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

Part 2: Effect of Natural Frequency and Damping Ratio on First Mode Wind Force

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Natural frequency, Damping ratio, Wind force estimation
1st mode force, Multi-degree of freedom analysis, Modal analysis

1. Introduction

1.1 Damping and Natural Frequency Estimation

Advancement in construction techniques and availability of new and more efficient materials have paved the way for the development of taller and lighter buildings which are more susceptible to stronger dynamic wind forces. As a result, the dynamic properties of the structure, such as natural frequency, damping ratio and modal parameters must be given more careful consideration [1]. Natural period and damping ratio are two very important but also highly uncertain parameters that greatly affect the dynamic response of a structure and an accurate prediction of these values must be guaranteed in the design process [2]. However, there is no absolute theoretical method to estimate the natural frequency and damping ratio and the assessment of these two parameters predominantly depends on full-scale data obtained from similar structures.

In Japan, full-scale measurements from existing structures are collected to create a reliable database that can be used to formulate effective evaluation techniques of above mentioned dynamic parameters but the current database is still insufficient to increase the accuracy of the prediction methods, particularly of the damping ratio, for different types of structures [1]. Satake et al. [3], Shioya et al.[4], and Tamura et al. [5] conducted studies on the estimation of natural frequencies obtained from recorded data and all reported to have only 10 to 20% difference from the measured values. On the other hand, estimation of damping ratio from full-scale data can result to errors that can reach about 100-200%, or even 1000% if low quality measured data were used [2]. This amount of error can be detrimental to the structural safety of the building.

In Part 1 of this paper, the calculated 1st mode wind force were observed to be effective in determining the response of an elastic, high-rise structure. This calculated force aims to act as a substitute to the scarce full-scale data if proven accurate enough. For this reason, the aforementioned dynamic parameters that may greatly affect the accuracy of the wind-induced response from estimated forces obtained in Part 1 must be carefully investigated.

1.2 Objective

The aim of this study is to formulate a method that can precisely approximate the value of the actual wind forces acting on a seismically base-isolated structure in order to be able 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 effect of certain dynamic properties particularly damping and natural frequency on an elastic structure must first be investigated. Hence this paper, which is the second part of the study aims to determine if errors in the estimation of damping ratio and natural frequency will significantly affect the accuracy of the 1st mode wind forces and its wind-induced responses when applied on an elastic, upper structure of a seismically base-isolated building.

2. Background of the Analysis

2.1 Multi-degree of Freedom (MDOF) Responses

The responses of a 10 MDOF model subjected to wind loading is calculated using the same principle used in Part 1 of this study. The equation of motion used is shown in Equation (1).

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

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

The modal responses are calculated by substituting the MDOF responses to Equation (2),

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

These equations were used in Part 1 of this study to perform SDOF analysis.

2.3 Force Calculation

The modal responses are substituted to Equation (3) to calculate the generalized 1st mode forces and Equation (4) is used to get the actual value of these 1st mode forces.

$$[{}_sM]\{\ddot{q}(t)\} + [{}_sC]\{\dot{q}(t)\} + [{}_sK]\{q(t)\} = \{{}_sP(t)\} \tag{3}$$

$$\{P(t)\} = [\phi]^{T^{-1}}\{{}_sP(t)\} \tag{4}$$

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In this part of the study, the effect of errors in damping and natural frequency estimation on the accuracy of 1st mode forces was investigated. Different natural frequency and damping ratios were used to calculate the 1st. mode wind force. The 1st mode wind forces were then compared to the to the actual forces applied to the MDOF model. The responses (acceleration, velocity and displacement) of the MDOF model to the actual wind force and the calculated 1st mode wind force (with varying damping ratios and natural period) were also compared.

The framework of the analysis is summarized in the flowchart shown in Figure 1 below.

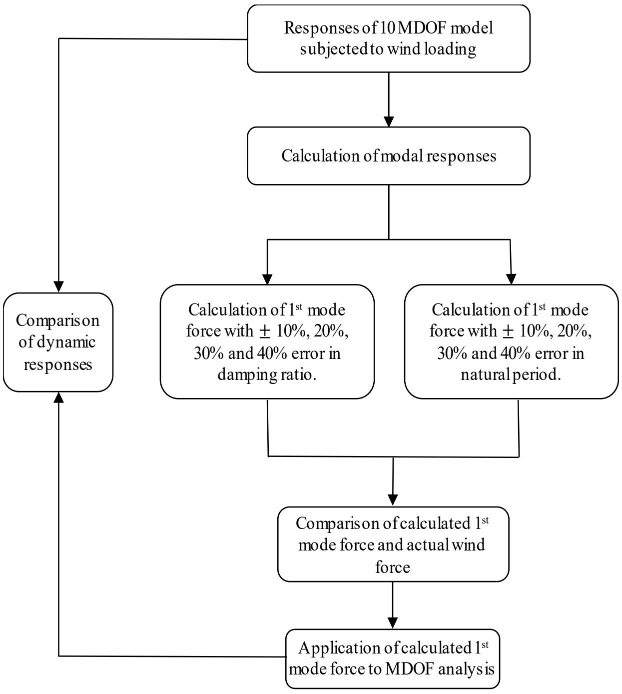

Figure 1. Conceptual framework

3. Overview of the Analytical Model

Figure 2 shows the simplified lumped mass 10-DOF system of the building to be analyzed and its equivalent 1st mode SDOF model. The model parameters used in Part 1 were adopted, namely upper structure height, H = 100 m, density, ρ_u = 180 kg/m^3 and floor area, A = 625 m^2. Furthermore, the structure has a natural period, T = 2.5 secs and a damping ratio, h = 2% (stiffness-proportional damping). The specifications of the analytical model (i.e., height, mass and stiffness per floor) were indicated in Table 1 of the Part 1 of this study.

The wind data used in the analysis were derived from a calculated typhoon simulation. In Part 1 of the study, it was observed that the mean component of the calculated 1st mode force greatly affected the accuracy of predicted responses. Also, the across-wind direction is known to be more susceptible to wind-induced motions. For these reasons, the mean component of the force was neglected and only the along-wind direction without mean component was used in the investigation.

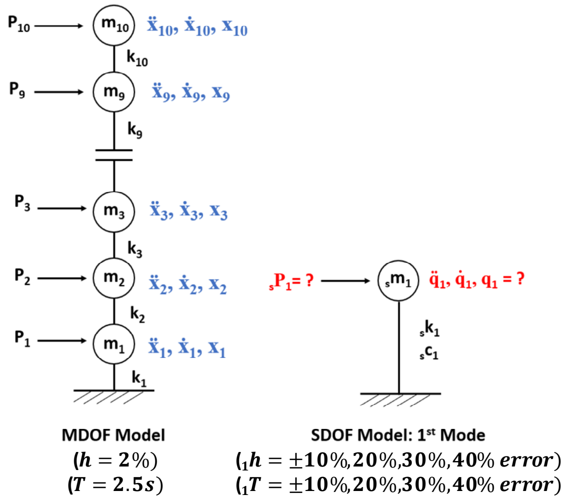

Figure 2. Analytical model

4. Results

4.1 Natural Frequency

4.1.1 Mode 1 Force with Different Natural Period

Figure 3 shows the comparison between the time-history of the actual wind force and the 1st mode wind force with different natural periods. It is shown here that an increment of ±10% error in the natural period caused a great discrepancy in the numerical values of the calculated 1st mode forces particularly on the roof level of the structure.

However, the correlation of these calculated 1st mode forces from the actual wind force computed using the same correlation equation, Equation 7 of Part 1, showed good agreement on the upper floors of the model (Figure 4). It can be observed that for an incremental error of ±10% in the natural period, the correlation coefficient of the upper floors only decreases by approximately 15%. This

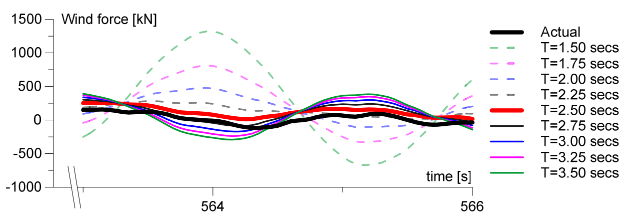

Figure 3. Time history of actual wind force and 1st mode force with varying natural periods (roof level)

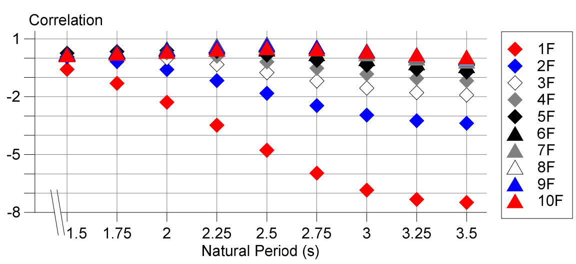

Figure 4. Correlation between actual wind force and 1st mode force with varying natural periods

contradicts the results shown in the time-history of the calculated Mode 1 forces with varying natural periods (Figure 3) and it must be noted that the correlation coefficient is limited only on the proximity of the trends of the forces being compared for the entire loading duration and cannot accurately depict the accuracy of each numerical value of the forces.

4.1.2 Responses to Mode 1 Force with Different Natural Period

The 1st mode forces with varying natural periods were applied to the MDOF model one at a time and the wind-induced responses were observed. Shown in Figure 6 are the correlation coefficients between the responses of the MDOF model to the actual wind force and the 1st mode forces with varying natural periods for all floors of the model. It can be seen here that only the responses of the model subjected to the 1st mode force that used the same natural period ($T = 2.5$s) gave good correlation results. The responses from the 1st mode forces that used other values for natural period have very poor correlation with that of the model subjected to the actual wind force. This is attributed by the large discrepancy in the calculated 1st mode force with varying natural periods (Figure 3).

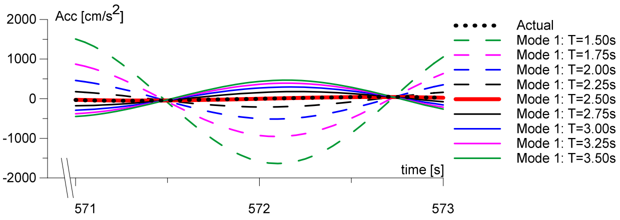

Figure 5. Time history of acceleration response from actual wind force and 1st mode force with varying natural periods (roof level)

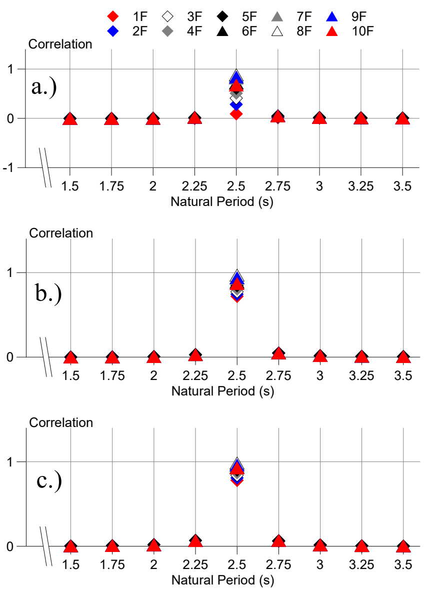

Figure 6. Correlation between response to actual wind force and 1st mode force with varying natural periods a.) acceleration, b.) velocity, c.) displacement

4.2 Damping Ratio

4.2.1 Mode 1 Force with Different Damping Ratio

Figure 7 shows the comparison between the time history of the actual wind force and the 1st mode wind force with different damping ratios. Based on Figure 8, the correlation coefficient of the actual force and the 1st mode force did not change significantly even when an error of ±40% was incorporated. The upper floors, which was also mentioned in Part 1 to be the most critical factor in structural wind design have correlation values close to 1.0.

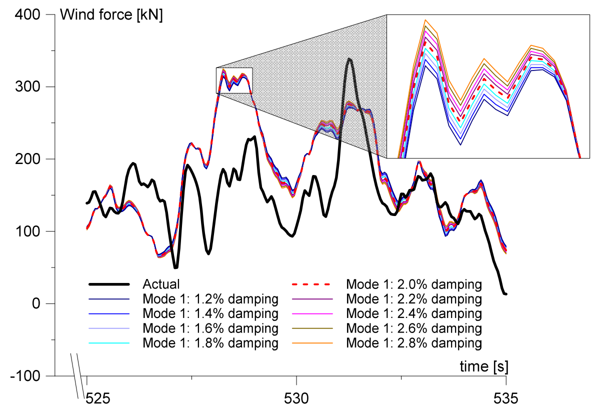

Figure 7. Time-history of actual wind force and 1st mode force with varying damping ratios. (roof level)

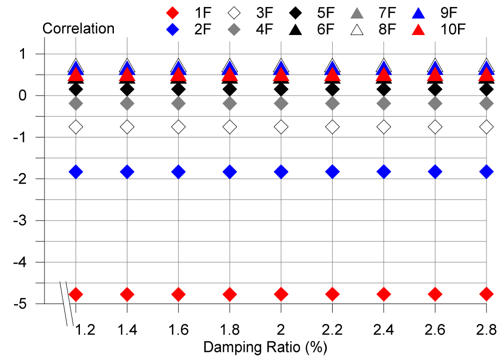

Figure 8. Correlation between actual wind force and 1st mode wind force with varying damping ratios

4.2.2 Responses to Mode 1 Force with Different Damping Ratio

The variation in damping ratio did not change the 1st mode force significantly; however, it is also important to determine whether the same can be said to the responses once calculated 1st mode forces with varying damping ratios are applied to the model. Figure 9 shows the correlation between the responses (acceleration, velocity and displacement) of the model from the actual force and from the 1st mode force with different damping ratios. It is shown here that increasing the damping ratio has lower effect on the correlation coefficient of the responses than decreasing its value. If a 40% decrease in damping ratio was incorporated to the calculated 1st mode force, the correlation coefficient of the responses moves farther to 1.0 by not more than 30%.

Figure 10 shows the maximum responses and story drift of the model subjected to the actual wind force and the calculated 1st mode forces with varying damping ratios. It is shown here that the maximum responses of the 1st mode forces behaved linearly. The maximum responses of the model subjected to the 1st mode force with 2% damping ratio closely matches that of the model subjected to the actual wind force having the same damping ratio of 2%. A decrease in the damping ratio also means a decrease in the calculated 1st mode force and the lower the 1st mode force applied to the model in MDOF analysis, the lower the responses obtained and vice versa. This explains the variation of the maximum responses in Figure 10.

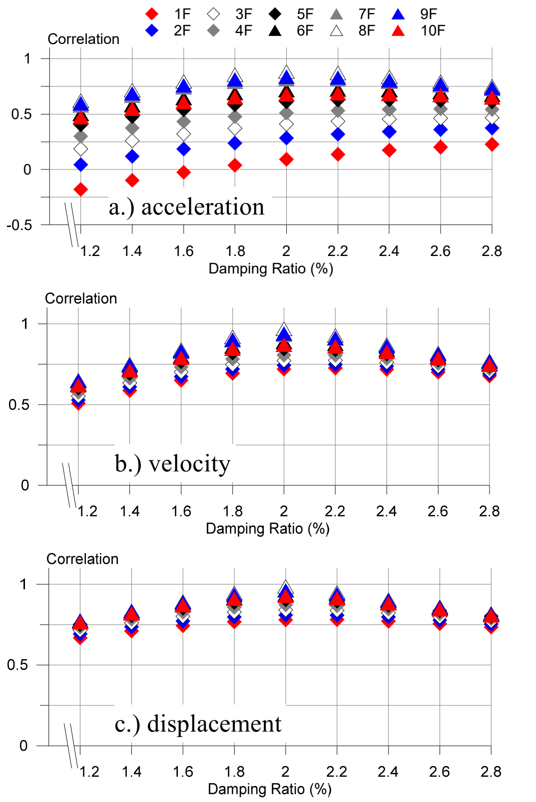

Figure 9. Correlation between response from actual wind force and 1st mode force with varying damping

5. Conclusion

Based on the results of the analysis shown in this paper, the following conclusions were made. First, the calculated 1st mode force and the model's responses to this force are greatly affected by the natural frequency. Second, variation in damping ratio does not significantly change the accuracy of the 1st mode force however, the responses of the model subjected to the 1st mode force with varying damping ratios considerably changed. Therefore, when estimating the wind force using the 1st mode modal forces, an accurate estimation of natural period and damping ratio of the model should still be taken into consideration.

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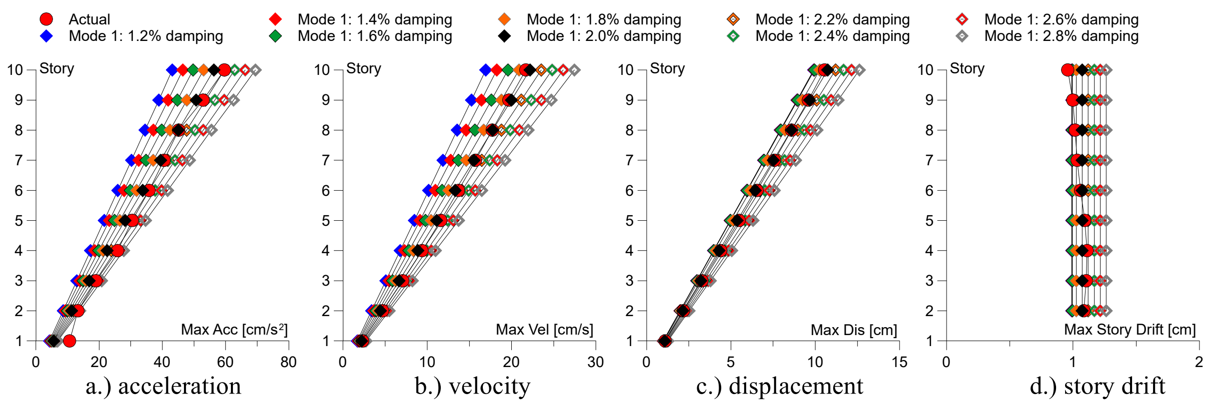

Figure 10. Maximum response of the model from actual wind force with varying damping ratios

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