論文 / 著書情報
Article / Book Information

論題(和文)	
Title(English)	WIND LOAD ESTIMATION ON A HIGH-RISE BUILDING BY MODAL ANALYSIS Part 1: Accuracy of using 1st Mode Wind Force in Response Calculation
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出典 / Citation	日本建築学会関東支部研究報告集, Ⅰ, , pp. 245-248
Citation(English)	, Ⅰ, , pp. 245-248
発行日 / Pub. date	2020, 3

2019年度日本建築学会
関東支部研究報告集 I
2020年3月

WIND LOAD ESTIMATION ON A HIGH-RISE BUILDING BY MODAL ANALYSIS

Part 1: Accuracy of using 1st Mode Wind Force in Response Calculation

構造ー振動

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Wind force estimation, Modal analysis, 1st mode force
Time-history analysis, Multi-degree of freedom analysis, Wind-induced responses

1. Introduction

1.1 Wind-induced Response of Seismically Base-Isolated Buildings in the Inelastic Range

Urbanization has been increasing demands for construction of taller and lighter buildings. Tall and light buildings are susceptible to dynamic forces such as extreme winds, making wind load analysis an integral factor in the design process. As the building gets higher and lighter, the increase in wind velocity and force causes large structural vibrations that may affect the serviceability and habitability of the structure. Passive control systems are installed in buildings to dissipate these vibrations without requiring any external power source.

Seismic base-isolation is one example of a passive control system that is being widely used in earthquake-prone countries nowadays. Design guidelines for wind-induced response of seismically base-isolated buildings are established but is limited only on the elastic range of the isolation system. However, as this type of structure gets higher and are being subjected to stronger winds, there is a greater possibility that the structural members in the isolation device will yield, causing the wind-induced response of the isolation system to exceed its elastic range[1]. If this is the case, consideration of the elasto-plastic characteristics of the isolation system is highly necessary and this can be done by performing time-history wind-induced response analysis to evaluate the response of the building [1].

Time-history analysis requires the use of actual wind forces acting on the structure. However, wind load depends on a lot of factors such as wind velocity and geometry of the building, it is difficult to predict it accurately or to measure it directly. Because of this, wind forces used in time-history analysis are only estimated by wind tunnel experiments or power spectral density assumption [1]. Since there is still limited knowledge on the wind-induced response of seismically base-isolated buildings in the inelastic range, it is important to accurately depict the actual conditions experienced by the structure to be designed. This can only be possible if the wind forces used in the time-history analysis are accurately estimated.

Monitoring systems on structures can record the wind-induced response of the building. These recorded responses can be used to determine the wind forces by performing modal analysis on the structure.

In modal analysis, the more modes of vibration included in the analysis, the higher the accuracy of the results; however, observation devices installed in structures are not capable of capturing higher modes of vibration. In time-history analysis of super high-rise buildings, considering only the 1st mode of vibration is sufficient since it is the dominating mode, though this might not be the case for seismically base-isolated structure.

1.2 Objective

The aim of this study is to formulate a method that can precisely approximate the actual wind forces acting on a seismically base-isolated structure in order to perform time-history analysis in the event that the seismic isolation device exceeds its elastic range. In order to do that, investigation of the fundamental theories to be used must be performed. Hence this paper, which is the initial part of the study aims to determine whether the 1st mode wind forces calculated by modal analysis is sufficient to accurately estimate the actual wind forces acting on an elastic, upper structure of a seismically base-isolated building.

2. Theoretical Background

2.1 Multi-degree of Freedom (MDOF) Analysis

The equation of motion for an MDOF system subjected to external dynamic forces $\{P(t)\}$ is

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{P(t)\}. \tag{1}$$

Here, $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrix, respectively. Also, $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$ and $\{x(t)\}$ are the acceleration, velocity and displacement vectors, respect-tively. Note that these are the dynamic responses of the structure. This shows a system of N ordinary differential equations in terms of dynamic responses due to the forces applied where N depends on the number of degrees of freedom (DOFs) of the structure.

2.2 Single-degree of Freedom (SDOF) / Modal Analysis

The system of simultaneous equations shown in Equation (1) is not efficient for structures with more DOFs and it is more convenient to express this system in modal coordinates. For example, a 10-DOF model can be simplified by ten separate SDOF models. The dynamic responses of each DOF of an MDOF system can be expressed as the sum of the modal contributions of each SDOF model, e.g., $x(t) = \sum_{n=1}^{N} \phi_n q_n(t)$. Accordingly, the vector responses (i.e., $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$ and $\{x(t)\}$) in Section 2.1 can be simplified as

$$\{\ddot{x}(t)\} = [\phi]\{\ddot{q}(t)\} \tag{2.a}$$
$$\{\dot{x}(t)\} = [\phi]\{\dot{q}(t)\} \tag{2.b}$$
$$\{x(t)\} = [\phi]\{q(t)\} \tag{2.c}$$

where $[\phi]$ = modal matrix, and $\{q(t)\}$, $\{q(t)\}$, $\{q(t)\}$ = modal responses. Therefore, Equation (1) becomes

$$[M][\phi]\{\ddot{q}(t)\} + [C][\phi]\{\dot{q}(t)\} + [K][\phi]\{q(t)\} = \{P(t)\}. \tag{3}$$

Multiplying each term of Equation (3) to the transpose of the modal matrix will gives

$$[_sM]\{\ddot{q}(t)\} + [_sC]\{\dot{q}(t)\} + [_sK]\{q(t)\} = \{_sP(t)\} \tag{4}$$

where $[_sM]$, $[_sC]$, $[_sK]$ and $\{_sP(t)\}$ are the generalized mass, generalized damping, generalized stiffness matrices and generalized force vectors, respectively. Solving Equation (4) will determine the acceleration, velocity and displacement per mode of vibration and substituting them to Equation (2) will determine the actual responses of the original MDOF system.

2.3 Force Calculation

After determining the modal responses of the system, (i.e., $\{\ddot{q}(t)\}$, $\{\dot{q}(t)\}$ and $\{q(t)\}$), it is now necessary to back substitute these calculated values to Equation (4) to determine the generalized force $\{_sP(t)\}$ applied to the model. The actual wind force $\{P(t)\}$ can be calculated as

$$\{P(t)\} = [\phi]^{T^{-1}}\{_sP(t)\} \tag{5}$$

The theoretical background of the analysis mentioned above is summarized in the flowchart shown in Figure 1.

3. Overview of the Analytical Model

Figure 2 shows the simplified lumped mass 10-DOF system of the building to be analyzed. Without the isolation layer, the upper structure has a height H = 100 m, density ρ_u = 180 kg/m^3 and each floor area A = 625 m^2. The structure has a natural period T = 2.5 s and a damping ratio h = 2%.

Table 1 indicates the specification of the analytical model. Stiffness $_uk_i$ of each floor i of the structure is calculated using Equation 6 in order to obtain a linear mode shape in the 1st mode.

$$_uk_i = \frac{_{us}\omega^2 \cdot m_i \cdot {_{us}\phi_i} + {_uk_{i+1}}\left({_{us}\phi_{i+1}} - {_{us}\phi_i}\right)}{_{us}\phi_i - {_{us}\phi_{i-1}}} \tag{6}$$

The wind force applied in the analysis was derived from a calculated typhoon simulation. The wind directions analyzed were the along-wind direction with and without mean component and across-wind direction. Stiffness-proportional damping is used in the analysis where damping ratio h = *2%.*

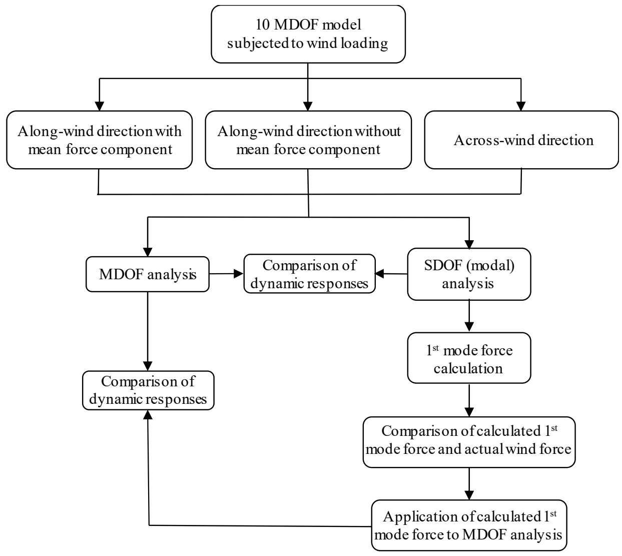


Figure 1. Conceptual framework.

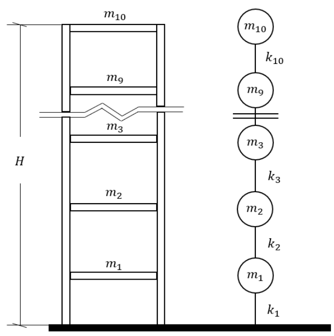


Figure 2. Analytical model.

Table 1. Specification of the analytical model

Floor	Height, H (m)	Mass, m (kN・s^2/cm)	Stiffness, k (kN/cm)
10F			710.6
9F			1350.2
8F			1918.7
7F			2416.1
6F	10	11.25	2842.4
5F			3197.8
4F			3482.0
3F			3695.8
2F			3837.3
1F			3908.4

4. Results

4.1 Modal Shapes

The natural mode of vibration for all ten modes is shown on Figure 3 below.

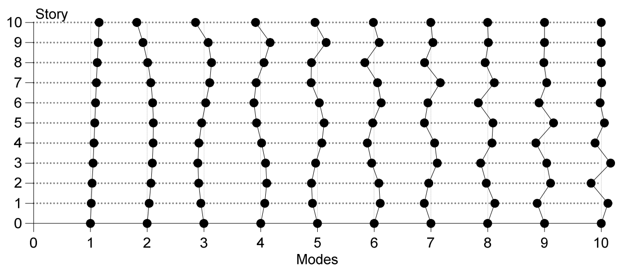


Figure 3. Modal shapes of the model

4.2 MDOF Response vs. SDOF Response

To calculate the 1st mode wind forces, the 1st mode responses obtained from the SDOF analysis are needed. The acceleration response obtained from SDOF analysis is compared to that of the MDOF analysis, as in Figure 4. Despite considering only the 1st mode responses, the SDOF analysis has acceleration response close to that of the MDOF analysis. Moreover, increasing the number of modes included in the superposition of the SDOF analysis (e.g., Modes 1-10), the acceleration response has a better agreement with that of the MDOF analysis. Although not shown here, the same can be said the velocity and displacement responses.

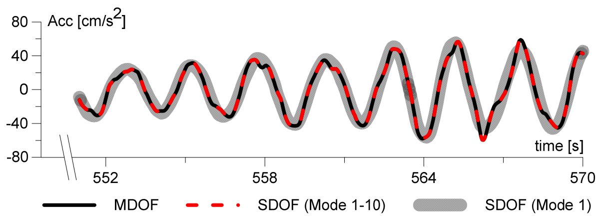


Figure 4. Comparison of acceleration response from MDOF and SDOF analysis (roof level)

4.3 Calculated 1st Mode Wind Force vs. Actual Wind Force

After obtaining the responses from the modal analysis, Equations (4) and (5) were used to calculate the modal forces. As shown in Figure 5, the time-history of the actual wind force and the obtained wind force from SDOF analysis considering all 10 modes have close numerical values. However, if only the 1st mode of vibration is considered from SDOF analysis, there is a significant difference between their time-histories. These observations are supported by investigating the correlation coefficient given by

$$Correlation = \left(1 - \frac{\sqrt{\sum_{k=1}^{N} \left(\hat{y}(k) - y(k) \right)^2}}{\sqrt{\sum_{k=1}^{N} \left(y(k) - \bar{y} \right)^2}} \right) \tag{7}$$

where $\hat{y}$ = theoretical (or recorded) value, $\bar{y}$ = mean of the calculated value y.

Figure 6a shows that the correlation coefficients between the actual wind force and the calculated 1st mode force (Modes 1~10) are close to 1.0 for all floors in all wind directions. This indicates a good agreement for the entire loading duration. In contrast, for Mode 1 only (Figure 6b), only the upper part of the structure (6th to 10th floors) showed acceptable correlation. Despite this, the ratio between the maximum SDOF force (Mode 1) and the

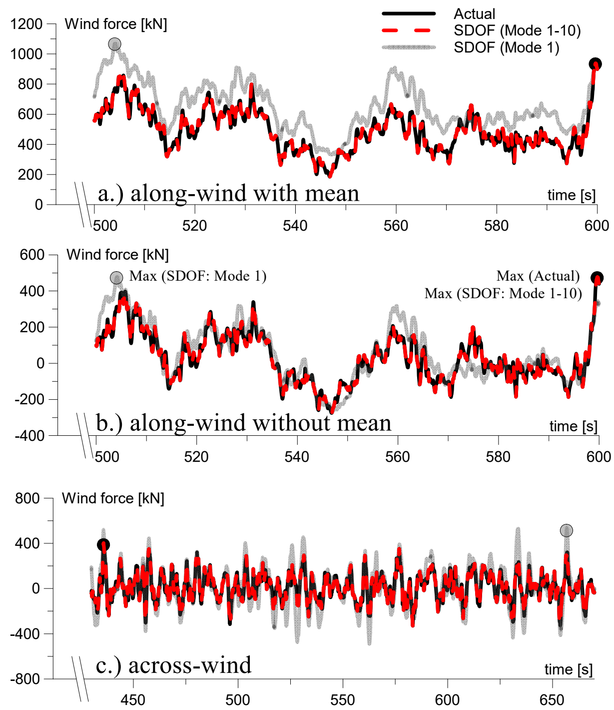


Figure 5. Comparison between actual force and calculated SDOF force (roof level)

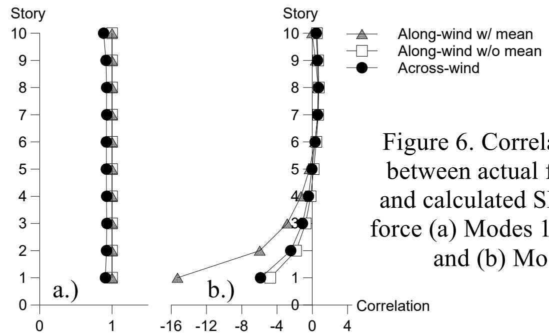


Figure 6. Correlation between actual force and calculated SDOF force (a) Modes 1~10, and (b) Mode 1.

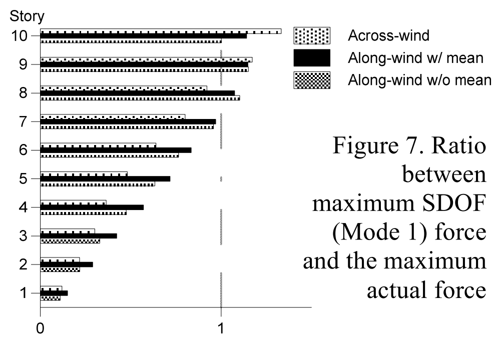
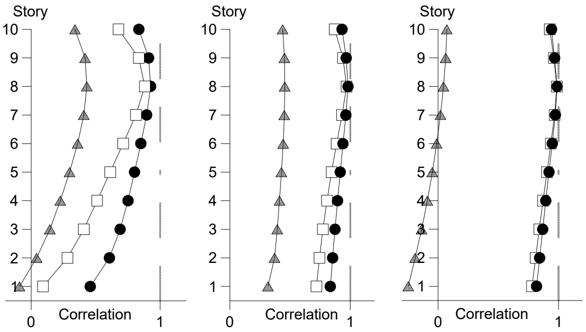


Figure 7. Ratio between maximum SDOF (Mode 1) force and the maximum actual force

actual force as in Figure 7 are close to 1.0. This indicates a good relationship between the maximum values of the forces although they did not occur at the same time (Figure 5). It is imperative to investigate the maximum wind force since it is a critical factor in the design process.

Since the forces in the lower part of the structure are small, they have insignificant contributions to the structural response. Therefore, the poor accuracy of the Mode 1 forces in the lower part of the structure (1^{st} to 5^{th} floors) as shown in Figures 6b and 7 can be neglected.



a.) acceleration b.) velocity c.) displacement

Figure 8. Correlation between response from actual force and response from calculated SDOF (Mode 1) force

4.4 MDOF Response vs SDOF Response

The calculated 1^{st} mode forces from SDOF analysis (Section 4.3) were applied to the MDOF model. Figure 8 shows the correlation between the dynamic responses of the model from the actual wind force and from the calculated 1^{st} mode SDOF force. The correlation of the responses is significantly low for the along-wind direction with mean component because the mean component of the 1^{st} mode force is significantly greater than the mean component of the actual wind force (Figure 5a). The difference between the value of the mean component induced a large increase in the calculated 1^{st} mode force, subsequently causing a large discrepancy in the responses even causing the structure to yield (Figure 9).

On the other hand, when the mean component was removed, the correlation values of the responses (Figure 8) improved. Moreover, the same can be said for the across-wind response due to the absence of the mean component of the across-wind forces.

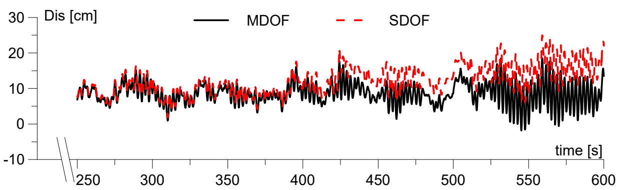
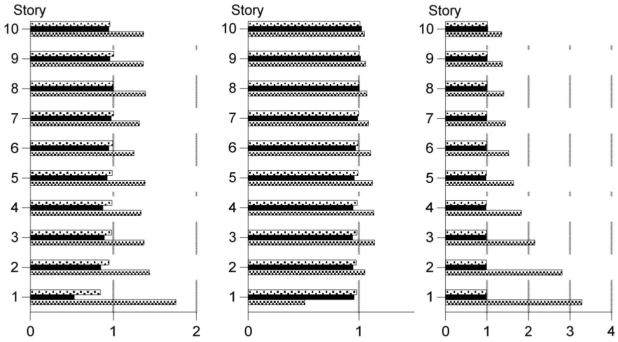


Figure 9. Displacement response in the along-wind direction with mean force component (roof level)



a.) acceleration b.) velocity c.) displacement

Figure 10. Ratio between maximum response from SDOF force (Mode 1) and maximum response from actual wind force

5. Conclusion

Based on the results of the analysis, the following conclusions can be drawn.

1. Modal analysis can be used to accurately estimate the actual wind forces acting on an elastic structure provided that acceptable number of modes were included in the analysis.
2. The calculated 1^{st} mode force is similar to the actual wind force only on the upper floors of the structure. Despite its limited accuracy, this force induced favorable responses on all floors of the structure.
3. The mean component of calculated 1^{st} mode force can greatly affect the accuracy predicted responses.
4. As long as the structure remains elastic, the above findings are valid. If the structure behaves beyond its elastic limit, and time history analysis is needed, using only the 1^{st} mode wind force may not be enough and developing a system identification technique to include higher modes of vibration must be considered.

References

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