論文 / 著書情報
Article / Book Information

論題(和文)	
Title(English)	Numerical Analysis of Viscoelastic Dampers under Long Duration Excitation(Part 4: Three-Dimensional Transient- and Steady-Heat Transfer Analyses of a Two-Layered VE Damper)
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出典(和文)	日本建築学会大会学術講演梗概集, , , pp. 243-247
Citation(English)	Summaries of technical papers of annual meeting, , , pp. 243-247
発行日 / Pub. date	2018, 9
権利情報	一般社団法人 日本建築学会

日本建築学会大会学術講演梗概集
（東北） 2018 年 9 月

Numerical Analysis of Viscoelastic Dampers under Long Duration Excitation (Part 4: Three-Dimensional Transient- and Steady-Heat Transfer Analyses of a Two-Layered VE Damper)

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Viscoelastic Damper　Long Duration Loadings　Elastic-Static Analysis
Heat Generation　3D Heat Transfer Analysis

1. INTRODUCTION

A viscoelastic (VE) damper (e.g., Fig. 1) works by converting the dissipated kinetic energy into small amount of heat, increasing its temperature and lowering its mechanical dynamic property. Depending on its geometric design, VE dampers can effectively disperse the heat generated into the surrounding air and eventually reach steady-state (*see* Part 3).

This study aims to simulate the behavior of a two-layered VE damper under long duration sinusoidal loading as observed in experiment. This may be highly useful in the future when investigating multi-layered VE dampers.

2. DAMPER TEST SPECIMEN

Experiment data of the two-layered VE damper (Fig. 1) by Sato et al.[1)] is used in this current study. The damper was deformed to simulate a long duration random and sinusoidal loadings (excerpt in Fig. 2). Sato et al. [1)] proposed the calculation of the equivalent sinusoidal wave. Loading cases considered are A-3L and C-3L with duration of each loading = 12000 seconds.

Only the sinusoidal loadings are considered in this study. Conveniently, the equivalent sinusoidal loadings of cases A-3L and C-3L are the same with displacement peaking at 0.707 cm at 0.288 Hz frequency. Ambient temperature was maintained at 24°C.

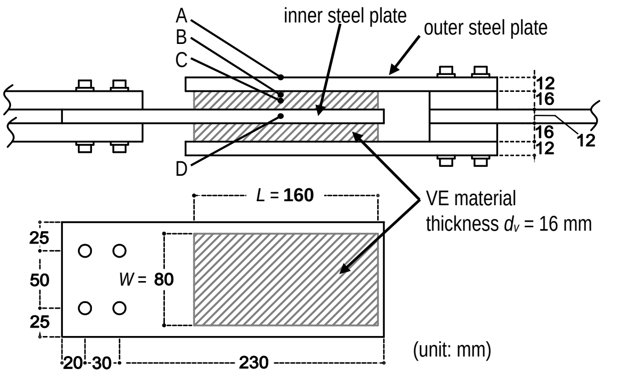

Fig. 1. Damper specimen and temperature measurement locations

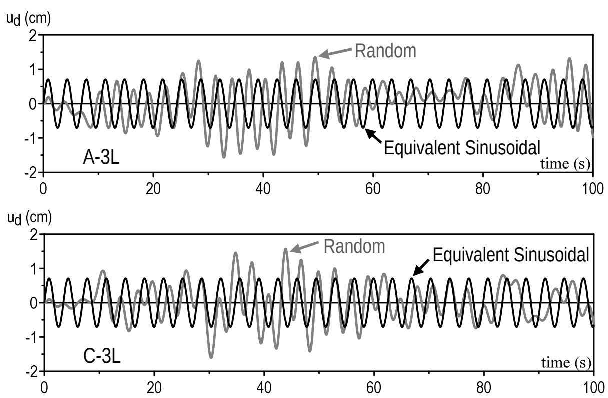

Fig. 2. Random and equivalent sinusoidal-wave damper deformation

As provided by the manufacturer for ISD 111 Type VE material: 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 and p_2 = 97.32.

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

The technique proposed by Kasai et al.[2)] which combines elastic-static analysis and transient-state heat transfer analysis for each loading cycle was used to carry-out the 3D-FEM analysis of damper test specimen. Fig. 3 shows the overview of this technique. A finite element analysis (FEA) software ABAQUS® Ver2017 was used as a tool in implementing this technique.

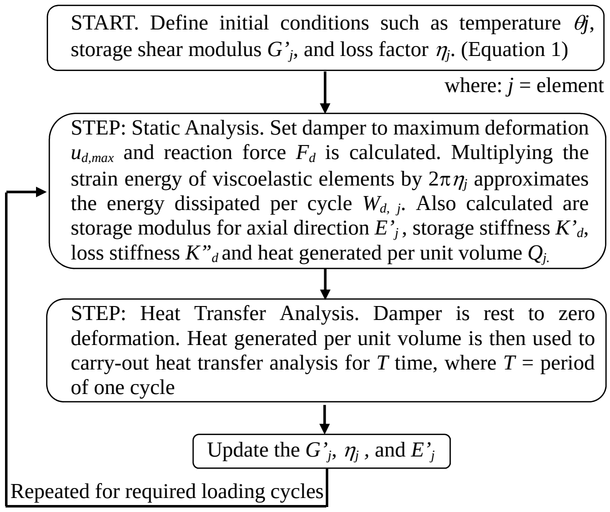

Fig. 3. Overview in the 3D-FEM analysis

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

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

where ω = circular frequency (rad/s), and parameters a_j and b_j are $a_j = a_{ref}\lambda_j^{\alpha}$, $b_j = b_{ref}\lambda_j^{\alpha}$, $\lambda_j = \exp[-p_1(\theta_j - \theta_{ref})/(p_2 + \theta_j - \theta_{ref})]$.

A subroutine program coded in FORTRAN® was linked to ABAQUS® in order to calculate G'_j, η_j, and E'_j and update the material.

For steady-steady heat transfer analysis, the same steps above are taken but each cycle will be considered as an iteration step until values converges. Typical FEA software has an option of either transient- or steady-state is to be carried-out.

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4. MODELING THE DAMPER

Fig. 4 shows the 3D-FEM model of the test specimen. Coupled temperature-displacement solid elements in ABAQUS® were used. The VE material was divided as follows: L into 32, W into 16 and d_v into 12 elements. Since the damper has symmetry in the XY- and XZ-planes, only a quarter portion is used in the analysis.

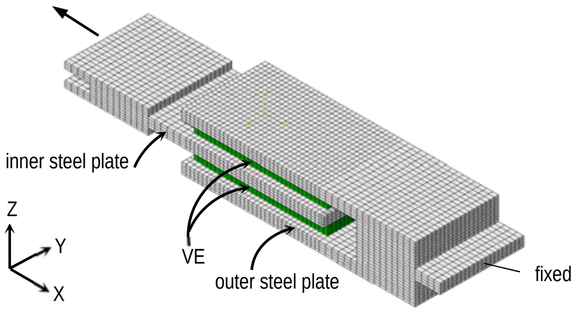

Fig. 4. 3D-FEM model of the damper

<u>*Damper Properties for Heat Transfer Analysis*</u>. Thermal conductivity κ for VE and steel are κ_{VE} = 0.188 N/s/°C and κ_{steel} = 43.128 N/s/°C, respectively. Specific heat capacity s are s_{VE} = 19.40 x 10^4 N·cm/kg/°C and s_{steel} = 46.63 x 10^3 N·cm/kg/°C, respectively for VE and steel. Mass density of viscoelastic material is ρ_{VE} = 1.00 x 10^{-3} kg/cm^3 and for steel is ρ_{steel} = 7.8 x 10^{-3} kg/cm^3.

<u>*Heat Convection Rate*</u>. The heat transfer coefficient α_c which defines the rate of heat transfer from the exposed surfaces to the surrounding is decided by comparing the analysis results of both transient- and steady-state analyses to those measured from experiments. For cases A-3L and C-3L, α_c = 0.06 N/s/cm/°C is adopted.

5. EXPERIMENTAL VERIFICATION

Figs. 5 and 6 compares the temperature θ at measurement locations (Fig. 1) and storage stiffness K'_d from the test and the 3D-FEM analyses. The most important aspect to be verified is the prediction of the VE material temperature as this will define the changes in the VE damper dynamic mechanical properties.

In Fig.5, transient-state analysis has some minor difference with the test but the temperature at points B and C of the steady-state analysis agree well with the test.

Overall, both the transient- and steady-state analyses agree well with the K'_d from the experiment (Fig. 6). The transient-state analysis predicts well the storage stiffness time-history of the VE damper, and the steady-state analysis also agrees well with the test. This gives us judgment to adopt the α_c = 0.06 N/s/cm/°C.

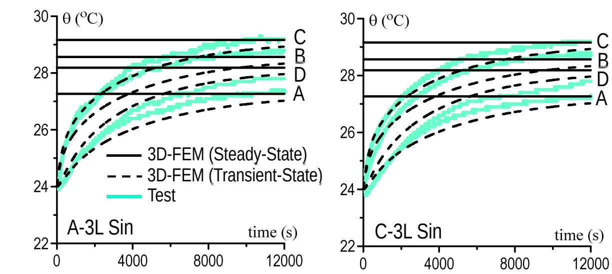

Fig. 5. Temperature: Test vs 3D-FEM Analyses

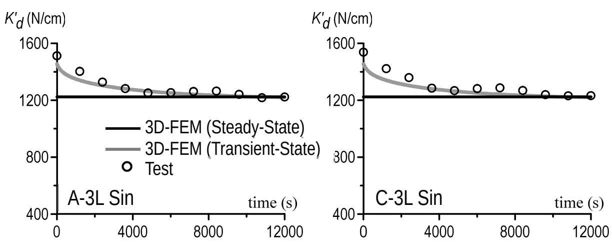

Fig. 6. Storage stiffness K'_d: Test vs 3D-FEM Analyses

6. TEMPERATURE DISTRIBUTION

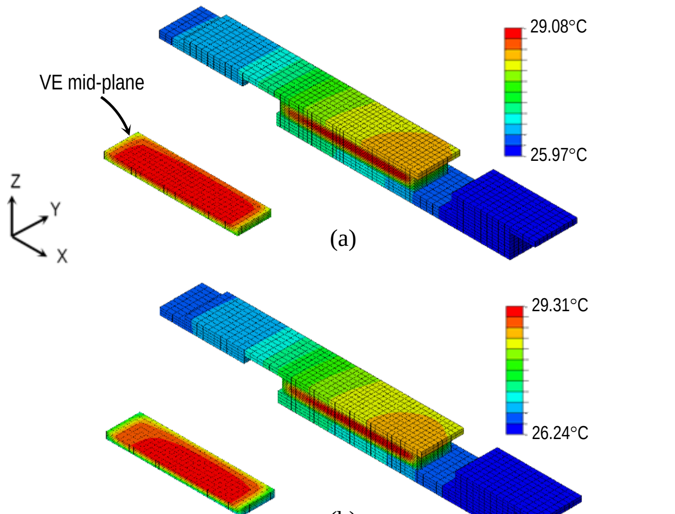

Fig. 7. Temperature Distribution: (a) Transient-state analysis at 12000 seconds, and (b) Steady-state analysis after 5th iteration

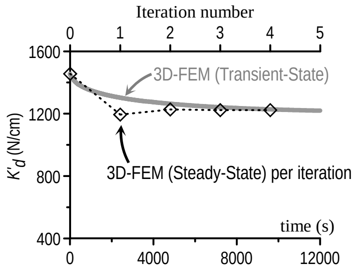

Fig. 8. Solution convergence of steady-state analysis.

Fig. 7 shows that the very similar temperature distribution of results from (a) transient-state analysis and (b) steady-state analysis. However, steady-state analysis holds great advantage in calculation runtime. After 4th iteration, solution has converged, thus, saving a lot of computer runtime (Fig. 8).

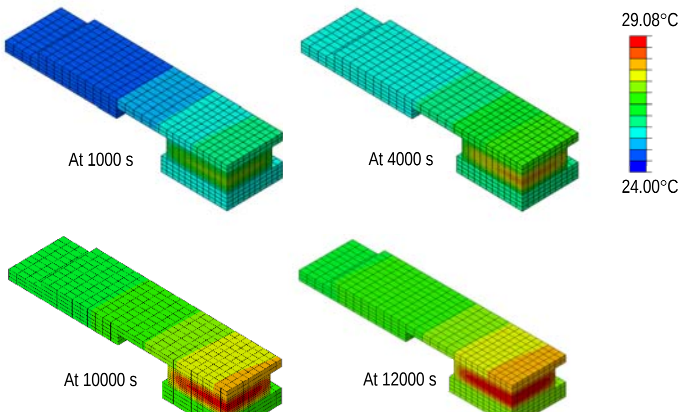

Fig. 9. Temperature distribution at different time

Fig. 9 depicts how the heat is transferred from the VE material to the steel. Due to its low conductivity, heat is accumulated in the VE material.

7. CONCLUSION

With the use of combined static analysis and heat transfer analysis, the behavior of a two-layered VE damper under long-duration excitation was predicted with high accuracy.

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