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Analytical Method for Viscoelastic Damper Considering Temperature, Frequency, and Strain Sensitivities

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Viscoelastic (VE) damper Temperature-frequency-strain dependency
Finite element method Large deformation Heat transfer analysis

1. INTRODUCTION

1.1. Viscoelastic Damper

Viscoelastic (VE) damper dissipates structural vibration through shear deformation of the VE material, then converts the absorbed energy into heat. Its properties can be evaluated by the stress τ - strain γ curve (Fig. 1) and used in analysis of buildings with dampers. Its storage shear modulus G' is defined as slope of τ-γ curve, and its loss factor $\eta = \tau'/\tau''$, where τ' and τ'' = stresses corresponding to maximum and zero strains, respectively.

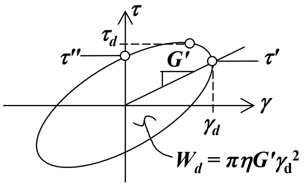

Fig. 1. Stress-strain curve

The VE damper properties are dependent on several factors such as loading frequency and temperature, they can significantly decrease with temperature rise. In 2001, Kasai et al[1] proposed a linear constitutive rule considering the temperature-frequency sensitivities to predict the cyclic behavior of VE damper. In 2006, Kasai et al[2] proposed the cycle-by-cycle three-dimensional finite element (3D-FE) method using the linear constitutive rule[1].

1.2. Objective

However, the above-mentioned studies[1-2] only considered damper strain of $\gamma_d \le 100\%$ (= damper deformation u_d / VE material thickness d_v). As found by Kasai et al[3] in 2002, VE damper manifests strain sensitivity under large deformation (about γ_d = 300%), such that they proposed a nonlinear constitutive rule based on temperature-frequency and strain sensitivities. Based on these, we propose a non-linear 3D-FE method which combines the above-mentioned original 3D-FE method[2] with the nonlinear constitutive rule[3]. The accuracy of this proposed method is investigated under loadings of γ_d = 10%, 100% and 300%.

2. VE DAMPER EXPERIMENT

This current study utilizes the experimental result of VE damper test conducted by Kasai et al. [3], particularly, the loading conditions of initial temperature θ_0 = 20 °C, frequency f_r = 0.3 Hz, γ_d = 10%, 100%, 300%. Each sinusoidal wave was loaded for 10 cycles. The two-layered VE damper has 3M-ISD111 VE material type whose material properties are presented in Reference [3].

3. ANALYSIS USING THE ORIGINAL 3D-FE METHOD[2]

3.1. Overview of the original 3D-FE method[2]

The original 3D-FE method only considers temperature-frequency sensitivities to calculate the storage shear modulus G'_j and the loss factor η_j of each VE element j (e.g., Fig 2), i.e.,

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

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

3.2. Analysis of the VE damper test

Since the VE damper test specimen is symmetrical in the *XY*- and *XZ*-planes, only a quarter was modeled (mesh type = C3D8T in ABAQUS), as shown in Fig. 2. The quarter section was subjected to deformation-controlled loading u_d at one end so that the reaction force from the other fixed end can be simulated. Since the test is only 10 loading cycles, heat generation and heat conduction are only considered, while heat convection is not.

Shown in Fig. 3 is the original 3D-FE method results of τ - γ curves compared with test in Cycles 1 and 10. The original 3D-FE method can accurately simulate the damper behavior under γ_d = 10% and 100%. However, it fails to simulate test result for γ_d = 300%. Thus, the strain sensitivity under large deformation needs to be considered in 3D-FE method.

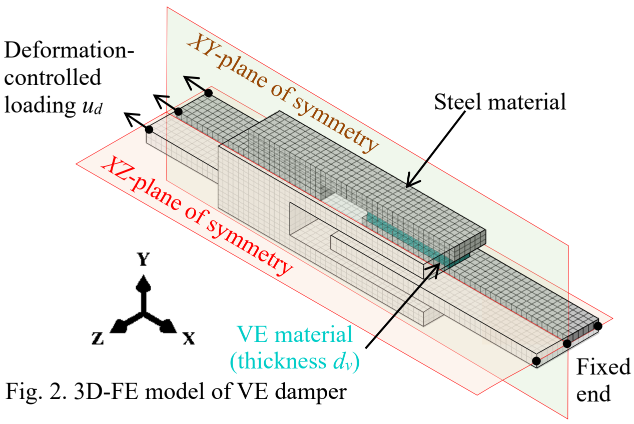

Fig. 2. 3D-FE model of VE damper

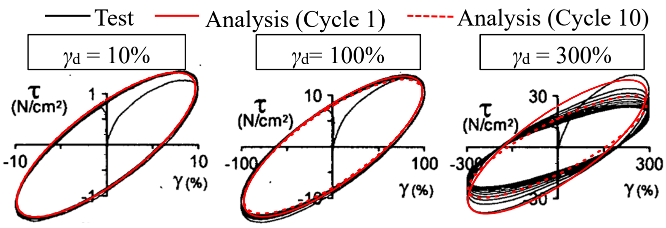

Fig. 3. Test vs. original 3D-FE method: stress-strain curves

4. PROPOSED NON-LINEAR 3D-FE METHOD

4.1. Algorithm of the proposed non-linear 3D-FE method

In order to consider the effect of large strain (e.g., > 100%) in 3D-FE analysis, Eqs.1 and 2 are modified as follows:

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LIANG Qijun, SATO Daiki, OSABEL Dave Montellano

$$G'_j = \lambda_2 G \frac{1 + a_j b_j \omega^{2\alpha} + (a_j + b_j)\omega^{\alpha} \cos(\alpha\pi/2)}{1 + a_j^2 \omega^{2\alpha} + 2a_j \omega^{\alpha} \cos(\alpha\pi/2)}, \quad (3)$$

$$b_j = b_{ref} \lambda_{0j}{}^{\alpha} \lambda_1, \quad (4)$$

where λ_1 and λ_2 are the linear factors of peak strain $\gamma_{j,\max}$ for each VE element j (C_1 = 0.124, C_2 = -0.182.), i.e.,

$$\lambda_1 = 1 + C_1(\gamma_{j,\max} - 1) \geq 1,\ \lambda_2 = 1 + C_2(\gamma_{j,\max} - 1) \leq 1, \quad (5)$$

These Eqs. 3-5[3] are implemented in proposed non-linear 3D-FE method as shown in the flowchart (Fig. 4). In cycle n = 1, using the initial temperature $\theta_j^{(0)}$, material properties G'_j and η_j are calculated by Eqs. 1 and 2. In the following elastic static analysis, the damper deformation is set to maximum $u_{d,\max}{}^{(n=1)}$ and then back to zero. The current element peak strain $\gamma_{j,\max}{}^{(n=1)}$ is recorded in this step. Using the $\gamma_{j,\max}{}^{(n=1)}$, the G'_j and η_j can be modified by Eqs. 3-5. In cycle n > 1, the G'_j and η_j can be calculated by using the recorded $\gamma_{j,\max}{}^{(n-1)}$ from the previous cycles. After obtaining the non-linear values of the G'_j and η_j, the elastic static analysis is carried out to obtain the reaction force F'_d. The energy dissipated per cycle W_j, which corresponds to the area of τ - γ curve (Fig. 1), can be estimated. Using W_j to calculate the rate of heat generation $\dot{q}_j$ per unit volume V_j, the 3D transient-state heat transfer analysis is then carried out to update element temperature θ_j. The above procedure is repeated for N_0^+ cycles.

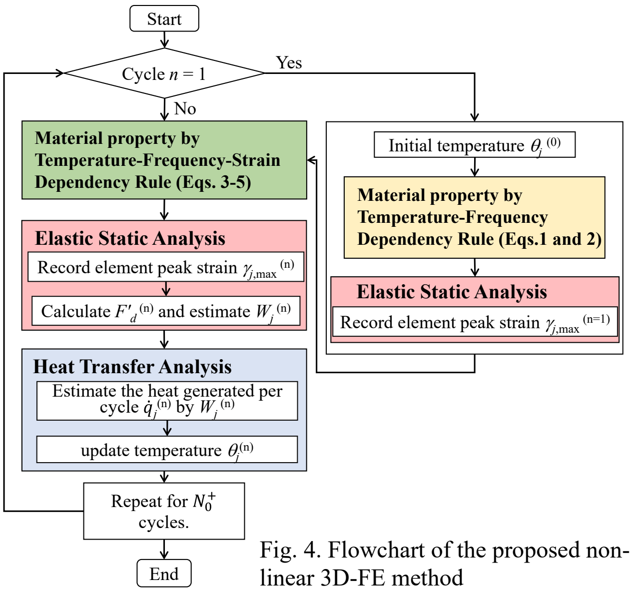

Fig. 4. Flowchart of the proposed non-linear 3D-FE method

4.2. Analysis of the VE damper test using proposed method

Fig. 5 shows the τ - γ curves (Cycles 1 and 10) obtained from proposed method. Similar to Fig. 3, the proposed method for γ_d = 10% and 100% are fit well with the test. Meanwhile, the proposed method performs better than the original 3D-FE method[2] in predicting large deformation (γ_d = 300%).

Furthermore, the energy density per cycle ($W_d = \pi\eta G'\gamma_d^2$, Fig. 1) obtained from the proposed method are about 0.97 and 0.97 times those from the test in Cycles 1 and 10. This signifies that the proposed method has good accuracy for γ_d up to 300%.

Fig. 6 shows the G'_j distributions of VE elements at Cycle 10 obtained from the original 3D-FE method and the proposed method, where the vertical axis is normalized to VE slab thickness d_v. The proposed method has the same accuracy with the original 3D-FE method under the loading of $\gamma_d \leq$ 100%, and can modify the G' value when γ_d > 100% by considering the strain sensitivity of VE material (Eqs. 3-5).

From the temperature distribution (γ_d = 300%, Cycle 10) shown in Fig. 7, the temperature in the mid-portion of VE slab is larger than that of the bounding plates. From θ_0 = 20 °C, the VE element temperature rises to a maximum of 27.6 °C.

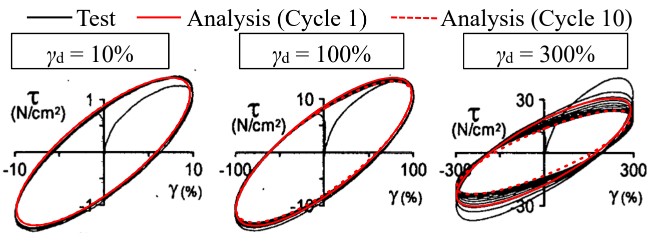

Fig. 5. Test vs. proposed 3D-FE method: stress-strain curves

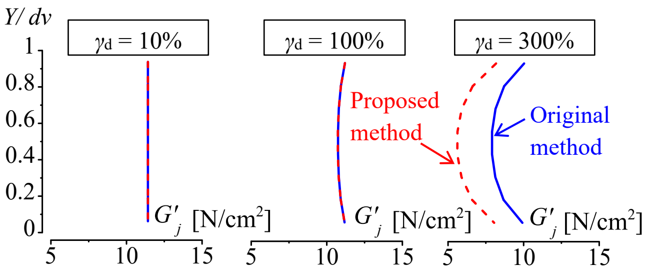

Fig. 6. Storage shear modulus distribution (Cycle 10)

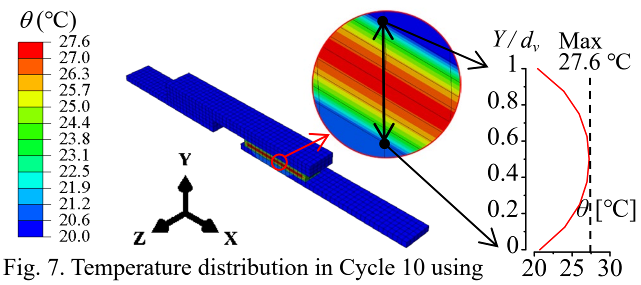

Fig. 7. Temperature distribution in Cycle 10 using proposed non-linear 3D-FE method (γ_d = 300%)

5. CONCLUSION

This study proposed a non-linear 3D-FE method by combining the original linear cycle-by-cycle 3D-FE method[2] with the strain sensitivity[3]. The proposed non-linear method predicted well the test results for γ_d up to 300%.

For future study, the proposed method will be used to analyze full-scale VE damper.

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