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EVALUATION METHOD FOR VISCOELASTIC DAMPER SUBJECTED TO LONG-DURATION WIND LOADING BY EQUIVALENT SINUSOIDAL WAVES

Dave M. OSABEL[1], Daiki SATO[2] and Kazuhiko KASAI[3]

ABSTRACT

Viscoelastic (VE) dampers are widely installed in tall buildings to mitigate structural vibrations induced by earthquake and strong wind. They dissipate the kinetic energy through shear deformation of the steel-sandwiched VE material, and in the process, heat is generated within the damper. Since the VE dampers properties (i.e., damping and stiffness) are temperature and frequency, significant damper increase from long-duration loading (e.g., wind loading) can greatly affect their performance. Customarily, their properties are easily evaluated from the hysteretic relationship of force and deformation obtained from harmonic loading. However, wind-induced vibrations of tall buildings are random by nature. Hence, the authors propose an evaluation method by considering equivalent sinusoidal waves of the long-duration random deformation based on the random vibration or spectral approach which is fundamentally used in wind engineering. Taking into account the frequency dependency of VE dampers, low-frequency and high-frequency components of the random deformation are separated, thus, two equivalent sinusoidal waves are considered in the dynamic analysis considering heat generation and transfer analysis. Combined results from these equivalent sinusoidal waves agree well those the original random deformation.

Key Words: Viscoelastic damper, Long-duration random wind loading, Temperature-frequency dependencies, Equivalent sinusoidal wave

1. INTRODUCTION

1.1 Viscoelastic Damper and Its Dynamic Properties

Properly employed viscoelastic (VE) dampers (e.g., Figure 1) in tall buildings can mitigate structural vibrations induced by earthquake and strong wind. Energy is dissipated through the shear deformation of the steel-sandwiched VE material and is converted to a small amount of heat. For long-duration loading, damper temperature significantly and consequently, changing the VE damper dynamic properties (i.e., damping and stiffness).

Customarily, dynamic properties of VE dampers from the hysteretic relationship of the damper force F_d and deformation u_d (Figure 2a), or of the shear stress τ and strain γ (Figure 2b) obtained from harmonic loading. Here: F_d' and F_d''= forces are at maximum deformation u_{d0} and zero deformations, respectively; K_d' and K_d'' = storage stiffness and loss stiffness, respectively; W_d = energy dissipated for one cycle which is equal to the area of the inclined ellipse;

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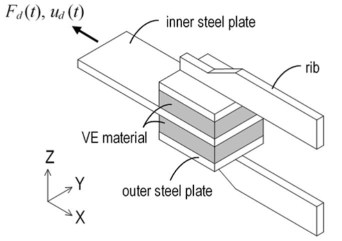

Figure 1. VE Damper

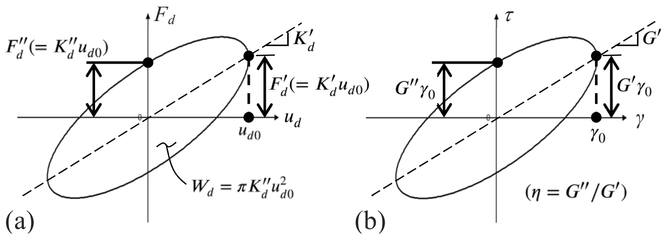

Figure 2. (a) Force-deformation curve and (b) shear stress-strain curve obtained from harmonic loading.

G' and G''= storage modulus and loss modulus, respectively, and; η = loss factor. Among many factors that affects the VE material behavior, structural engineers are mostly concern with the significant effect of frequency and temperature at which the VE damper operates. At low frequency and high temperature, a VE damper has low dynamic properties. On the other hand, at high frequency and low temperature, a VE damper has high dynamic properties(1).

1.2 Evaluating VE Properties for Random Loading

VE properties can be easily determined by considering harmonic loading. However, real world excitations such earthquakes and strong wind act randomly – thereby, VE dampers deform in random manner (e.g., Figure 3a), and damper forces have will have similar wave pattern as those of damper deformation (Figure 3b). Under random loading, the VE damper force-deformation hysteresis curves (Figure 3c) are not the typical elliptical curves shown in Figure 2, thus, it is quite difficult to grasp the properties of VE dampers.

In 2015, Sato et al.(2) addressed the aforementioned matter by proposing the use of equivalent sinusoidal deformation. They calculated the frequency f_r and amplitude A_r of the equivalent sinusoidal deformation as:

$$f_r = N_0^+ / t_a \quad \text{and} \quad A_r = \sigma_u \sqrt{2} \ , \qquad (1a, b)$$

where N_0^+ = number of positively sloped x-intercept, t_a = duration of random loading, and σ_u = standard deviation of the random deformation. An example of the random deformation and its equivalent sinusoidal deformation are shown in Figure 4.

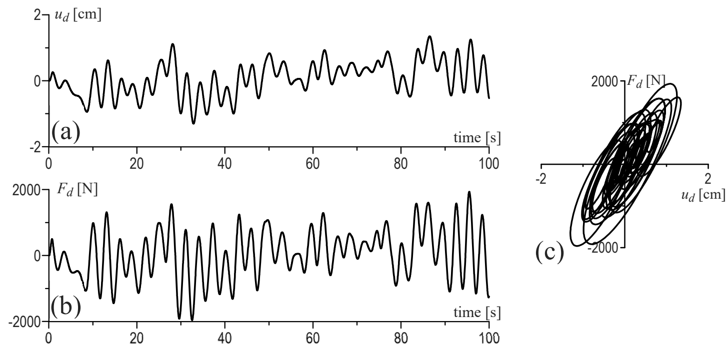

Figure 3. Example of (a) damper deformation and (b) damper force from random excitation, and (c) their F_d-u_d curve.

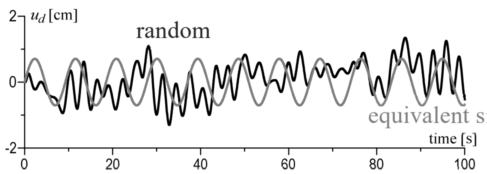

Figure 4. An example of a random deformation vs. equivalent sinusoidal deformation(2).

1.3 Objective of the Study

As will be demonstrated in Chapter 2, there is a noticeable difference between the cumulative energy dissipated W_d of the original random deformation and equivalent sinusoidal loading. Therefore, the goal of this study is to introduce a modified equivalent sinusoidal deformation for the analysis of VE dampers.

2. ANALYSIS OF VISCOELASTIC DAMPER BY PREVIOUS MODELS

2.1 VE Damper Details

The VE damper (Figure 5) with ISD 111 type at ambient temperature θ_0 = 24°C in the study of Sato et al.(2) is used in this paper. Please refer to reference article(2) for the material properties of the VE damper.

2.2 Displacement-Controlled Random Loading

Random Deformation. Figure 6 (leftmost column) shows the random deformation time-histories used in the analysis. These were determined from the time-history analysis of a building with natural period T_n = 3 seconds (or natural frequency f_n = 0.333 Hz) and damping ratio h = 2% subjected to long-duration wind loading. These deformations were normalized such that their root-mean square (RMS) values were the same. This normalization was done in order to eliminate the effect of different strain levels at which the VE damper deforms, thus, better grasping the effect of frequency content of the response.

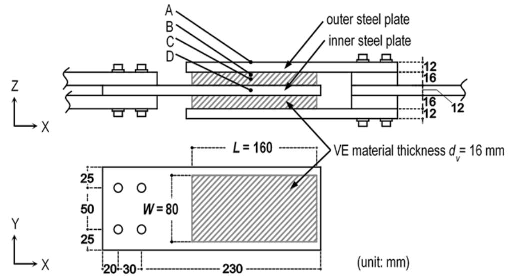

Figure 5. VE damper in the study of Sato et al. [2].

In addition, the power spectral density (PSD) plots of the along-and across-wind damper deformations are shown in Figure 6 (center column). Both these PSD plots have peaks at natural frequency f_n but the along-wind deformation contains more low-frequency vibration than in across-wind deformation.

Equivalent-Sinusoidal Deformation. For the along-wind random deformation, N_0^+ = 3452 and σ_u = 0.50 cm. For the across-wind VE damper random deformation, N_0^+ = 3460 and σ_u = 0.50 cm. For both wind directions, t_a = 12000 seconds. By Equation (1), the equivalent-sinusoidal deformations in the along- and across-wind directions are the similar with f_r = 0.288 Hz and A_r = 0.707 cm.

2.3 VE Damper Analyses

The two prediction models proposed by Kasai et al.(3) were used in the analyses of the VE damper. The first model is a combination of three-dimensional heat transfer analysis and static analysis using common finite element model of the damper. Using the equivalent-sinusoidal deformations mentioned above, the first model was used to estimate the heat transfer coefficient α_c of the VE damper. The results were validated with test.

The second model(3) is a combination of one-dimensional (1D) heat transfer analysis and viscoelastic constitutive rule using the fractional-derivatives of stress and strain. This model can carry out time-history analysis and can accurately simulate VE damper under long-duration loading, thus, referred as *Long-Duration (LD) Model*. The equivalent 1D heat transfer coefficients $\alpha_{c,out}$ and $\alpha_{c,in}$ for the outer and inner plates, respectively, used for the LD model were determined from the α_c values estimated from the first model (details presented in reference article(3)).

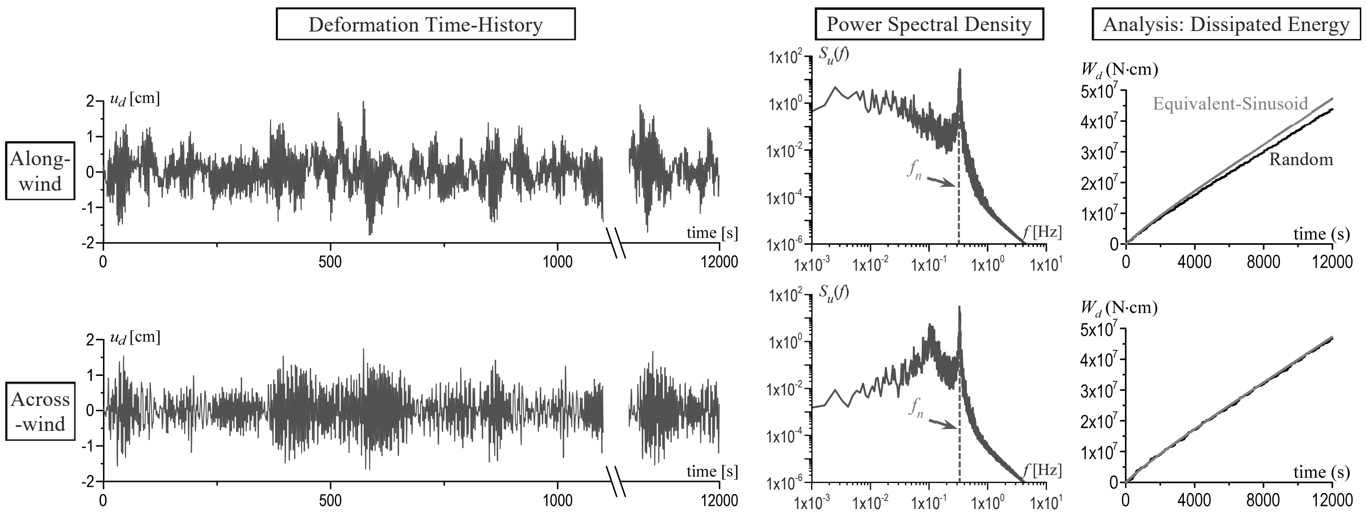

Figure 6. Damper deformation time-history. Power spectral density of damper deformation. Cumulative energy dissipated: random vs. equivalent-sinusoidal of damper deformation.

Although not shown, the temperature, storage stiffness and loss stiffness from the LD model analysis of VE damper with the equivalent-sinusoidal deformation appear to be similar to those from the original random loading. However, upon closer look into the cumulative energy dissipated W_d shown in Figure 6 (rightmost column), significant variation can be seen in the along-wind direction. The W_d obtained from the equivalent-sinusoidal deformation is higher than those from the original random deformation – such variation is inherently attributed to using only one equivalent-sinusoid. Since only one single frequency is used, significant contribution of the low-frequency broad-band content of the along-wind random deformation is neglected. As demonstrated by Ogawa et al.(6), such low-frequency quasi-static response component of base-isolated building is significant.

Since VE damper performance decreases with temperature rise, and temperature increase is directly linked to the amount of energy dissipated, it is therefore imperative to modify the equivalent-sinusoidal deformations to better evaluate VE damper under long-duration wind loading. A good agreement of energy dissipated is a strong indicator that the random deformation is well represented.

3. MODIFIED EQUIVALENT SINUSOIDAL DEFORMATIONS CONSIDERING SPECTRAL APPROACH

3.1 Theoretical Background: Dynamic Response of Structures to Wind Loading by Spectral Approach

Figure 7a shows the random vibration approach to resonant dynamic response of structures against wind loadings outlined by Davenport(4), where the spectral density (which uses frequency domain) is used to perform calculations (e.g., gust spectrum, wind force, and structure responses). Accordingly, the determined response spectrum has two components: the background and resonant (Figure 7b). The broadband background component B represents the quasi-static response due to the wind gust lower than the natural frequency of the structure, thus, similar shape to wind force spectrum. On the other hand, the narrowband resonant component R represents the structure response due to resonance(5).

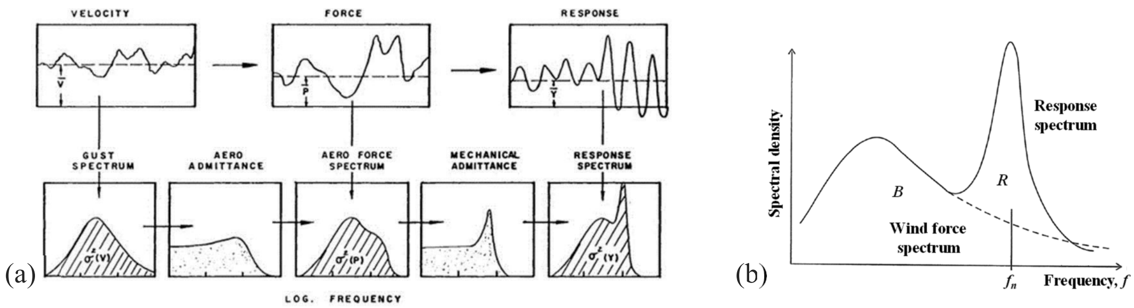

Figure 7. (a) Random vibration (frequency domain) approach to resonant dynamic response(4), and (b) background and resonant components of response(5).

3.2 Modified Equivalent Sinusoidal VE Damper Deformation by Spectral Approach

Since viscoelastic (VE) damper employed to tall buildings deforms similarly to that of the building dynamic response, its response spectra will be similarly shaped as those of building response (Figure 7b). As such, the PSD plots of the damper deformations due wind loading shown in Figure 6 (center column) can also be described by the random vibration approach (Section 3.1). With VE dampers being highly sensitive to excitation frequency, thus, the individual effects of the low-frequency broadband background component and high-frequency narrowband resonant component are considered in modifying the equivalent-sinusoidal deformation which is summarized below.

Flowchart on how to carry out analysis using the modified equivalent-sinusoidal deformation is shown in Figure 8. First, quasi-static frequency f_{qs} is considered. According to Ogawa et al.(6), f_{qs} is reasonably equal to 1/3 of f_n. Response lower than f_{qs} will be considered to be background component, and those higher than f_{qs} will be considered to be resonant component.

In order to determine the random damper deformation corresponding to the background and resonant components, the original random damper deformation u_d will be filtered using low-pass filter and high-pass filter, respectively.

From these filtered random deformations, the equivalent sinusoidal background and resonant deformations are determined using the same calculation technique by Sato et al.[(2)] (Equation (1)). Accordingly,

$$f_{r,B} = N^{+}_{0,B} / t_a \text{ , and } A_{r,B} = \sigma_{u,B}\sqrt{2} \text{ ,} \qquad (2a, b)$$

$$f_{r,R} = N^{+}_{0,R} / t_a \text{ , and } A_{r,R} = \sigma_{u,R}\sqrt{2} \text{ ,} \qquad (3a, b)$$

where subscripts B and R refer to the values corresponding to the background and resonant components, respectively.

The VE damper is then analyzed using the LD model[(3)] considering the modified equivalent-sinusoidal deformations from Equations 2 and 3. Finally, results from the VE damper analyses using the equivalent-sinusoidal background and resonant deformations are then combined, and compared with those from the original random deformation.

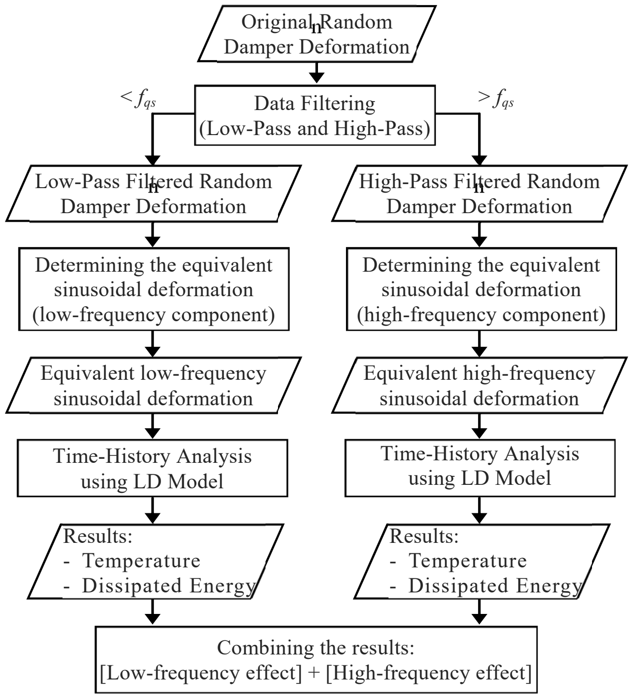

Figure 8. Flowchart of viscoelastic damper analysis using modified equivalent sinusoidal deformation.

4. VERIFICATION OF THE MODIFIED EQUIVALENT SINUSOIDAL DEFORMATION

The VE damper and random damper deformations in Chapter 2 are used to verify the proposed method. Since the natural frequency of the structure f_n = 0.333 Hz, the quasi-static frequency f_{qs} = 0.111 Hz. For the low-pass and high-pass filtering of the random damper deformation, the built-in Butterworth filter approximation (filter order = 5) in MATLAB was used. The adopted filter approximation was validated by checking the area of the PSD and the σ_u of the thus-filtered random deformations. Figure 9 shows the PSD and the time-history of the thus-filtered random deformations. As indicated in Table 1, for both the along- and across wind directions, $N^{+}_{0,B} < N^{+}_{0} < N^{+}_{0,R}$ but $\sigma_{u,B} < \sigma_{u,R} < \sigma_u$.

Using Equations 2 and 3, the parameters for the background and resonant components of the modified equivalent sinusoidal deformations are calculated and indicated in Table 1, where $f_{r,B} < f_r < f_{r,R}$ and $A_{r,B} < A_{r,R} < A_r$. Note that parameters for the background component are consistently the least and that $A_{r,B} \leq 0.5A_r$. The time-history of the equivalent sinusoidal deformations are shown in Figure 9.

Analyses using the modified equivalent sinusoidal deformations using the model[(3)] were then carried out. As seen in Figure 9, the effect of the equivalent-sinusoidal background deformation is very small compared to that of the resonant deformation, which is attributed to the small $f_{r,B}$ and $A_{r,B}$. Finally, the individual energy dissipated from the background and resonant deformations are combined, and result matches well with those from original random deformation – greatly improving the previous method result shown in Figure 6.

Although not shown here, temperatures from the analysis using the modified equivalent sinu-

Table 1. Parameters for the equivalent sinusoidal deformations.

Direction	Component	N^{+}_{0}	σ_u (cm²)	f_r (Hz)	A_r (cm)
Along-wind	Unfiltered (Original)	3452	0.500	0.288	0.707
	Background	424	0.068	0.035	0.369
	Resonant	3933	0.183	0.328	0.606
Across-wind	Unfiltered (Original)	3460	0.500	0.288	0.707
	Background	1108	0.025	0.092	0.224
	Resonant	3729	0.206	0.311	0.642

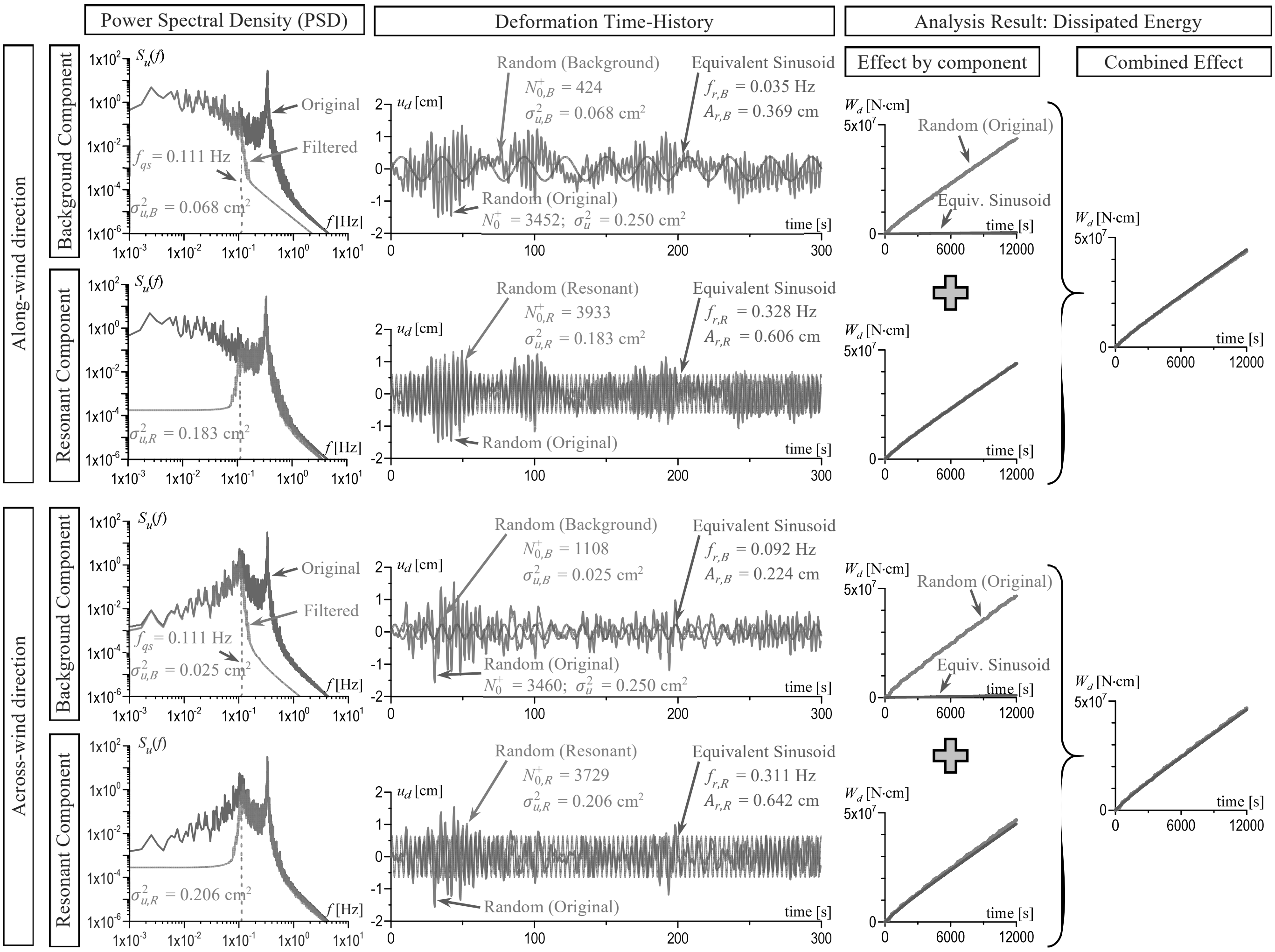

Figure 9. LD model results using the modified equivalent-sinusoidal deformations.

soidal deformations also match well with those from the original random damper deformation.

5. CONCLUSIONS

Based on the principle of random vibration or spectral approach, this paper proposed modified equivalent-sinusoidal deformations to evaluate VE dampers under long-duration wind-loading. By this, the frequency sensitivity of VE damper is greatly considered. Since the individual effects of each response component are combined to evaluate the VE damper, only the damper temperature and the cumulative dissipated energy can be readily investigated by direct summation. Results show improved accuracy with the original random loading than the previous evaluation method. Technique of evaluating the dynamic properties (damping and stiffness) is still being formulated.

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