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Abstract

The construction of tall buildings can be regarded as one of the most complex and expensive projects. It thus seems important to design the structure of a tall building in terms of cost effectiveness to ensure the success of a construction project. The structural cost of a tall building is generally determined by lateral wind loads and responses. Also, lateral wind loads and responses generally depend on dynamic properties, such as natural frequencies and damping ratios. Although the computational method has been remarkably well developed, there are still considerable uncertainties in the analysis of natural frequencies. Moreover, damping ratios tend to be rather subjectively assumed in response analysis, although the analysis results might be quite distorted due to the improper assumption of damping ratios. Hence, as an effort to investigate actual dynamic properties of tall buildings, a full-scale measurement of a tall residential building was performed when the typhoon, Man-yi, hit Korea in 2007. The natural frequencies of the building were identified with the measured acceleration responses and compared with the FE modal analysis results. Also, the measured damping ratios were compared with the results of the damping predictor proposed by the Architectural Institute of Japan (AIJ). Based on these comparisons, a proper evaluation procedure of dynamic properties was proposed for practical engineering works of tall building design.

Keywords: Natural frequencies, damping ratios, full-scale measurement, tall buildings

Introduction

In order to derive reliable wind loads and responses, not only the reliability of wind tunnel tests but also the accuracy of the determined dynamic properties is quite important in the structural design of large-scale structures such as tall buildings. It is because the resonant components of wind loads and responses for tall buildings are evaluated using the dynamic properties such as natural frequencies and damping ratios.

Although the computational analysis method used in deriving natural frequencies has been remarkably well developed, it is generally reported that measured natural frequencies show some discrepancies with the analyzed results especially for building structures (AIJ, 2000; Su et al. 2005). Moreover, the damping ratios tend to be rather excessively assumed for the analysis of wind-induced responses in practical engineering works compared with the measured damping ratios (Tamura, 2005).

Based on previous measurement results, several natural frequencies and damping predictors have been suggested in national codes and recommendations. It seems, however, to be unwarranted to directly use foreign predictors for the design of tall buildings constructed in Korea as structural systems and details of tall Korean buildings could somewhat differ from those of buildings in other countries. Thus, the actual dynamic properties of tall buildings are required to be compared with the analyzed results according to the Korean practice of structural analysis and design.

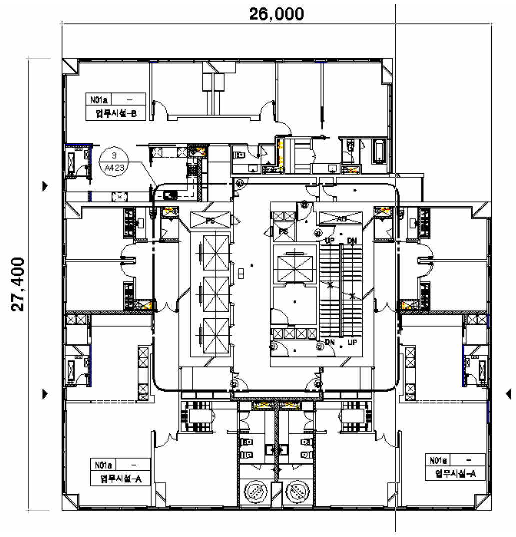
For this purpose, a full-scale measurement of a tall residential building was performed during a typhoon in 2007. Using the measured data, the natural frequencies and damping ratios were evaluated and compared with the results of the FE analysis and a damping predictor, respectively. Based on the comparison results, guidance for practical structural analysis was tentatively suggested and future studies were presented.

Full-scale measurement of a tall residential building

A tall residential building constructed in Pusan city was chosen for a full-scale measurement of accelerations. The chosen building could be regarded as a typical example of a tall residential building in Korea. The overall view and drawings of the building are shown in Fig. 1 and the detailed information is summarized in Table 1. The building's core walls are connected with the exterior moment-resisting frames by shear walls at each floor. At the 41st floor, outrigger walls are located to increase the building's lateral stiffness.

When the typhoon, Man-yi, descended on the Pusan area, translational and torsional accelerations were measured for three setups of accelerometers assigning the top floor as a reference as shown in Fig. 2. A total of 24 accelerometers were installed on eight floors of the building for each measurement setup, and three accelerometers were installed on each floor. For

(a)



(b)

Figure 1. Tall residential building: (a) overview; (b) planar plan

measurement convenience, two data loggers were used for the acceleration measurement and 12 accelerometers were connected to each data logger. To ensure data synchronization of both data loggers, GPS time was used for time triggering. In most cases of field measurements, data loggers were located far from each other on different floors. Using the wireless LAN system, the data loggers were remotely controlled by a server computer and the measured data were transferred. Also, an ultrasonic anemometer was installed at the top of the building to measure wind velocities with corresponding wind directions.

The acceleration data of each setup were measured for over 2 hours at the rate of 100 Hz. An anti-aliasing filter was used during the measurement and the row data were digitally filtered using a band pass filter ranging from 0.01 Hz to 10 Hz to remove the drifting trends and high frequency noises.

Table 1. Detailed information of the residential tall building

Items	Descriptions
Purpose of use	Residential/commercial
Story (height, m)	41-story (134.3 m)
B (m) × D(m)	26.0 × 27.4
Structural type	RC core and moment frames Outriggers at 41 FL.
State of construction progress	Under construction - Main structure: done - Masonry partition: done - Finishing: almost done
Location	Pusan

Frequency Domain Decomposition method

To derive the building's dynamic properties, the Frequency Domain Decomposition (FDD) method was used (Brincker, 2000). Firstly, the Cross Power Spectral Density (CPSD) matrix is calculated from the measured acceleration data. And then the CPSD matrix was decomposed into singular values at each frequency using the Singular Value Decomposition (SVD) method. The natural frequencies of the building were determined using the peak locations of the Singular Value (SV) plot shown in Fig. 3. Also, the vibration mode shapes were calculated from the singular vectors selected at the natural frequencies of the vibration modes.

The Auto Spectral Density (ASD) function of an arbitrary mode could be conveniently extracted from the SV plot using the Modal Assurance Criterion (MAC). The extracted ASD function could be transformed back into a free-decaying signal and the damping ratio of a mode could be estimated from it by the Logarithmic Decrement (LD) or linear regression method.

Comparisons of natural frequencies and mode shapes

Using the FDD method, the natural frequencies and mode shapes were evaluated from the measured acceleration data and compared with the results of the FE modal analysis. According to the general practice of structural analysis at the design stage, the floor slabs were assumed as rigid diaphragms and non-structural members were not considered in the FE model of the building.

The actual natural frequencies of the building were picked at the peak values of the SV plot shown in Fig. 3 and compared with the analysis results in Table 2. It can be found in Table 2 that the discrepancies between the measured and the analyzed results are between 13.3% and 30.6% for the six lowest modes. Such discrepancies could be induced mainly due to the diaphragm assumption of

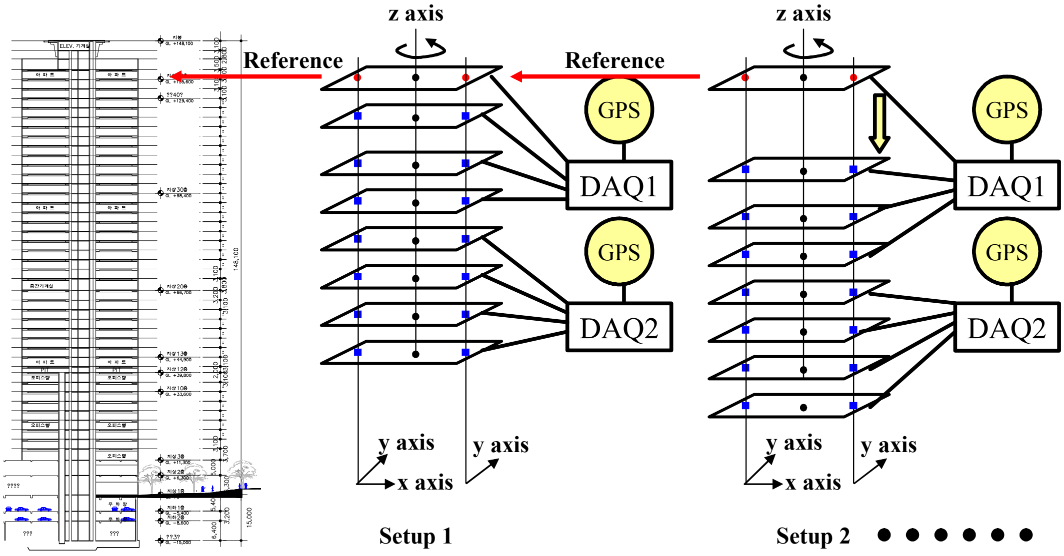


Figure 2. Measurement setups

the slabs, the contributions of the non-structural elements to the lateral stiffness, the increase of the elastic modulus of in-situ concrete, etc. These results, therefore, indicate that the FE models constructed at the design stage could not properly represent the actual buildings. Accordingly, the design wind loads and wind-induced responses could be considerably overestimated due to the underestimation of the natural frequencies.

On the contrary, it can be observed in Fig. 4 that the analyzed mode shapes properly follow the measured mode shapes. This implies that the discrepancies in the natural frequencies are mainly caused not by local problems in the FE models but by global factors, such as elastic modulus, floor slabs, non-structural members and stiffness reduction of RC members.

Damping ratios

The damping ratios of the building for the lowest translational mode for each structural axis were also evaluated by the FDD analysis according to the *r.m.s.* accelerations at the top floor to investigate the amplitude-dependency of the damping ratios. It can be found in Fig. 5 that the damping ratios for the translational modes increase from 0.49% to 1.33% according to the increase of *r.m.s.* responses from 5.39×10^{-3} to 3.45×10^{-3} cm/s^2.

In Fig. 5, the amplitude-dependent damping ratios were compared with the results of the damping predictor suggested by Tamura et al. (2000). The damping predictor was proposed based on the AIJ damping database of full-scale measurements. The range of the building height for the damping predictor is 10.8 m < H <129.8 m for RC buildings and 19.1 m < H <282.3 m for steel buildings. The equations of the damping predictors for RC buildings are given by

$$\varsigma_1 = \frac{0.93}{H} + 470\frac{x_H}{H} - 0.0018 \qquad (1)$$

Table 2. Comparisons of natural frequencies (Hz)

FDD	Analysis
0.328	0.199
0.360	0.226
0.609	0.306
1.307	0.811
1.361	0.832
1.868	0.983

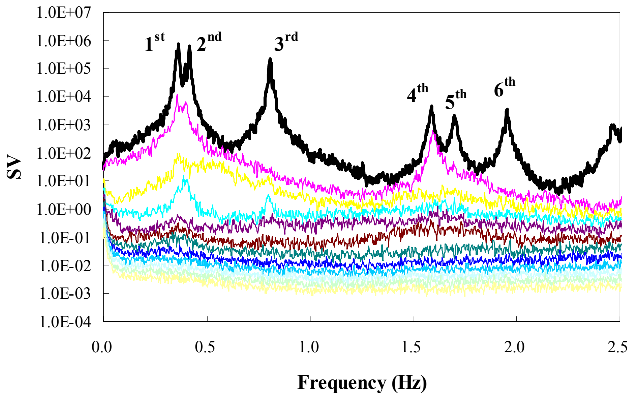


Figure 3. Singular value plot of the tall residential building

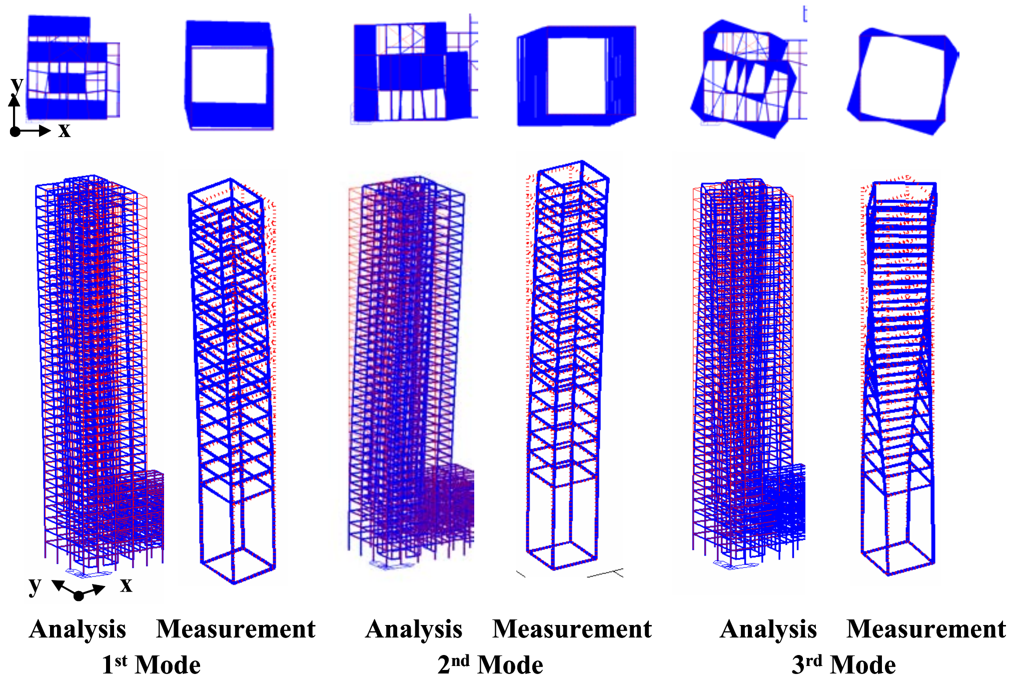


Figure 4. Comparisons of mode shapes

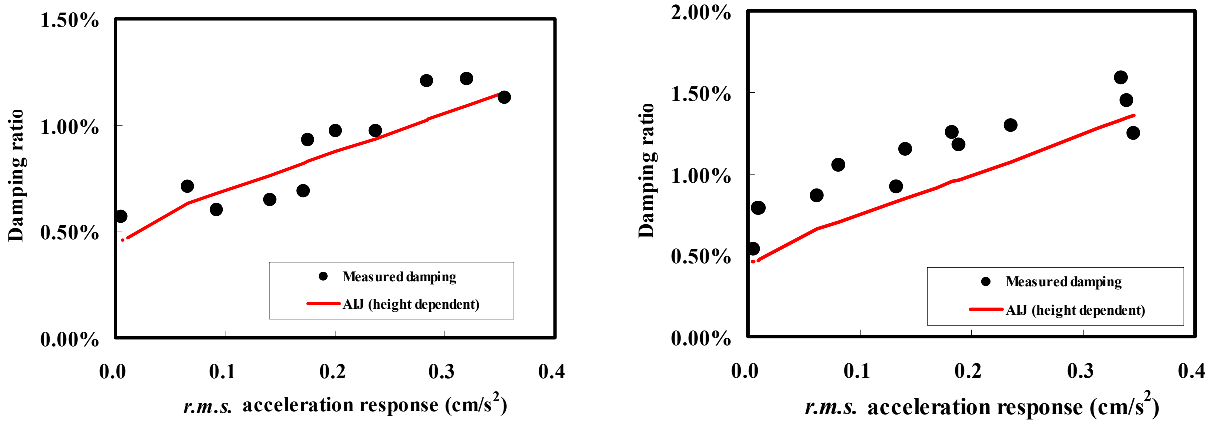
Where, x_H/H is the drift ratio and shall be less than 2×10^{-5}.

Comparison results in Fig. 5 show that amplitude-dependent damping ratios for the building could be properly estimated by Eq. (1), although it slightly underestimates the measured damping ratios. Also, it should be noted that increasing damping ratios according to the increase of responses show a tendency to stop increasing or to decrease at a limited response value (Okada et al, 1993; Jeary, 1992). It thus seems to be tentatively suggesting that the damping ratio could be determined in two different categories. In the low amplitude range, the damping predictors suggested by Tamura et al. could be properly used to evaluate the damping ratio for steel and RC buildings. Based on ISO 4354, 1% and 1.5% could be the maximum damping ratios for the evaluations of high-amplitude responses for steel and RC buildings, respectively.

Comparisons of acceleration responses

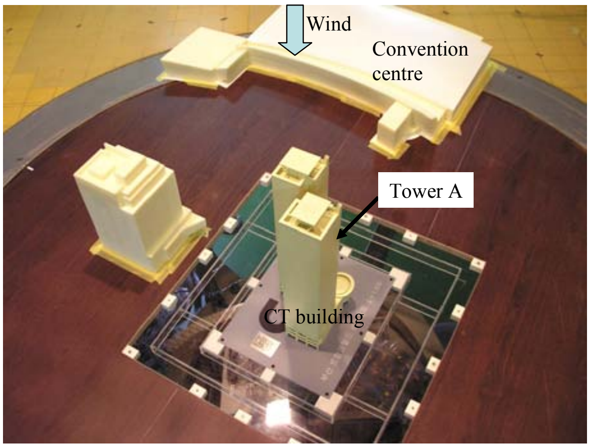
To investigate the effects of errors in dynamic properties for the evaluation of wind-induced responses, the measured accelerations at the top of the building were compared with the results of wind tunnel studies. A pressure test model was constructed as shown in Fig. 6 and surrounding buildings were modeled in the proximity model based on on-site survey results.

The exposure category was assumed to be an open terrain. Accordingly, the power law exponent of the

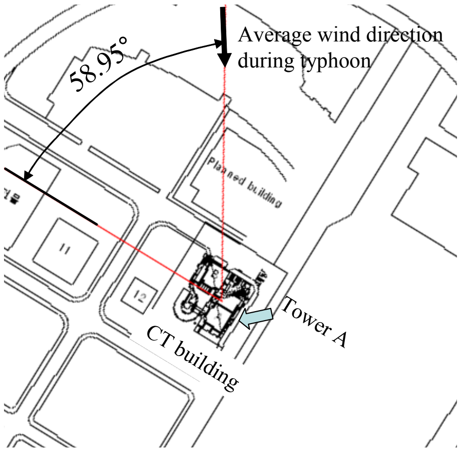


(a) (b)

Figure 5. Amplitude dependent damping ratios for the tall residential building: (a) x-axis; (b) y-axis



(a)



(b)

Figure 6. Construction of a test model for a wind tunnel test: (a) test model; (b) site map

model wind was 0.15 and its turbulent intensity was modeled according to KBC 2004 (KBC, 2004). The wind direction during the wind tunnel test was adjusted to be identical with the average wind direction during the typhoon, Man-yi. The pressure data were sampled for over 40 seconds at the rate of 400 Hz.

The acquired time-series pressure data were converted into full-scale time-series wind forces by integrating pressures over the entire tributary areas as shown in Fig. 7. Using the time-series wind forces, the time-history analysis was performed for two cases of dynamic properties. For Case 1, the time-history analysis was performed using measured dynamic properties. For Case 2, the analyzed natural frequencies were used in the time-history analysis and the damping ratio was assumed to be 1.5%.

The measured accelerations were compared with the analyzed results in Fig. 8. As for the x-axis, the results of Cases 1 and 2 are observed to show a slight discrepancy and a similar trend to follow the measured accelerations. In case of the y-axis, however, it can be observed that the discrepancy between Cases 1 and 2 is rather considerable and the results of Case 2 show remarkable differences with the measured accelerations. It seems mainly because the natural frequencies for the y-axis are considerably underestimated compared with the natural frequencies for the x-axis. This result implies that the evaluations of accurate natural frequencies are important for reasonable assessments of wind-induced responses.

Conclusion

To investigate the accuracy of dynamic properties used in the analysis of wind tunnel test results, a full-scale measurement of accelerations for a tall residential building was performed in this study. Based on the measurement results, it was found that the natural frequencies of tall buildings could be considerably underestimated by the FE modal analysis. To accurately evaluate natural frequencies, it seems preferable to consider the factors that are generally ignored in practical structural analysis, such as floor slabs, non-structural members, and elastic modulus of in-situ concrete. It was also found from the measurement results that the

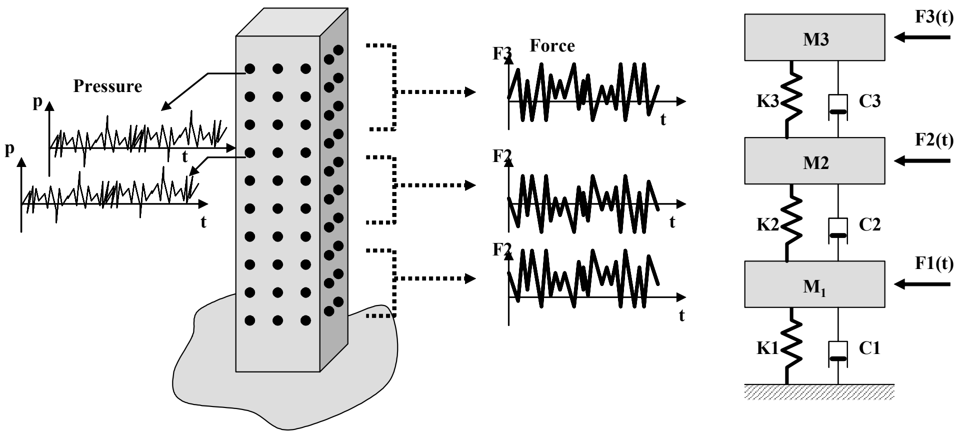
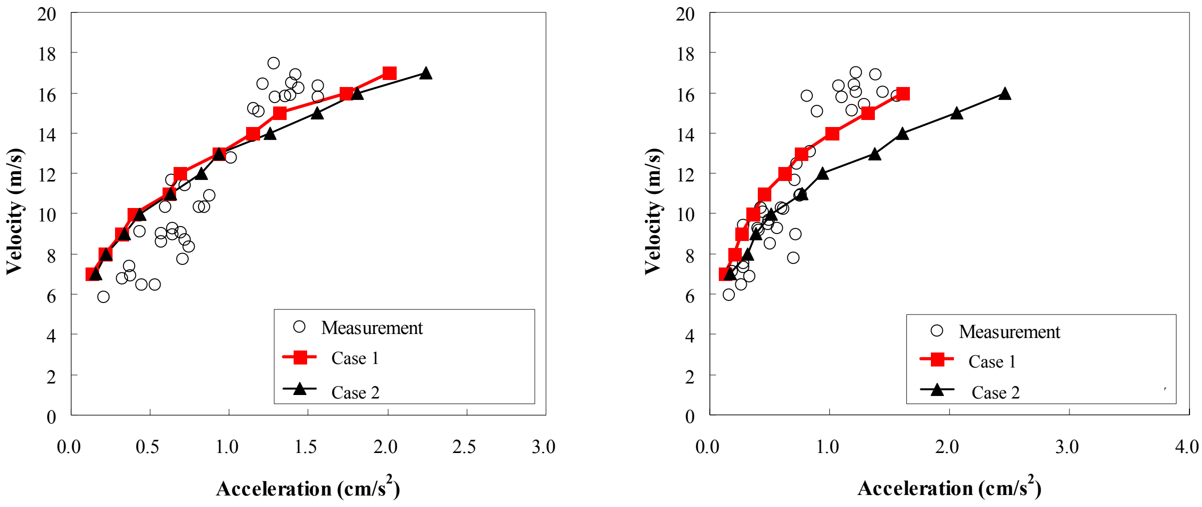


Figure 7. An example of pressure integration



(a) (b)

Figure 8. Comparisons of acceleration responses: (a) for x-axis; (b) for y-axis

damping ratios could be properly expected by the damping predictors suggested in previous researches for practical response analysis.

In addition, by comparing the measured and the analyzed acceleration responses, it was observed that the wind-induced responses could be quite distorted due to the improper evaluation of dynamic properties. Thus, in order to improve the reliability of wind tunnel studies, it seems required to find a way to accurately derive natural frequencies and damping ratios.

A proper procedure for the more accurate evaluation of the dynamic properties could not be fully established by a few comparison results. In the future, we believe it is necessary to perform additional full-scale measurements for providing a more organized evaluation procedure.

Acknowledgement

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