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# Basic study on wind-induced responses of high-rise building - Effects of differences in damping models on response -

構造—振動

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High-rise building, Stiffness-proportional damping,  
Rayleigh damping, Wind-induced response

## 1. Introduction

The wind-induced response of high-rise buildings is greatly affected by the attenuation performance. So, it is necessary to carefully evaluate the attenuation of the building when we evaluate the wind-induced response of a high-rise building<sup>[1]</sup>. When evaluating the seismic-induced response of a high-rise building using time history analysis, the stiffness proportional damping or Rayleigh damping are often used as damping models<sup>[2]</sup>. However, there are few studies on the effects of different damping models on the wind-induced response of high-rise buildings. So, in this paper, the dynamic response of a high-rise building under wind load is compared when the stiffness proportional damping and Rayleigh damping are used respectively. As a first step of this study, the specific investigation is to evaluate inter-layer deformation angle, displacement, and acceleration distributions to understand building behavior. The results of this study will help to understand the effects of damping selection on the safety and comfort of structures and help to make informed decisions in the process of structural design and optimization.

## 2. Model information

In this study, a building model of ten degrees of freedom and wind input across and along two directions are used. The model parameters and wind input parameters used in the analysis are same as the Ref[3]. The parameters of the model and the source of wind input are introduced in detail in this chapter.

The building has the following properties: height  $H = 200$  m, width  $B = 40$  m, depth  $D = 40$  m, density  $\rho = 175$  kg/m<sup>3</sup>, natural period  $T = 0.025H = 5$  s. The mass of each layer  $i$  is equal, which is calculated as follow,

$$m_i = \rho \cdot H \cdot B \cdot D = 5.6 \times 10^3 \text{ ton.} \quad (1)$$

The mode of the shear-type building is same as the Ref[4]:

$$k_i = \frac{\omega_1^2 \cdot m_i \cdot \phi_i + k_{i+1} (\phi_{i+1} - \phi_i)}{\phi_i - \phi_{i-1}}, \quad (2)$$

where,  $\omega_1$  is the first order natural circle frequency,  $\phi_i$  is the modulus vector of order 1 of layer  $i$ .

The damping matrix adopts the stiffness-proportional damping model and Rayleigh damping model. The stiffness-proportional damping model can be evaluated as

$$[C] = \alpha_k [K], \quad (3)$$

where,  $\alpha_k$  is calculated by the first mode damping ratio  $h_1$  as

$$\alpha_k = \frac{2h_1}{\omega_1}.$$

The Rayleigh damping model is:

$$[C] = \alpha_M^{RL} [M] + \alpha_K^{RL} [K] \quad (4)$$

where,  $\alpha_M^{RL}$  and  $\alpha_K^{RL}$  can be approximated with following equations. Here,  $h_2$  is the second mode damping ratio,  $\omega_2$  is the second mode natural frequency.

$$\alpha_M^{RL} = \frac{2\omega_1 \cdot \omega_2 (h_1 \cdot \omega_2 - h_2 \cdot \omega_1)}{\omega_2^2 - \omega_1^2},$$

$$\alpha_K^{RL} = \frac{2(h_2 \cdot \omega_2 - h_1 \cdot \omega_1)}{\omega_2^2 - \omega_1^2}.$$

In this analysis, one percent damping ratio, two percent damping ratio and five percent damping ratio were used to explore the dynamic response of the building under different damping models and different damping ratios. The external excitation consists of across wind load and along wind load, acting on each individual particle separately. The Newmark- $\beta$  method is used to solve the response of structural systems, where  $\beta = 0.25$ .

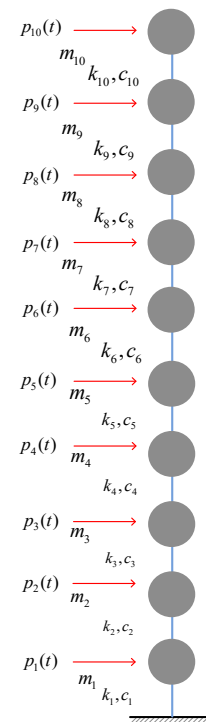


Figure 1. The ten-point model used for analysis

### 3. Comparison of dynamic response of building layers under different working conditions

In this part, the maximum dynamic response of two kinds of damping models (stiffness proportional damping and Rayleigh damping) under different working conditions (1% damping ratio, 2% damping ratio, 5% damping ratio, horizontal and vertical wind input directions), including each layer displacement, Inter-layer deformation angle  $R$ , and each layer acceleration, is compared.

#### 3.1 Displacement response of building

This section discusses the maximum displacement response of each layer under different damping models, different damping ratio and different wind input.

Figure 2 shows the distribution of the maximum displacement of each layer of the building with different damping model under different wind input and different damping ratio. As can be seen from Figure 2, different damping models have little influence on the maximum response even if the different damping ratio and different wind input cases.

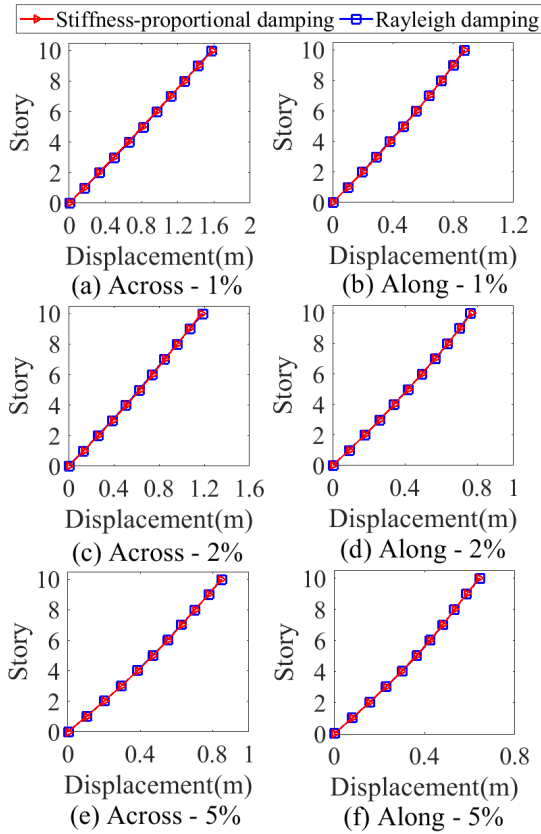


Figure 2. Comparison of displacement response

The possible reason is that, according to Ref[5], in this report, both the stiffness ratio and Rayleigh damping are set to the primary mode damping, and the wind response is dominated by the primary mode. The damping matrix of Rayleigh damping model can be expressed as:  $C_R = \alpha M + \beta K$ . When only one modal damping is considered, the  $\alpha$  and  $\beta$  in the damping matrix can be determined as:  $\alpha = 2\xi\omega$ ,  $\beta = \omega^2$ , where  $\xi$  is the damping ratio of the primary mode and  $\omega$  is the natural frequency of the primary mode. The damping matrix of the rigid proportional damping model is:  $C_p = \alpha K$ . When only one modal damping is considered, the damping ratio  $\alpha$  can be expressed as:  $\alpha = 2\xi\omega$ . Here,  $\xi$  is the damping ratio of the

primary mode, and  $\omega$  is the natural frequency of the primary mode. It can be seen that the damping matrices of both Rayleigh damping models and rigid proportional damping models can be expressed in similar forms when considering the first modal damping. Therefore, when the primary mode is dominant, and the damping ratio and natural frequency are the same, the damping matrix obtained by both is almost the same. This leads to the phenomenon that the displacement response results obtained by Rayleigh damping and rigid proportional damping are almost the same in the time-history analysis.

#### 3.2 Interlayer displacement response of building

This section discusses the maximum Inter-layer deformation angle  $R$  response of each layer under different damping models, different damping ratio and different wind input.

Figure 3 shows the distribution of maximum inter-layer deformation angle  $R$  of different damping buildings under different wind inputs and different damping ratios. As can be seen from Figure 3, when the wind is input from the direction along, under different damping ratios, different damping model has little influence on the maximum inter-layer deformation angle  $R$  of each layer of the building. When the wind is input from across the direction, the inter-layer deformation angle  $R$  of the ninth and tenth layers obtained by Stiffness proportional damping is smaller than that of the ninth and tenth layers obtained by Rayleigh damping when the damping is relatively small (0.01 and 0.02). When the damping ratio is large (0.05), the results of the maximum inter-layer deformation angle  $R$  obtained by different damping models are not different

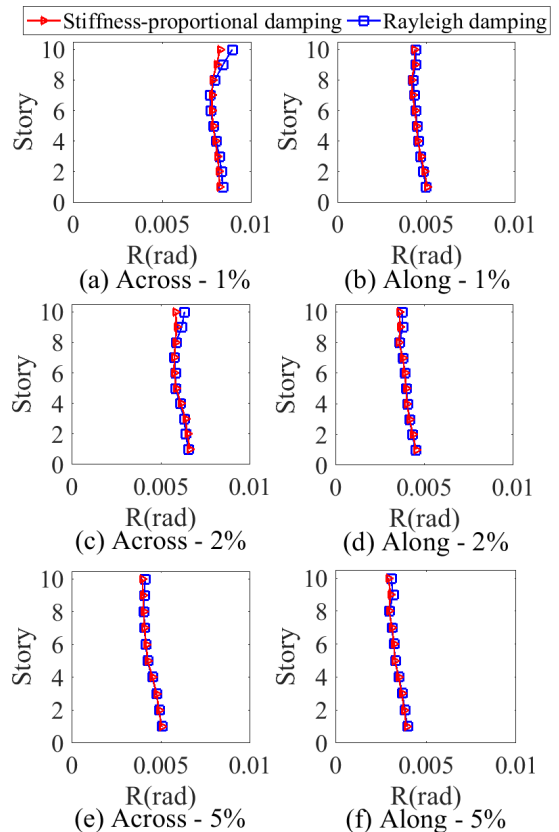


Figure 3. Comparison of Inter-layer deformation angle  $R$

When the damping ratio is small, the maximum inter-layer deformation angle  $R$  obtained by Stiffness proportional

damping is smaller than the maximum inter-layer deformation angle  $R$  obtained by Rayleigh damping, which may be the difference of energy dissipation between them. Stiffness proportional damping is proportional to the stiffness of the building, while Rayleigh damping contains a linear combination of mass and stiffness. When the damping ratio is small, the Stiffness proportional damping is relatively small, resulting in relatively less energy dissipation of structural vibration, while Rayleigh damping may provide a more efficient energy dissipation mechanism. This may result in that the maximum Inter-layer deformation angle  $R$  obtained by Stiffness proportional damping is less than the result of Rayleigh damping in the vibration response of high floors. Considering the influence of vibration modes, Stiffness proportional damping and Rayleigh damping may be different under different vibration modes. If the vibration of a high floor is dominated by a particular vibration mode, and the effect of Stiffness proportional damping is weak in that mode, then its vibration response may be small.

### 3.3 Acceleration response of building

This section discusses the maximum acceleration response of each layer under different damping, different damping ratio and different wind input.

Figure 4 shows the distribution of the maximum acceleration of each layer of different damping buildings under different wind input and different damping ratios. As can be seen from Figure 4, when the wind input is across direction, the result of Stiffness proportional damping is not much different from that of Rayleigh damping. When the wind input is along the direction, the result of Stiffness proportional damping is very different from that of Rayleigh damping. In general, the result of Rayleigh damping is greater than that of Stiffness proportional damping.

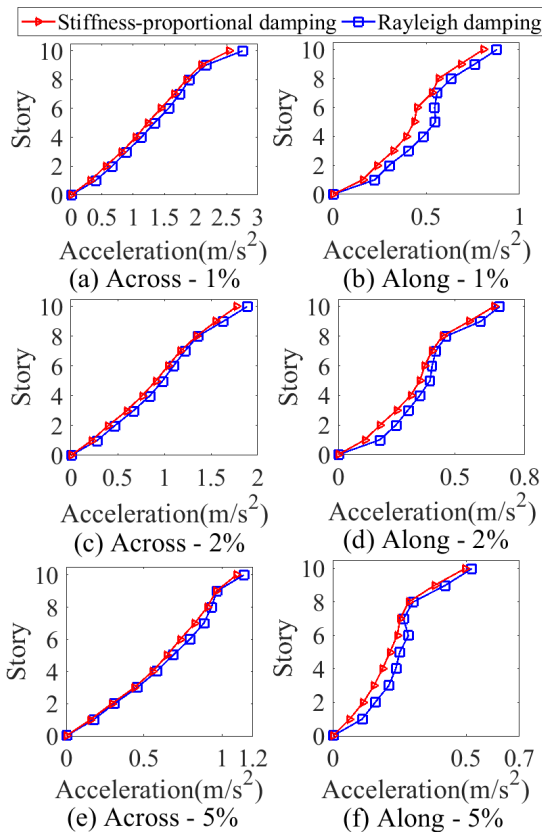


Figure 4. Comparison of Acceleration response

In the low and middle floors, the acceleration response of Rayleigh damping is greater than that of Stiffness proportional damping, which may be due to the difference of damping models. Rayleigh damping and Stiffness proportional damping are two different damping models. Rayleigh damping takes into account mass damping and stiffness damping through linear combination, while Stiffness proportional damping is proportional to structural stiffness. In the case of low and intermediate floors, Rayleigh damping may more accurately capture the actual damping characteristics of the building, resulting in a greater acceleration response. At the same time, considering the influence of stiffness distribution, the low floor and the middle floor have different stiffness distribution. The Stiffness proportional damping is proportional to the stiffness of the building, so the effect of Stiffness proportional damping may be more significant in the part with large stiffness. If Rayleigh damping can be better adapted to different stiffness distributions, then it may produce a greater acceleration response on low and intermediate floors.

### 3.4 A comprehensive discussion of structural dynamic response

In this section, the dynamic response of the building is comprehensively discussed by calculating the ratio of the results obtained by using Rayleigh damping analysis to those obtained by using Stiffness proportional damping analysis under different working conditions.

Figure 5 shows the ratio distribution of different dynamic response results obtained by Rayleigh damping analysis and those obtained by Stiffness proportional damping analysis under different damping ratios (0.01, 0.02, 0.05) under wind input in two directions across and along.

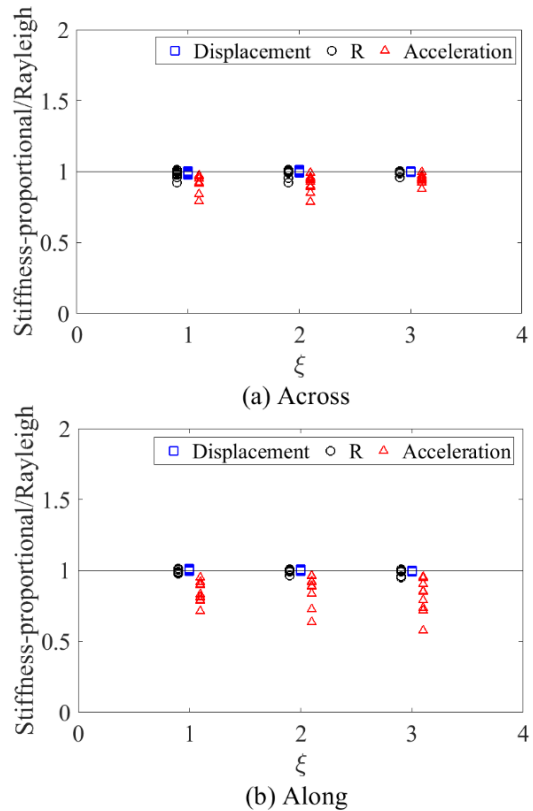


Figure 5. The ratio distribution of Stiffness/ Rayleigh

As can be seen from Figure. 5, in general, the results of the maximum acceleration response of the building obtained by

Rayleigh damping analysis are significantly bigger than those obtained by Stiffness proportional damping analysis, while the results of the maximum displacement response and maximum displacement Angle obtained by Rayleigh damping analysis are better than those obtained by Stiffness proportional damping analysis. At the same time, when the wind input is across, the difference between the results obtained by Rayleigh damping analysis and those obtained by Stiffness proportional damping analysis is larger when the damping ratio is low (0.01, 0.02), and smaller when the damping ratio is high (0.05). However, when the wind input is along direction, the difference between the results obtained by Rayleigh damping analysis and those obtained by Stiffness proportional damping analysis increases with the increase of the damping ratio.

According to the above analysis, it may be due to the damping model and stiffness distribution that the acceleration response obtained by Rayleigh damping analysis is greater than that obtained by Stiffness proportional damping analysis. The influence of different damping analysis on the acceleration response is much greater than that on the displacement response, the most obvious reason is the role of damping in the structural dynamics equation.

The dynamic equation of the building is:

$$M\ddot{u}+C\dot{u}+Ku=F \quad (5)$$

Usually a second-order linear ordinary differential equation in which the damping matrix  $C$  contains the velocity term, which means that the damping directly affects the velocity and acceleration. Since acceleration is the derivative of velocity, the effect of damping on velocity is more direct on acceleration. In high frequency vibration, the relative relationship between velocity and acceleration is closer, so the influence of damping on acceleration is more significant. In addition, acceleration is the second derivative of vibration, while displacement is the first derivative, so damping has a stronger effect on acceleration, especially at higher frequencies. Therefore, the most obvious reason lies in the influence of damping on velocity and acceleration in the structural dynamics equation, and acceleration is the higher derivative of structural response, making the role of damping in acceleration response more significant. At the same time, considering the energy dissipation mechanism, one of the main functions of damping is to weaken the vibration of the building through energy dissipation. In the process of vibration, damping consumes the energy of the vibration system through the dissipation of velocity and acceleration. Since acceleration is the derivative of velocity, damping affects acceleration more directly in this process, so the acceleration response is more sensitive.

Generally speaking, when the damping is relatively small, the difference between the dynamic response results of the two damping models may be more significant. This is because in the case of a small damping ratio, the influence of damping is relatively small, and the system is more likely to exhibit its inherent vibration characteristics. Therefore, the difference between Rayleigh damping and rigid proportional damping may be more prominent in this case. However, it is found in this study that when the wind input is along, the difference between the results obtained by Rayleigh damping analysis and those obtained by rigid proportional damping analysis increases with the increase of damping ratio, which should be due to the

influence of different wind input on the dynamic response of the building.

#### 4. Conclusion

In this paper, two different damping models, Rayleigh damping and stiffness proportional damping, are used to study the wind response of high-rise buildings. The comparison between the two damping methods revealed several key findings.

Firstly, the choice of damping model has a significant effect on the dynamic response of high-rise buildings. Rayleigh damping takes into account the contributions of mass and stiffness, and exhibits more complex and frequency-dependent behavior than stiffness proportional damping, which is linearly proportional to structural stiffness. The frequency dependence of Rayleigh damping allows a more realistic representation of the dynamic characteristics of buildings under different wind loads and frequencies.

Secondly, the influence of damping ratio on the difference between Rayleigh damping and stiffness proportional damping is discussed. It is observed that the difference between the two damping models tends to increase as the damping ratio decreases. This is due to the reduced effectiveness of damping in the building, which makes the frequency-dependent properties of Rayleigh damping more obvious. At the same time, different wind inputs may also lead to opposite trends, so all factors should be taken into account when considering the dynamic response of the building.

In addition, the study emphasizes that for small damping ratios, Rayleigh damping can produce a more significant difference in dynamic response than stiffness proportional damping. This highlights the importance of selecting the right damping model, especially in the context of high-rise buildings where wind-induced vibration is a key consideration. The research results of this paper are helpful to better understand the significance of selecting different damping models in wind vibration analysis of high-rise buildings. The damping characteristics should be carefully considered in the design, and the most appropriate model should be selected according to the specific structural characteristics, the intended application, and the desired accuracy of the dynamic response prediction.

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