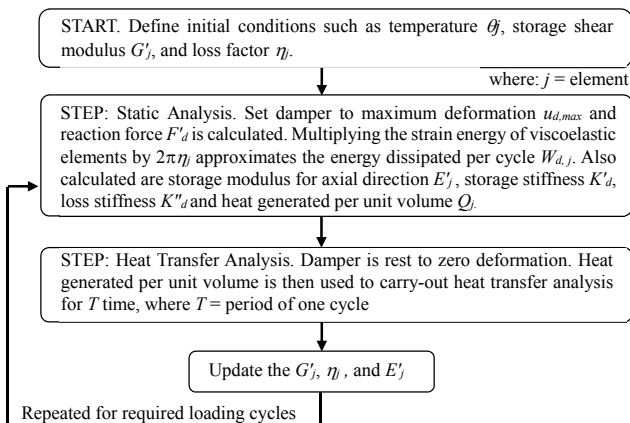


Figure 1. Overview of the 3D-FEM Analysis⁵⁾

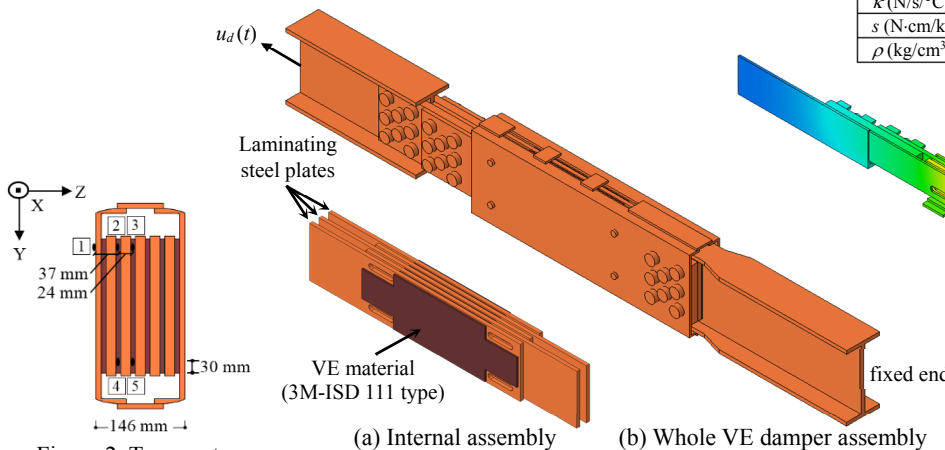


Figure 2. Temperature measurement position

Figure 3. 3D-FEM model of the VE damper

$$G'_j = G \frac{1 + a_j b_j \omega^{2\alpha} + (a_j + b_j) \omega^\alpha \cos(\alpha\pi/2)}{1 + a_j^2 \omega^{2\alpha} + 2a_j \omega^\alpha \cos(\alpha\pi/2)} \quad \text{Eq. (1a)}$$

$$\eta_j = \frac{(-a_j + b_j) \omega^\alpha \sin(\alpha\pi/2)}{1 + a_j b_j \omega^{2\alpha} + (a_j + b_j) \omega^\alpha \cos(\alpha\pi/2)} \quad \text{Eq. (1b)}$$

where ω = circular frequency (rad/s), α = fractional derivative order, and a_j and b_j are functions of the shift factor λ calculated as $a_j = a_{ref} \lambda_j^\alpha$, $b_j = b_{ref} \lambda_j^\alpha$, $\lambda_j = \exp[-p_1(\theta_j - \theta_{ref}) / (p_2 + \theta_j - \theta_{ref})]$. Here, a_{ref} and b_{ref} are values at reference temperature θ_{ref} .

3. DAMPER SPECIMEN AND LOADING CONDITIONS

Test number 14 of Part 1 is analyzed and presented in this report. For Specimen VE05 specifications and loading conditions, please see Tables 1 and 2 of Part 1. As provided by the manufacturer, the shear modulus $G = 3.92 \text{ N/cm}^2$, $\alpha = 0.558$, at $\theta_{ref} = 20.0^\circ\text{C}$, $a_{ref} = 0.0056$ and $b_{ref} = 2.10$, $p_1 = 14.06$ and $p_2 = 97.32$. Figure 2 shows the locations of some thermocouples at the mid-section of the VE damper.

4. 3D-MODEL OF THE VE DAMPER

Figure 3 shows the 3D-FEM model of the test specimen. Coupled temperature-displacement solid elements in ABAQUS® were used. Each of the VE laminations was divided into 6 elements in the thickness direction (Z-direction), and in the X- and Y- directions was meshed close to 10 mm. Only quarter section was analyzed since the damper has symmetry in the XY- and XZ-planes. A subroutine in Fortran® was linked to ABAQUS® to calculate G'_j and η_j .

Damper Properties for Heat Transfer Analysis. Table 1 indicates the material properties of steel and VE for heat transfer analysis.

Heat Convection Rate. The heat transfer coefficient α_c which defines the rate of heat transfer from the exposed surfaces to the surrounding air is decided from trial-and-error approach. For the VE damper in this report, $\alpha_c = 2.60 \text{ N/s/m}^2\text{C}$ is adopted for all air-exposed surfaces.

Ambient temperature. As per record, the ambient temperature θ_e was about $30^\circ\text{C} \pm 1^\circ\text{C}$.

Table 1. Material Properties of Steel and VE

	Steel	VE
$\kappa \text{ (N/s}^\circ\text{C)}$	43.128	0.188
$s \text{ (N-cm/kg}^\circ\text{C)}$	46.63×10^3	19.40×10^4
$\rho \text{ (kg/cm}^3)$	7.80×10^{-3}	1.00×10^{-3}

1 N/s/cm²C = 100 W/m²°C

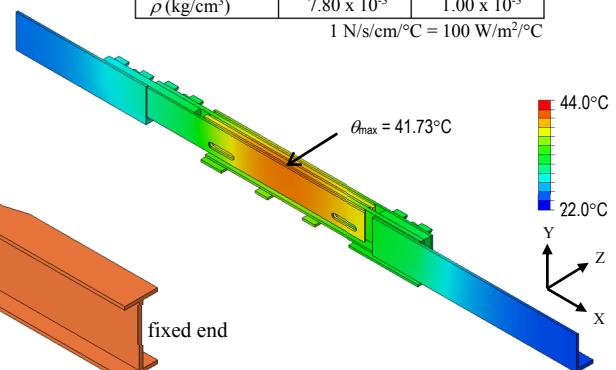


Figure 4. Temperature distribution at $t = 25,863.67 \text{ s}$ (7,172nd cycle)

Temperature distribution at mid-section at $t = 25,863.67$ s (7,172nd cycle)

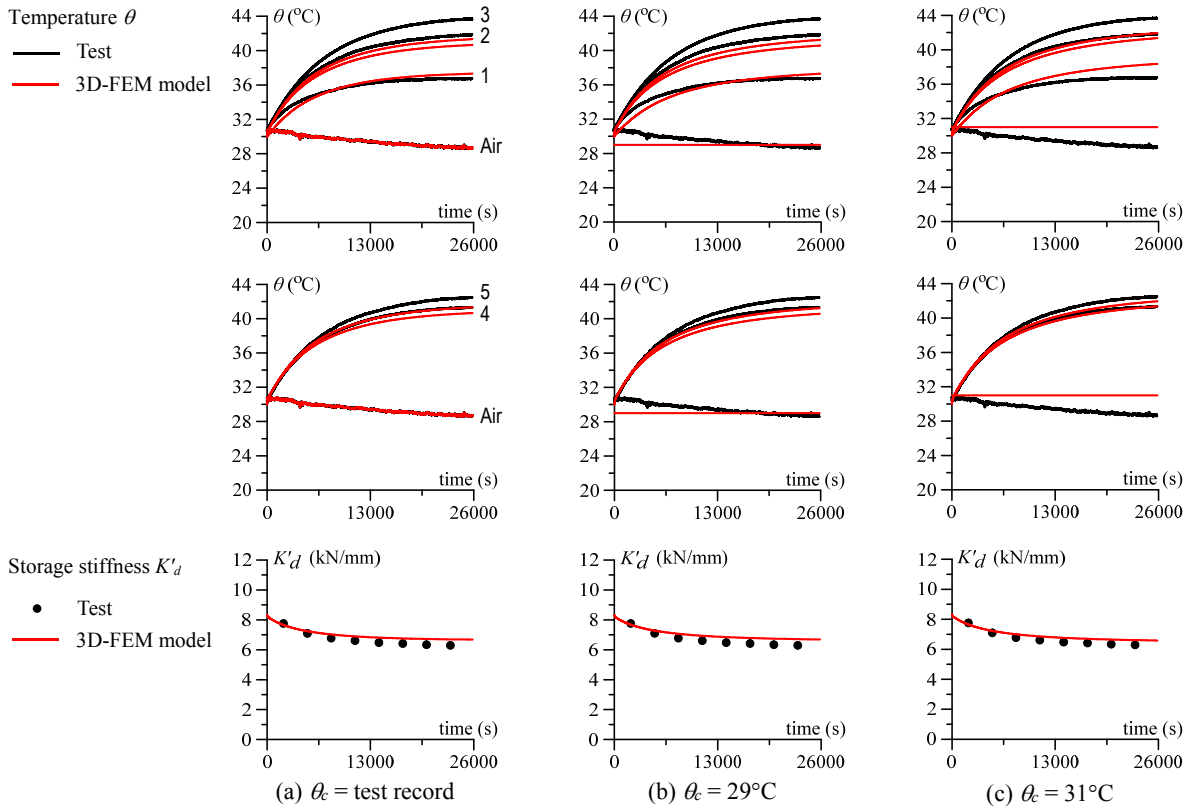
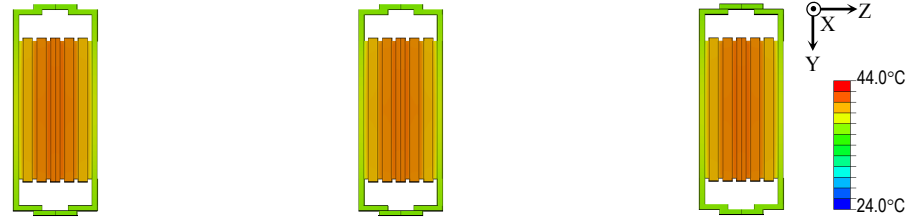


Fig. 5. Results: Test vs. 3D-FEM Analyses

5. ANALYSIS RESULTS AND VERIFICATION

Figure 4 shows the temperature distribution from at end of the analysis of VE damper (quarter section) using $\theta_e =$ test record. After 7,172 loading cycles, the VE damper reached a maximum of temperature of 41.73°C, an increase of about 40% from initial $\theta = 30^\circ\text{C}$. As expected, heat accumulates in the innermost portion of the damper due to the low thermal conductivity of the VE material.

Figure 5(a) compares the results from test and those from the 3D-FEM analysis using ambient temperature $\theta_e =$ test record. As seen, although there are recognizable differences between the predicted temperature θ at measurement points 2 and 3, the storage stiffness K'_d match well with the test.

Since the recorded ambient temperature ranges from 29°C to 31°C, analytical investigations are also carried-out using constant values of θ_e , as in Figures 5(b) $\theta_e = 29^\circ\text{C}$ and (c) $\theta_e = 31^\circ\text{C}$. When compared to (a), there are no significant variations in the results, except on the temperature at the steel surface, i.e., at point 1. With $\theta_e = 31^\circ\text{C}$, the temperature at point 1 is noticeably higher than those in (a) and (b), but the temperature at the VE material, i.e., at points 2 – 5, are very similar. Since the temperature in the VE material for the varying θ_e are very similar, their K'_d are also very similar and have good agreement with the test.

7. CONCLUSION

This paper utilized the proposed 3D-FEM model of Kasai *et al.*⁵⁾ to analytically investigate the behavior of a full-scale multi-layered viscoelastic damper under long-duration harmonic excitation. The

analyses were computationally expensive due to the complexity of the model. Also, since the heat transfer coefficient is not a thermo-physical property, several trials had to be made to successfully model the real VE damper. Despite these, it was shown in this paper that the behavior of full-scale VE damper can be predicted with high accuracy.

It was found that substantial amount of heat accumulated in the innermost VE laminations. The analysis also showed that the steel assembly was effective in dispersing heat to the surrounding air.

ACKNOWLEDGEMENT

This work was supported by JST Program on Open Innovation Platform with Enterprises, Research Institute and Academia.

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