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# Design for VE Damper with ZR-GD model considering Frequency Dependency

構造－振動

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ZR-GD model　wind-resistant design　viscoelastic damper
frequency dependency　zero-crossing rate

## 1. Introduction

According to wind resistance design codes, such as Architectural Institute of Japan (AIJ) recommendations for loads on buildings (Japan Standard) [1], the design method for wind-resistant buildings considers factors of natural frequency and damping ratio. Those parameters are based on the assumption of linear elastic structure.

However, the wide-band frequency of wind force affects viscoelastic-damped buildings significantly due to the frequency dependency of the viscoelastic (VE) damper. The zero-crossing-rate-based global damping (ZR-GD) model, the simple model considering its frequency dependency is proposed in the previous chapter. Besides, most of the VE damper designs for high-rise buildings are limited to seismic, and the wind-resistant design is lacking considering the frequency dependency of the structure.

In this study, a design method for the VE damper is proposed, which is based on the AIJ recommendation to calculate the static wind loads with the ZR-GD model. Note that, the AIJ recommendation is based on the probability theory, so the ensemble average of 10 maximum responses (simulated by time history analysis) is used to verify the feasibility of the design method.

## 2. Design method for VE damper

The goal is to design the 1st modal VE damper of an SDOF model to obtain $A_s/d$, a parameter of the fractional derivative (FD) model. The design flow (with the flow chart shows in Fig. 1) is expressed as follows:

***Step 1:***

1-1. Determine the target building with height $H$, width $B$, and depth $D$.

1-2. Determine the wind load with the terrain of III, the return period of 500 years, and the design wind speed of $57.9\ m/s$.

1-3. Determine parameters of the VE damper, including $a$, $b$, $\alpha$, $G$, and $K_\mathrm{b}$.

***Step 2:***

2-1. Set a target drift ratio $R$ (Eq. (1)) of the wind-induced response, and set the natural period $T_\mathrm{f}$. Note that, the single-degree-of-freedom (SDOF) model of the 1st mode is employed in the simulation.

$$R = \delta_\mathrm{max}\Phi_{11}/H. \tag{1}$$

Where $\delta_\mathrm{max}$ is the 1st modal target deformation, and $\Phi_{11}$ is (1,1) of the eigenvector.

2-2. According to Fig. 2 to set the referring damping ratio $\xi'$.

2-3. Based on Architectural Institute of Japan (AIJ) recommendations for loads on buildings [1]), the 1st modal wind load in the along- and across-wind directions $(W_\mathrm{D}, W_\mathrm{L})$ are calculated. Note that, when calculating $W_\mathrm{D}$ in the along-wind direction, the mean component is considered. Then, select the maximum wind load (Eq. (2)) for the design of the VE damper.

$$W_\mathrm{max} = max\{W_\mathrm{D}, W_\mathrm{L}\}. \tag{2}$$

According to Eq. (3), the 1st modal stiffness of system $K'$ is obtained.

$$K' = W_\mathrm{max}/\delta_\mathrm{max}. \tag{3}$$

***Step 3:***

3-1. Calculate the storage stiffness $K'_\mathrm{a}$ (Eq. (4)), loss factor $\eta_\mathrm{a}$ (Eq. (5)), lost stiffness $K''_\mathrm{a}$ (Eq. (6)) of the added component of VE system, and build up the transfer function of the VE system [2,3] (Eq. (7)).

$$K'_\mathrm{a} = K' - K_\mathrm{f}. \tag{4}$$

$$\eta_\mathrm{a} = 2\xi'(1 + K_\mathrm{f}/K'_\mathrm{a}). \tag{5}$$

$$K''_\mathrm{a}(\omega) = K'_\mathrm{a}(\omega)\eta_\mathrm{a}(\omega). \tag{6}$$

$$H_\mathrm{D}(i\omega) = \frac{1}{1 - \left(\frac{\omega}{\omega_n}\right)^2 + \frac{K'_\mathrm{a}(\omega)}{K_\mathrm{f}} + i\left(\frac{K''_\mathrm{a}(\omega)}{K_\mathrm{f}}\right)}\frac{1}{K_\mathrm{f}}. \tag{7}$$

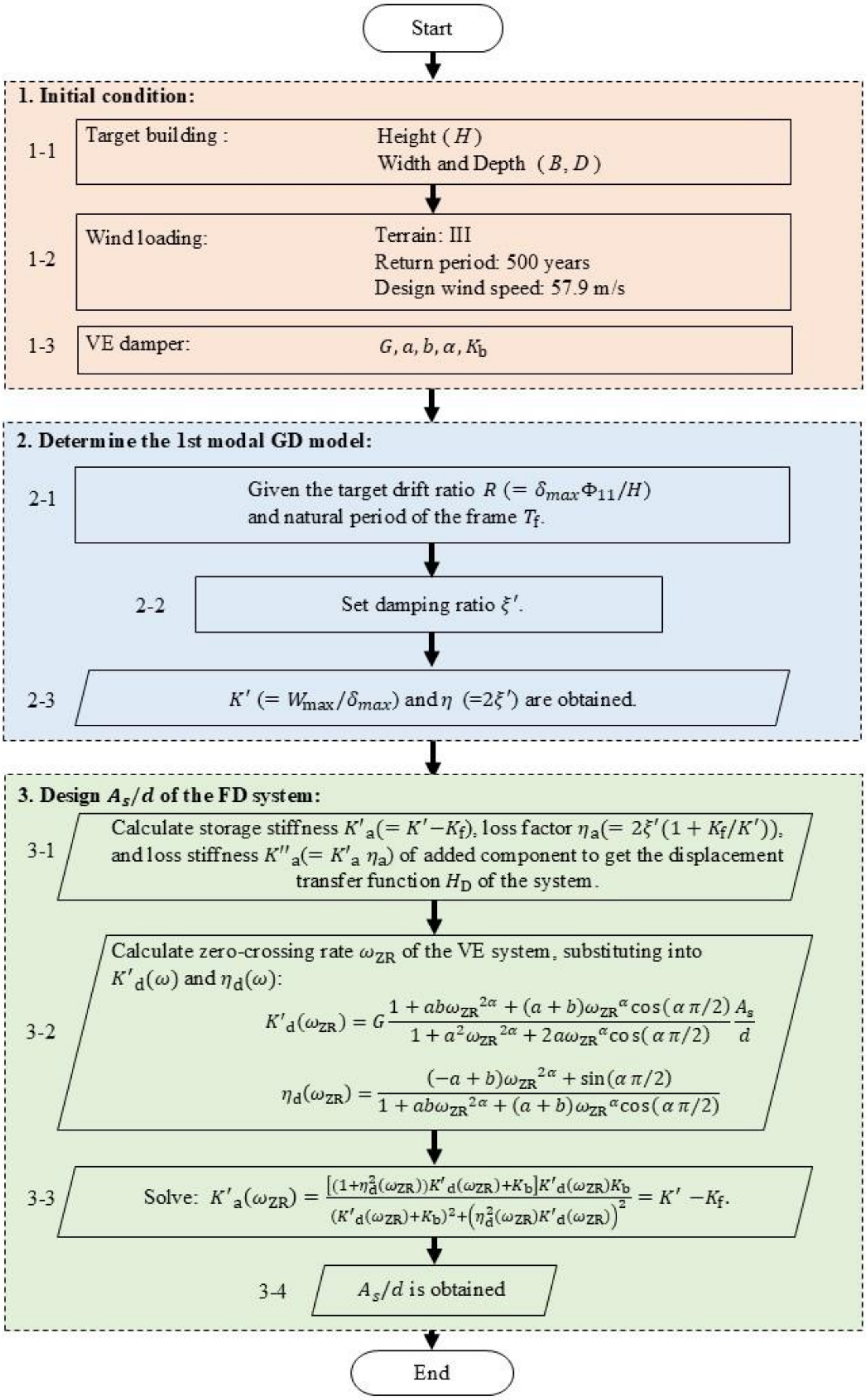
3-2. Use the frequency domain method to obtain the zero-crossing rate $\omega_\mathrm{ZR}$ (Eq. (8)) of the VE system with the power spectral density (PSD) of wind force $S_\mathrm{F}(\omega)$ and the transfer function of the VE system. Note that, the zero-crossing rate $\omega_\mathrm{ZR}$ is not affected by the mean component. Here, use one wind force $S_\mathrm{F}(\omega)$ to get the zero crossing rate.

$$\omega_\mathrm{ZR} = \frac{\sigma_\mathrm{V}}{\sigma_\mathrm{D}} = \frac{\sqrt{\int_0^\infty |i\omega H_\mathrm{D}(i\omega)|^2\, S_\mathrm{F}(\omega)d\omega}}{\sqrt{\int_0^\infty |H_\mathrm{D}(i\omega)|^2\, S_\mathrm{F}(\omega)d\omega}} \tag{8}$$

The storage stiffness $K'_\mathrm{d}$ and loss factor $\eta_\mathrm{d}$ of the VE damper considering $\omega_\mathrm{ZR}$ are given by Eq. (9) and Eq. (10).

$$K'_\mathrm{d}(\omega_\mathrm{ZR}) = G\frac{1 + ab\omega_\mathrm{ZR}^{2\alpha} + (a+b)\omega_\mathrm{ZR}^{\alpha}\cos(\alpha\pi/2)}{1 + a^2\omega_\mathrm{ZR}^{2\alpha} + 2a\omega_\mathrm{ZR}^{\alpha}\cos(\alpha\pi/2)}\frac{A_\mathrm{s}}{d}. \tag{9}$$

$$\eta_\mathrm{d}(\omega_\mathrm{ZR}) = \frac{(-a+b)\omega_\mathrm{ZR}^{2} + \sin(\alpha\pi/2)}{1 + ab\omega_\mathrm{ZR}^{2\alpha} + (a+b)\omega_\mathrm{ZR}^{\alpha}\cos(\alpha\pi/2)}. \tag{10}$$



**1. Initial condition:**

1-1 Target building : Height ($H$) Width and Depth ($B, D$)

1-2 Wind loading: Terrain: III Return period: 500 years Design wind speed: 57.9 m/s

1-3 VE damper: $G, a, b, \alpha, K_{\mathrm{b}}$

**2. Determine the 1st modal GD model:**

2-1 Given the target drift ratio $R\ (=\delta_{max}\Phi_{11}/H)$ and natural period of the frame $T_{\mathrm{f}}$.

2-2 Set damping ratio $\xi'$.

2-3 $K'\ (=W_{\max}/\delta_{max})$ and $\eta\ (=2\xi')$ are obtained.

**3. Design $A_s/d$ of the FD system:**

3-1 Calculate storage stiffness $K'_{\mathrm{a}}(=K'-K_{\mathrm{f}})$, loss factor $\eta_{\mathrm{a}}(=2\xi'(1+K_{\mathrm{f}}/K'))$, and loss stiffness $K''_{\mathrm{a}}(=K'_{\mathrm{a}}\ \eta_{\mathrm{a}})$ of added component to get the displacement transfer function $H_{\mathrm{D}}$ of the system.

3-2 Calculate zero-crossing rate $\omega_{\mathrm{ZR}}$ of the VE system, substituting into $K'_{\mathrm{d}}(\omega)$ and $\eta_{\mathrm{d}}(\omega)$:

$$K'_{\mathrm{d}}(\omega_{\mathrm{ZR}}) = G\frac{1+ab{\omega_{\mathrm{ZR}}}^{2\alpha}+(a+b){\omega_{\mathrm{ZR}}}^{\alpha}\cos(\alpha\pi/2)}{1+a^2{\omega_{\mathrm{ZR}}}^{2\alpha}+2a{\omega_{\mathrm{ZR}}}^{\alpha}\cos(\alpha\pi/2)}\frac{A_s}{d}$$

$$\eta_{\mathrm{d}}(\omega_{\mathrm{ZR}}) = \frac{(-a+b){\omega_{\mathrm{ZR}}}^{2\alpha}+\sin(\alpha\pi/2)}{1+ab{\omega_{\mathrm{ZR}}}^{2\alpha}+(a+b){\omega_{\mathrm{ZR}}}^{\alpha}\cos(\alpha\pi/2)}$$

3-3 Solve: $K'_{\mathrm{a}}(\omega_{\mathrm{ZR}}) = \frac{\left[(1+\eta_{\mathrm{d}}^2(\omega_{\mathrm{ZR}}))K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})+K_{\mathrm{b}}\right]K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})K_{\mathrm{b}}}{(K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})+K_{\mathrm{b}})^2+\left(\eta_{\mathrm{d}}^2(\omega_{\mathrm{ZR}})K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})\right)^2} = K' - K_{\mathrm{f}}$.

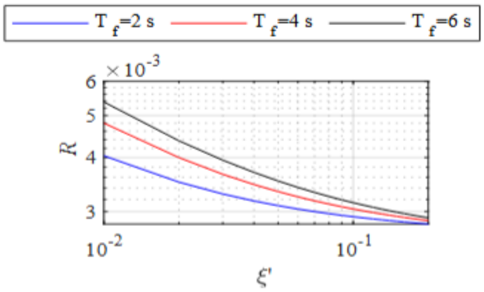
3-4 $A_s/d$ is obtained

Figure 1. Flow chart for the design method of VE system

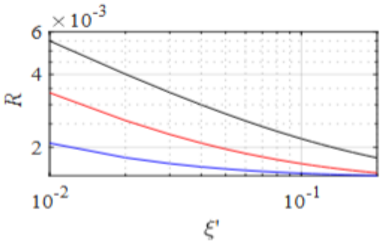
3-3. Solve the equation of storage stiffness $K'_{\mathrm{a}}$ (Eq. (11)) equaling the storage stiffness $K'_{\mathrm{a}}(\omega_{\mathrm{ZR}})$ considering $\omega_{\mathrm{ZR}}$ (Eq. (8)).

$$K'_{\mathrm{a}}(\omega_{\mathrm{ZR}}) = \frac{\left[\left(1+\eta_d^2(\omega_{\mathrm{ZR}})\right)K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})+K_{\mathrm{b}}\right]K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})K_{\mathrm{b}}}{(K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})+K_{\mathrm{b}})^2+\left(\eta_{\mathrm{d}}(\omega_{\mathrm{ZR}})K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})\right)^2} \qquad (11)$$
$$= K' - K_{\mathrm{f}}.$$

3-4. $A_{\mathrm{s}}/d$ is obtained.



**(a) Along-wind**



**(b) Across-wind**

Figure 2. Relationship of $R$ and $\xi'$

## 3. Example for Design method of VE damper

To verify the feasibility of the design method for the frequency-dependent VE dampers, this section is based on the design flow to express three design samples in the following sections.

### 3.1. Initial settings of the building and target deformation

The initial settings of the building consider a is $H = 200$ m with an aspect ratio $H/\sqrt{BD} = 4$, whose $D = B = 50$ m. The natural period of the frame is set as $T_{\mathrm{f}} = 0.02H$ (4 sec). The referring damping ratio $\xi' = 12\%$ (see Fig. 2). The target drift at the top of the building is set as $R = 0.003$. The 1st modal target deformation is $\delta_{max} = 113.8$ m.

### 3.2. Maximum wind load

Based on Architectural Institute of Japan (AIJ) recommendations for loads on buildings [1], to calculate the 1st modal wind load in the along- and across-wind directions $(W_{\mathrm{D}}, W_{\mathrm{L}})$, and select the maximum wind load (Eq. (2)) for designing of the VE damper.

$$W_{\max} = max\{W_{\mathrm{D}}, W_{\mathrm{L}}\}.$$
$$= max\{1132.4, 631.6\}.$$
$$= 1132.4 \quad [\mathrm{kN}].$$

### 3.3. Stiffness of system and added component

The 1st modal stiffness of system $K'$ is given by Eq. (3).

$$K' = W_{\max}/\delta_{\max}.$$
$$= \frac{1132.4}{113.8}.$$
$$= 9.951 \quad [\mathrm{kN/m}].$$

The storage stiffness $K'_{\mathrm{a}}$, loss factor $\eta_{\mathrm{a}}$, lost stiffness $K''_{\mathrm{a}}$ of the added component of VE system are given by Eq. (4) - Eq. (6).

$$K'_{\mathrm{a}} = K' - K_{\mathrm{f}}.$$
$$= 9.951 - 2.467.$$
$$= 7.484[\mathrm{kN/m}].$$

$$\eta_{\mathrm{a}} = 2\xi'(1 + K_{\mathrm{f}}/K'_{\mathrm{a}}).$$
$$= 2 \cdot 0.12(1 + 2.467/7.484).$$
$$= 0.319.$$

$$K''_{\mathrm{a}} = K'_{\mathrm{a}}\eta_{\mathrm{a}}(\omega).$$
$$= 7.484 \cdot 0.319.$$
$$= 2.388[\mathrm{kN/m}].$$

### 3.4. Zero-crossing rate $\omega_{\mathrm{ZR}}$ of wind-induced response

Based on the frequency domain method, the zero-crossing rate $\omega_{\mathrm{ZR}}$ of the VE system is obtained with the power spectral density (PSD) of wind force $S_{\mathrm{F}}(\omega)$ and the transfer function of the VE system, which is given by Eq. (8).

$$\omega_{\mathrm{ZR}} = \frac{\sigma_{\mathrm{V}}}{\sigma_{\mathrm{D}}} = \frac{\sqrt{\int_0^\infty |i\omega H_{\mathrm{D}}(i\omega)|^2 S_{\mathrm{F}}(\omega)d\omega}}{\sqrt{\int_0^\infty |H_{\mathrm{D}}(i\omega)|^2 S_{\mathrm{F}}(\omega)d\omega}}.$$
$$= 0.037 \quad [\mathrm{rad}].$$

### 3.5. Stiffness and loss factor of the damper

The storage stiffness $K'_{\mathrm{d}}$ and loss factor $\eta_{\mathrm{d}}$ of the VE damper considering $\omega_{\mathrm{ZR}}$ are given by Eq. (9) and Eq. (10).

$$K'_{\mathrm{d}}(\omega_{\mathrm{ZR}})$$
$$= G\frac{1 + ab\omega_{\mathrm{ZR}}^{2\alpha} + (a+b)\omega_{\mathrm{ZR}}^{\alpha}\cos(\alpha\pi/2)}{1 + a^2\omega_{\mathrm{ZR}}^{2\alpha} + 2a\omega_{\mathrm{ZR}}^{\alpha}\cos(\alpha\pi/2)}\frac{A_{\mathrm{s}}}{d}.$$
$$= 4.758 \cdot 10^4\left(\frac{A_{\mathrm{s}}}{d}\right).$$

$$\eta_{\mathrm{d}}(\omega_{\mathrm{ZR}}) = \frac{(-a+b)\omega_{\mathrm{ZR}}^{2} + \sin(\alpha\pi/2)}{1 + ab\omega_{\mathrm{ZR}}^{2\alpha} + (a+b)\omega_{\mathrm{ZR}}^{\alpha}\cos(\alpha\pi/2)}.$$
$$= 0.636.$$

Where $a = 5.6 \times 10^{-5}$, $b = 2.10$, $\alpha = 0.558$, and $G = 3.92 \times 10^4$ $[\mathrm{N/cm^2}]$ [4].

### 3.6. Get the design value of $A_s/d$

Do convergence of storage stiffness $K_a'$ with the storage stiffness $K_a'(\omega_{ZR})$ considering $\omega_{ZR}$ to obtain the design value of $A_s/d$.

$$K'_a(\omega_{ZR}) = \frac{\left[\left(1+\eta_d^2(\omega_{ZR})\right)K_d'(\omega_{ZR}) + K_b\right]K_d'(\omega_{ZR})K_b}{(K'_d(\omega_{ZR}) + K_b)^2 + \left(\eta_d(\omega_{ZR})K'_d(\omega_{ZR})\right)^2} = 7.484.$$

$$\frac{\left[(1+0.636^2)4.758\cdot 10^4\left(\frac{A_s}{d}\right) + 2.47\cdot 10^5\right]4.758\cdot 10^4\left(\frac{A_s}{d}\right)2.47\cdot 10^5}{\left(4.758\cdot 10^4\left(\frac{A_s}{d}\right) + 2.47\cdot 10^5\right)^2 + \left(0.636\cdot 4.758\cdot 10^4\left(\frac{A_s}{d}\right)\right)^2} = 7.484.$$

$$\therefore A_s/d = 1.573\cdot 10^{-4} \quad [\mathrm{m}].$$

Where $K_b$ is determined as $K_b = 10^5 K_f$.

Fig. 3 shows the comparison of the 10-ensemble-averaging 1st modal maximum wind-induced displacement and target deformation. It expresses that the 10-ensemble-averaging 1st modal maximum wind-induced displacement (obtained by time history analysis) is smaller than the 1st modal target deformation. Thus, $A_s/d$ satisfies the target amount of the VE damper.

## 4. Conclusions

This study proposed a design method for the VE-damped tall buildings considering their frequency dependency subjected to wind forces. The simple model of the zero-crossing-rate-based global damping (ZR-GD) model is used in the design method to reduce the complicated procedure of convergence in the algorithm of the fractional derivative (FD) model. In addition, the design method also considered wind load as the inner shear force of the VE system, which makes the VE damper for wind resistance. Finally, the time history analysis results of the FD model verified good agreements with target deformation. Thus, the proposed design method is efficient for designing VE dampers equipped in tall buildings.

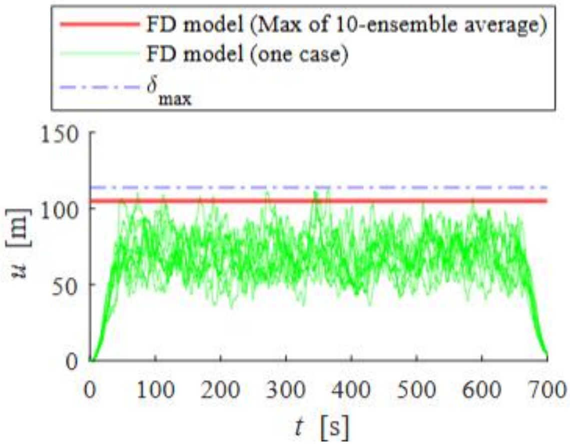


Figure 3. Comparison of maximum wind-induced displacement and target deformation
($R = 0.003$, $T_f = 4$s, and $\xi' = 12\%$)

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