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Accuracy of Mass Reduction Method for High-Rise Buildings with Steel Dampers under Wind Load with Varying Mass Count

High-rise building　Steel damper　CFD
Wind response　Reduction method

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1. Introduction

The estimation of the wind-induced responses is crucial for wind-resistant design. Full-scale detailed model simulations yield a relative high accuracy but is highly time-consuming. Hiratsuka et al.[1)] proposes a mass reduction method, which preserves the fundamental dynamic characteristics and parameters of the original structure, to enhance analysis efficiency of original model subjected to wind force. However, reduces the number of the lumped mass will decrease the accuracy of the accuracy of simulation results. This paper aims to investigate a relatively reasonable reduction in the number of mass points.

2. 60-DOF model

2.1 Frame model

In this study, a building with height H_f = 240 m, depth D_f = 64 m, and breadth B_f = 40 m (side length ratio D_f/B_f = 1.6) is taken as the object. The layer height of the model is h_i = 4 m, thus the number of particles N of the model is N = 240/4 =60. The density of the frame is ρ_f = 200 kg/m^3. The natural period T_f of the structure is: T_f = 0.02H_f = 4.8 s. In this study the first natural mode of the building is a straight line (${}_1\phi_i = i/60$).

2.2 Setting of the Damper

The distribution of dampers setting is shown in Fig. 2 considering shear stiffness and effective deformation ratio. Fig. 3 shows the effective deformation ratio α_{ei} for each layer. Fig. 4 shows the frame and damper model. The effective deformation ratio is assumed to be 1 for the first layer and 0.1 for the N-th layer, with a linear distribution from the first to the N-th layer. The yield displacement of the additional system δ_{ayi} is represented by the following equation:

$$\delta_{ayi} = R_{dy} \cdot h/a_{ei} \tag{1}$$

Here, R_{dy}=1/1000, is the yield deformation angle.

The damper force for each layer is divided into four stages based on the Ai distribution shown in Fig. 2. The first story yield strength Q_{dy1} and the i-th story yield strength Q_{dyi} are:

$$Q_{dy1} = \alpha_{dy1} \cdot W \tag{2}$$

$$Q_{dyi} = \frac{Q_i}{Q_1} \cdot Q_{dy1} \tag{3}$$

Here, W is the total weight of the object model, α_{dy1}=0.005, is the yield shear force coefficient, Q_i is the shear force for the i-th layer, Q_1 is the shear force for the first layer. The additional system stiffness k_{ai} is calculated by:

$$k_{ai} = \frac{Q_{dyi}}{\delta_{ayi}} \tag{4}$$

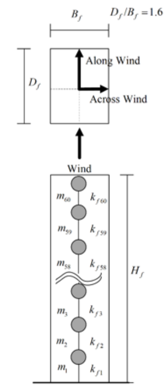


Fig 1. Frame model

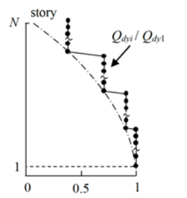


Fig 2. Dampers setting.

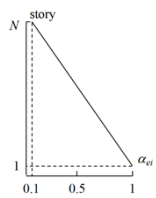


Fig 3. Deformation ratio

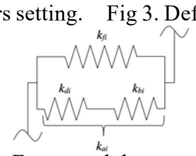
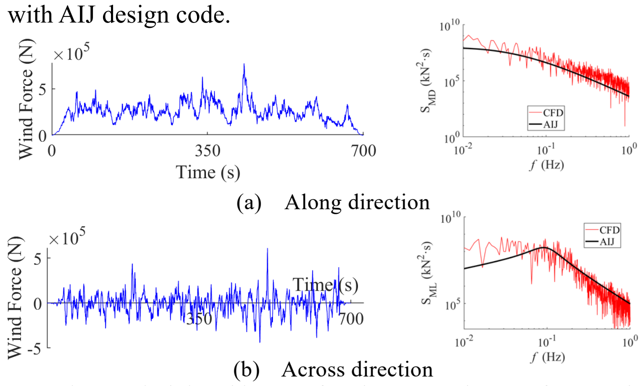


Fig 4. Frame and damper model

3. Wind wind force information of the research

The computational fluid dynamics (CFD)[2)] results were used for wind force analysis. Fig. 5 presents the wind time-history at the top story (60th story) and the PSD of the first modal wind force, of along-wind and across-wind directions comparing with AIJ design code.



(a) Along direction

(b) Across direction

Fig 5. Wind time history of 60th story and PSD of 1st mode

4. Reduction method

The reduction of the original model involves simplifying the frame, dampers, and wind force. Key parameters include mass m, frame and system's stiffness k_f and k, and additional system yield force Q_{ay}.

4.1 Reduction of the frame model

The first-order mode vector after the reduction is calculated from:

$${}_1\phi'_j = {}_1\phi_{\eta j} \tag{5}$$

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Here, $\eta = N / N'$, is the mass point ratio, is an integer. N' is the number of lumped masses after reduction.

The mass m'_j after the reduction is:

$$m'_j = \sum_{i=\eta(j-1)+1}^{\eta \cdot j} m_i \tag{6}$$

The frame stiffness k'_{fj} and the system stiffness k'_j after the reduction are expressed by the following equations:

$$k'_{fj} = \frac{{}_1\omega_f^2 \cdot m'_j \cdot {}_1\phi'_{fj} + k'_{fj+1}\left({}_1\phi'_{fj+1} - {}_1\phi'_{fj}\right)}{{}_1\phi'_{fj} - {}_1\phi'_{fj-1}} \tag{7}$$

$$k'_j = \frac{{}_1\omega^2 \cdot m'_j \cdot {}_1\phi'_j + k'_{j+1}\left({}_1\phi'_{j+1} - {}_1\phi'_j\right)}{{}_1\phi'_j - {}_1\phi'_{j-1}} \tag{8}$$

Here, ${}_1\omega_f$ is the first mode circular frequency of the steel frame. ${}_1\omega$ is the first mode circular frequency of the system.

4.2 Reduction of the damper

The stiffness k'_{ayj} of the contracted additional system is expressed using the k'_j and the k'_{fj} as follows:

$$k'_{ayj} = k'_j - k'_{fj} \tag{9}$$

The yield displacement of the additional system after the reduction is expressed as follows:

$$\delta'_{ayj} = R'_{ayj} \cdot h'_j \tag{10}$$

Here, R'_{ayj} is the interlayer deformation angle of the additional system after the reduction, is assumed to be equal to the yield interlayer angle of the corresponding layer, can be calculated from:

$$R'_{ayj} = R_{ay\eta j} \tag{11}$$

h' is the distance between mass points in the model after the reduction, can be calculated from:

$$h'_j = \sum_{i=\eta(j-1)+1}^{n \cdot j} h_i \tag{12}$$

Therefore, the yield shear force Q'_{ayi} of the additional system is calculated as follows:

$$Q'_{ayj} = k'_{ayj} \cdot \delta'_{ayj} \tag{13}$$

4.3 Reduction method of wind forces

Suzuki et al. proposes a method to reduce the wind force [3]. We reduce the wind forces from N-DOF to N'-DOF using a $N \times N'$ transformation matrix $[T]$, where $T_{nm} = 1$ if displacements correspond and $T_{kl} = 0$, otherwise (row, column order).

$$\{y'\} = [T]\{y\} \tag{14}$$

Here, $\{y\}$ is the displacement vector of the original model, and $\{y'\}$ is the displacement vector of the reduced structure model. The wind force before and after reduction are:

$$\{F\} = [K]\{y\}, \{F'\} = [K']\{y'\} \tag{15a.b}$$

The reduced wind force $\{F'\}$ is expressed as follows.

$$\{F'\} = [K'][T]\{y\} = [K'][T][K^{-1}]\{F\} \tag{16}$$

$[K]$ and $[K']$ are the stiffness matrices of the original model and the reduced structure model.

5. Numerical examples

This section uses three models with different DOFs, 60DOF, 10DOF, and 5DOF, to compare the accuracy of the method.

Fig. 6 shows the mode shapes of the first three modes for the original structure, as well as for the reduced models with 10 and 5 lumped masses. Fig. 7 shows the comparison of the dynamic responses of 60DOF, 10DOF, and 5DOF structures. From Fig. 7, it can be observed that the 60DOF structure retains the most information and achieves the highest accuracy. The 5DOF model offers the fastest analysis speed while maintaining reasonable accuracy; however, it loses excessive information regarding energy absorption by dampers, which is detrimental to evaluating damper damage. Overall, the 10DOF reduction provides a balance between computational efficiency and information retention.

6. Conclusion

This study compares the accuracy of the reduction method using different numbers of lumped mass, balancing computational efficiency and accuracy in analyzing the dynamic characteristics and wind-induced responses of high-rise structures. Numerical examples show that the 10 DOF model provides a balance between computational efficiency and information retention.

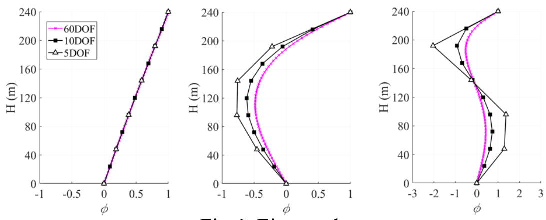
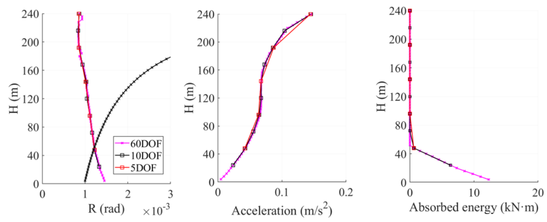
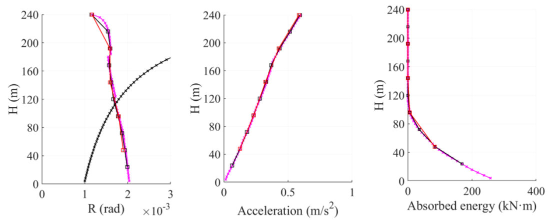


Fig 6. Eigen value



(a) Along



(b) Across

Fig 7. Response with dampers

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