論文 / 著書情報
Article / Book Information

論題(和文)	大歪依存性を考慮した実大複層粘弾性ダンパーの一次元解析手法 その1 理論構築と計算手順
Title(English)	One-dimensional Analytical Methods for Full-scale Multilayer Viscoelastic Damper Considering Strain Sensitivity Part 1. Theoretical Construction and Computational Process
著者(和文)	梁其峻, 佐藤大樹, OSABEL DAVE M
Authors(English)	Qijun Liang, Daiki Sato, Dave M Osabel
出典(和文)	日本建築学会大会学術講演梗概集, 構造II, , pp. 513-514
Citation(English)	, 構造II, , pp. 513-514
発行日 / Pub. date	2024, 8
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
（関東） 2024 年 8 月

One-dimensional Analytical Methods for Full-scale Multilayer Viscoelastic Damper Considering Strain Sensitivity
Part 1. Theoretical Construction and Computational Process

正会員 ○梁 其峻*1 同 佐藤大樹*2
同 OSABEL Dave M.*3

One-dimensional modeling Time-history analysis
Multilayer Viscoelastic (VE) damper Strain sensitivity

1. INTRODUCTION

Viscoelastic (VE) dampers are effective passive control devices, offering stiffness and damping to control the vibrations from wind to earthquakes by converting shear energy into heat [1]. Their properties decrease with temperature-rise, a well-researched sensitivity via 1D time-history analysis [2, 3] for small-scale two-layered VE damper. Moreover, their properties lower down if the strain level is larger than a certain value, e.g., Kasai et al.[4] found non-linear behavior when strain level > 100%.

To consider the non-linear behavior induced by the so-called strain sensitivity, Part 1 of this study proposes a 1D time-history analysis method based on multilayer VE damper model. Moreover, from the approach in Ref. [3], Part 1 further proposes a simplified 1D method improving the computation-efficiency.

2. ONE-DIMENSIONAL (1D) MODELING METHOD FOR MULTILAYER VE DAMPER

In previous 1D time-history analysis[2] that idealizes temperature variation in the thickness direction only, the two-layered small-scale VE damper was modeled as only one VE slab considering symmetry. In this current study, full-scale multilayer VE dampers are the focus – where even after considering symmetry, there are two or more layers of VE material. As such, this study divides the multilayer VE damper into 1D nodes and elements as illustrated in Fig. 1, and defines the layer index v (ranging from 1 to L) for the VE layers after considering symmetry. Nodes are numbered j = 0 to m, and the nodes at interface of steel slab and VE slab are defined by $j = j_a$ and $j = j_b$, respectively. Element j (1 to m) with thickness d_j is defined by the node j-1 and j. For the eight-layered VE damper[5] that will be introduced in Part 2, L = 4, m = 48 (= 4 × 12, each VE layer is divided into 12 segments).

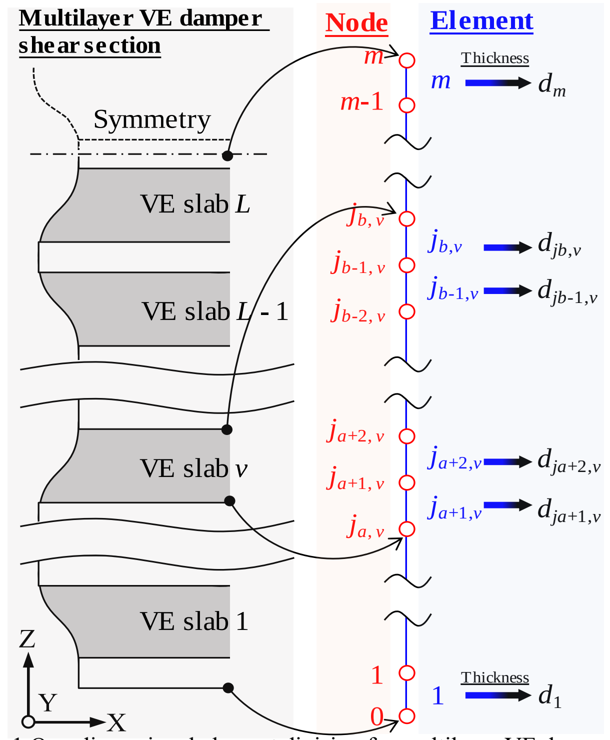


Fig. 1 One-dimensional element division for multilayer VE damper

3. NON-LINEAR ONE-DIMENSIONAL (NL-1D) TIME-HISTORY ANALYSIS METHOD

The herein NL-1D method is a combination of the 1D time-history analysis method[2] and non-linear constitutive rule[4] of strain sensitivity. After carrying out several large strain level loading experiments, the non-linear constitutive rule[4] imported two factor λ_1 and λ_2 (calculated using maximum strain level γ_{max} experienced thus-far by the VE damper), and implemented them

Material property calculations [1, 3]

Fractional derivative equation

$$\tau_v^{(n)} + a_j^{(n)} D^\alpha \tau_v^{(n)} = G_j^{(n)} [\gamma_j^{(n)} + b_j^{(n)} D^\alpha \gamma_j^{(n)}] \quad \text{--- (1)}$$

Storage shear modulus G' and loss factor η

$$G_j'^{(n)} = G_j^{(n)} \frac{1 + a_j^{(n)} b_j^{(n)} \omega^{2\alpha} + (a_j^{(n)} + b_j^{(n)}) \omega^\alpha \cos(\alpha\pi/2)}{1 + (a_j^{(n)})^2 \omega^{2\alpha} + 2(a_j^{(n)})^2 \omega^\alpha \cos(\alpha\pi/2)} \quad \text{--- (2)}$$

$$\eta_j^{(n)} = \frac{(-a_j^{(n)} + b_j^{(n)}) \omega^\alpha \sin(\alpha\pi/2)}{1 + a_j^{(n)} b_j^{(n)} \omega^{2\alpha} + (a_j^{(n)} + b_j^{(n)}) \omega^\alpha \cos(\alpha\pi/2)} \quad \text{--- (3)}$$

Weight factor w

$$w^{(0)} = 1/[(\Delta t)^\alpha \Gamma(2-\alpha) \quad \text{--- (9a)}$$

$$w^{(i)} = w^{(0)} [(i-1)^{1-\alpha} - 2i^{1-\alpha} + (i+1)^{1-\alpha}] \quad \text{--- (9b)}$$

$$w^{(N)} = w^{(0)} [(V-1)^{1-\alpha} - N^{1-\alpha} + (1-\alpha) N^{-\alpha}] \quad \text{--- (9c)}$$

Parameters

$$a_j^{(n)} = a_{ref} (\lambda_{0,j}^{(n)})^\alpha \quad \text{--- (4)}$$

$$b_j^{(n)} = b_{ref} (\lambda_{0,j}^{(n)})^\alpha \lambda_{1,v}^{(n)} \quad \text{--- (5)}$$

$$G_j^{(n)} = G \lambda_{2,v}^{(n)} \quad \text{--- (6)}$$

Temperature-rise effect

$$\lambda_{0,j}^{(n)} = \mathrm{e}^{-p_1(\theta_j^{(n)} - \theta_{ref})/(p_2 + \theta_j^{(n)} - \theta_{ref})} \quad \text{--- (7)}$$

Strain sensitivity effect

$$\lambda_{1,v}^{(n)} = 1 + C_1 (\gamma_{\max,v}^{(n)} - 1) \geq 1 \quad \text{--- (8a)}$$

$$\lambda_{2,v}^{(n)} = 1 + C_2 (\gamma_{\max,v}^{(n)} - 1) \leq 1 \quad \text{--- (8b)}$$

$C_1 = 0.124$

$C_2 = -0.182$

Dynamic analysis

Shear stress for each VE slab v

$$\tau_v^{(n)} = \frac{2G_j^{(n)} u_d^{(n)} - \sum_{j=j_a}^{j_b} \left[\zeta_j \left(a_j^{(n)} \sum_{i=1}^{N} w^{(i)} \tau^{(n-i)} - G_j^{(n)} b_j^{(n)} \sum_{i=1}^{N} w^{(i)} \gamma_j^{(n-i)} \right) / \left(1 + b_j^{(n)} w^{(0)} \right) \right]}{\sum_{j=j_a}^{j_b} \left[\zeta_j \left(1 + a_j^{(n)} w^{(0)} \right) / \left(1 + b_j^{(n)} \lambda_{1,v}^{(n)} w^{(0)} \right) \right]} \quad \text{--- (10)}$$

Nodal strain in each VE slab v

$$\gamma_j^{(n)} = \frac{\tau_v^{(n)} \left(1 + a_j^{(n)} w^{(0)} \right) + a_j^{(n)} \sum_{i=1}^{N} w^{(i)} \tau^{(n-i)} - G_j^{(n)} b_j^{(n)} \sum_{i=1}^{N} w^{(i)} \gamma_j^{(n-i)}}{G_j^{(n)} \left(1 + b_j^{(n)} w^{(0)} \right)} \quad \text{--- (11)}$$

Damper reaction force

$$F_d'^{(n)} = A_s \left(\sum_{v=1}^{L} \tau_v^{(n)} \right) / L \quad \text{--- (12)}$$

Elemental dissipated energy density ΔW_j

$$\Delta W_j^{(n)} = (\tau_v^{(n)} + \tau_v^{(n-1)})(\gamma_j^{(n)} - \gamma_j^{(n-1)}) / 2 \quad \text{--- (13)}$$

Heat transfer analysis [2]

α = fractional derivative order
G = static shear modulus
ω = circular frequency
Γ = gamma function
A_s = total shear area

Fig. 2 Algorithms used in NL-1D method

大歪依存性を考慮した実大複層粘弾性ダンパーの一次元
解析手法 その 1 理論構築と計算手順

LIANG Qijun, SATO Daiki, OSABEL Dave Montellano

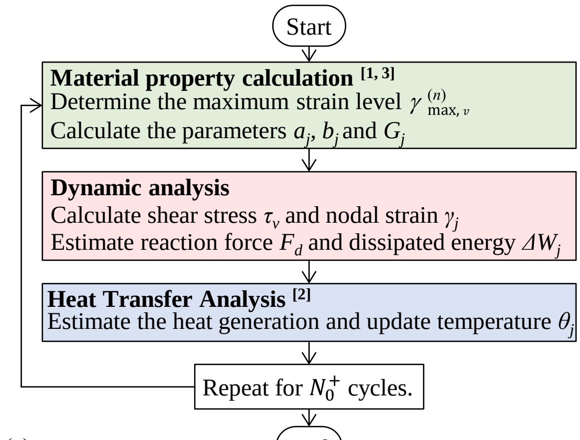
into the calculation of material properties. Hence, the non-linear behavior induced by strain sensitivity can be predicted.

The algorithms and flowchart for NL-1D method are shown in Figs. 2 and 3a, respectively. In time step n, the current maximum strain level $\gamma_{\max}^{(n)}$ of each VE slab v is determined from the average nodal strains in previous time step (from 0 to n-1). Using the $\gamma_{\max}^{(n)}$ and nodal temperature $\theta_j^{(n)}$, the shear stress $\tau_v^{(n)}$ in each VE slab v and the nodal strains $\gamma_j^{(n)}$ can be obtained considering the effects of strain sensitivity and temperature-rise. The damper reaction force $F_d^{(n)}$ (a global response) can then be estimated by $\tau_v^{(n)}$. The element dissipated energy density $\Delta W_j^{(n)}$ is calculated by Eq. 13. Finally, the nodal temperature $\theta_j^{(n+1)}$ for next time step can be obtained after heat transfer analysis[2]. The above procedure is then repeated for subsequent time step.

4. SIMPLIFIED NON-LINEAR 1D (SN-1D) TIME-HISTORY ANALYSIS METHOD

The 1D time-history analysis for VE damper is usually combined with structural analysis, therefore it must be numerically efficient. Kasai et al.[4] idealized the heat generation to be uniform in thickness direction for efficient computation. This current study adopted the same approach[4] for the NL-1D method, hence, proposing a simplified non-linear 1D (SN-1D) time-history analysis method.

The algorithms and flowchart for SN-1D method are shown in Figs. 4 and 5a, respectively. The SN-1D method calculates the weighted average temperature in each VE slab (Eq. 22) for material property calculation. Such that, the computation memory of relevant parameters can be reduced from nodes (m+1) multiplied by the time steps n (Eqs.1 - 7) to only VE layers L times the time steps n (Eqs.14 - 20). Moreover, SN-1D method idealizes the multilayer VE material as one element to have uniform shear strain $\gamma_d = u_d / d_v$ that only relates to the current deformation u_d and VE slab thickness d_v. This contrasts to the NL-1D method which uses multiple elements for one VE slab in thickness direction that results to great calculation time. With these two simplifications, SN-1D method can reduce floating-point operations and memory size (Fig. 5b) to have greater computational efficiency than NL-1D method (Fig. 3b).



(a)

Memory size (example: eight-layered VE damper [5])

$\gamma_{\max,v}^{(n)}$: 4 flops, a_j, b_j and G_j : 4 × (48+1) flops (Eqs. 4 to 6)

τ_v: 4 flops (Eq. 10), γ_j : 4 × (48+1) flops (Eq. 11),
F_d : 1 flop (Eq. 12), ΔW_j: 4 × 48 flops (Eq. 13)

(b)

Fig. 3. (a) Flowchart and (b) memory size of NL-1D method

5. CONCLUSION

Part 1 proposed a 1D time-history analysis method based on a multilayer VE damper model considering the non-linear behavior induced by strain sensitivity. Furthermore, drawing upon the approach outlined in Ref. [3], Part 1 proposed a simplified 1D method aimed at enhancing computational efficiency. The accuracy of these methods will be confirmed in Part 2 by comparing them with experimental data.

REFERENCES (See Part 2)

Material property calculations [1, 3]

Fractional derivative equation

$$\tau_v^{(n)} + a_v^{(n)} D^\alpha \tau_v^{(n)} = G_v^{(n)} [\gamma_d^{(n)} + b_v^{(n)} D^\alpha \gamma_d^{(n)}] \quad \text{--- (14)}$$

Storage shear modulus G' and loss factor η

$$G_v'^{(n)} = G^{(n)} \frac{1 + a_v^{(n)} b_v^{(n)} \omega^{2\alpha} + (a_v^{(n)} + b_v^{(n)}) \omega^\alpha \cos(\alpha\pi/2)}{1 + (a_v^{(n)})^2 \omega^{2\alpha} + 2(a_v^{(n)})^2 \omega^\alpha \cos(\alpha\pi/2)} \quad \text{--- (15)}$$

$$\eta_v^{(n)} = \frac{(-a_v^{(n)} + b_v^{(n)}) \omega^\alpha \sin(\alpha\pi/2)}{1 + a_v^{(n)} b_v^{(n)} \omega^{2\alpha} + (a_v^{(n)} + b_v^{(n)}) \omega^\alpha \cos(\alpha\pi/2)} \quad \text{--- (16)}$$

Weight average temperature in each VE slab v [4]

$$\bar{\theta}_v^{(n)} = \frac{1}{2d_v} \left[\theta_{j_a}^{(n)} d_{j_a+1} + \sum_{j=j_a+1}^{j_b-1} \theta_j^{(n)} (d_j + d_{j+1}) + \theta_{j_b}^{(n)} d_{j_b} \right] \quad \text{--- (22)}$$

Parameters

$$a_v^{(n)} = a_{ref} (\lambda_{0,v}^{(n)})^\alpha \quad \text{--- (17)}$$

$$b_v^{(n)} = b_{ref} (\lambda_{0,v}^{(n)})^\alpha \lambda_1^{(n)} \quad \text{--- (18)}$$

$$G^{(n)} = G \lambda_2^{(n)} \quad \text{--- (19)}$$

Temperature-rise effect

$$\lambda_{0,v}^{(n)} = e^{-p_1 \left(\bar{\theta}_v^{(n)} - \theta_{ref} \right) / \left(p_2 + \bar{\theta}_v^{(n)} - \theta_{ref} \right)} \quad \text{--- (20)}$$

Strain sensitivity effect

$$\lambda_1^{(n)} = 1 + C_1 (\gamma_{\max}^{(n)} - 1) \geq 1 \quad \text{--- (21a)}$$

$$\lambda_2^{(n)} = 1 + C_2 (\gamma_{\max}^{(n)} - 1) \leq 1 \quad \text{--- (21b)}$$

$C_1 = 0.124$

$C_2 = -0.182$

Dynamic analysis

Shear stress for each VE slab v

$$\tau_v^{(n)} = \frac{G^{(n)} \gamma_d^{(n)} ((\Delta t)^\alpha + b_v^{(n)} w^{(0)}) + G^{(n)} b_v^{(n)} \sum_{i=1}^{N} w^{(i)} \gamma_d^{(n-i)} - a_v^{(n)} \sum_{i=1}^{N} w^{(i)} \tau_v^{(n-i)}}{(\Delta t)^\alpha + a_v^{(n)} w^{(0)}} \quad \text{--- (23)}$$

Uniform strain in time step n [4]

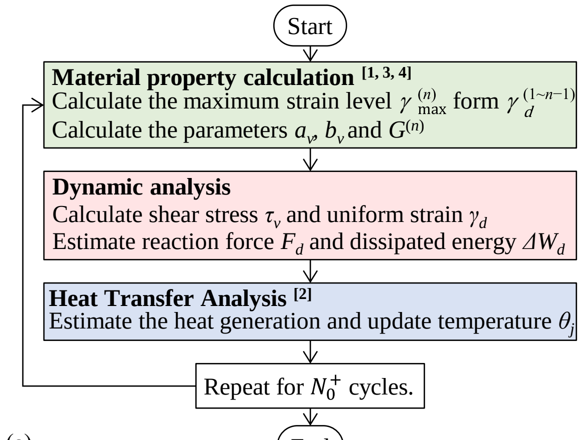
$$\gamma_d^{(n)} = u_d^{(n)} / d_v \quad \text{--- (24)}$$

Dissipated energy density in time step n

$$\Delta W_d^{(n)} = (\tau_v^{(n)} + \tau_v^{(n-1)})(\gamma_d^{(n)} - \gamma_d^{(n-1)}) / 2 \quad \text{--- (26)}$$

Heat transfer analysis [2]

Fig. 4. Algorithms used in SN-1D method.



(a)

Memory size (example: eight-layered VE damper [5])

$\gamma_{\max}^{(n)}$: 1 flops, a_v, b_v and $G^{(n)}$: 4 flops (Eqs. 17 to 19)

τ_v: 4 flops (Eq. 23), γ_d : 1 flop (Eq. 24),
F_d : 1 flop (Eq. 12), ΔW_d: 4 flops (Eq. 26)

(b)

Fig. 5. (a) Flowchart and (b) memory size of SN-1D method

*1 Graduate Student, Tokyo Institute of Technology
*2 Associate Professor, Tokyo Institute of Technology, Dr. Eng.
*3 Postdoctoral Researcher, Chonnam National University, South Korea, Ph.D.
(Former: Tokyo Institute of Technology)

＊　東京工業大学　大学院生
＊　東京工業大学　准教授・博士（工学）
＊　チョンナム大学　韓国　博士研究員
（元東京工業大学）