Field Monitoring and Wind Tunnel Test of a 30-story Building

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ABSTRACT

A 30-story building located in Taipei City was instrumented with anemometers and accelerometers and velocity sensors. The wind speed and building motions were monitored for several typhoons during 2005-2006. The building dynamic characteristics identified from the field data and the wind induced building responses were presented in this paper. Furthermore, FEM model of the target building was built and calibrated with respect to field data. Aerodynamic wind tunnel tests of the target building were performed in a well simulated wind tunnel environment. The building responses based on wind tunnel test show good agreement with field measurements.

INTRODUCTION

Taiwan locates at an area that catastrophes from Mother Nature are severe. Both wind and earthquake loads are important for building design. For high-rise building, buildings with large area of facade, long span structures or the lightweight industrial structures, wind load is an important or even dominant lateral loading. Every year from July to November is the typhoon season in Taiwan. It averages 3.5 typhoons per year over the past century. With such a severe typhoon background, there has been very few wind engineering related field measurements in this region. There were some measurements of atmospheric wind in the past, but never the behaviors of building under strong wind reported. Under these circumstances, a 30-story building located at the southeast district of Taipei City

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was selected for the field monitoring of wind induced building motion. Anemometers, velocity sensors and accelerometers are installed at building roof. Wind speed and building behaviors under strong wind were recorded. In this paper, the building behaviors under wind action are presented and compared with wind tunnel experimental results. It is this project's intention to use this instrumented building to collect field data for later wind code validation and the human perception on vibration.

The field measurement system became functional in May 2005. Total of 3 typhoons were recoded during 2005-2006: Haitang (2005/7), Matsa (2005/8) and Saomai (2006/8). Among them, Typhoon Haitang, was classified as a strong typhoon, the maximum wind speed at center was 55m/s; Matsa and Saomai were classified as medium intensity with maximum wind speed at 40 and 48 m/s, respectively. All three typhoons approached Taiwan from east; Haitang made landfall on the east coast, Matsa and Saomai passed through at a short distance to the north-east corner of Taiwan. Taipei was within the storm radius of all three typhoons.

DESCRIPTION OF FIELD MONITORING PROJECT

Bai-Shi Building is a 30-story building located at the southeast district of Taipei city. Bai-Shi Building is 103.1 m in height and the cross-section is roughly symmetrical rectangular, 35.4 m by 26.8 m in its longest dimension. The terrain condition surrounding the building in Taipei city is shown in Figure 1. At the close neighborhood of the Bai-Shi Building are mostly 4~6 story buildings, except an 81 meter, 24-story building located 36 meter to its west. Within a 2 kilometer radius, in the south quadrant lays a university campus with mostly scattered 3-5 storey buildings; in the other quadrants, most of the buildings are 5 to 10 story buildings. 1.1 kilometers away to its east are hills with apex at about 140 meters. The surrounding terrain can be roughly classified as an urban area.

Figure 1: Bai-Shi Building and the surrounding terrain.

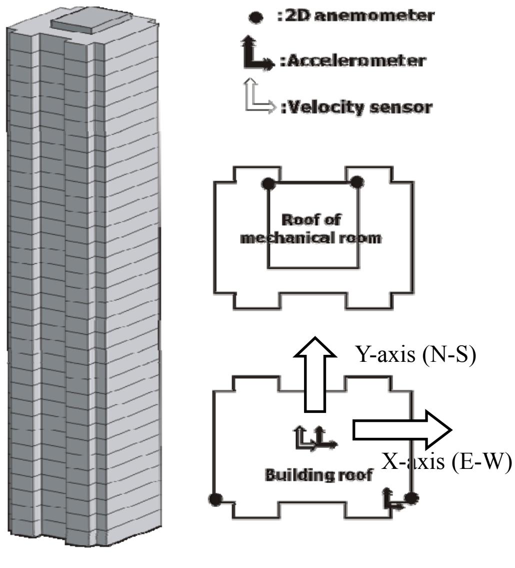
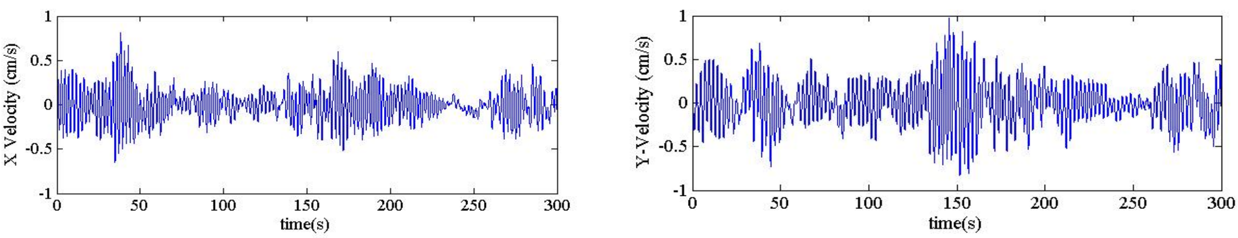


Figure 2: Configuration of Bai-Shi Building and Measuring Instrumentation

This paper will first present the field data measured at Bai-Shi Building during the aforementioned three typhoons. Shown in Figure 2 are the cross-section of Bai-Shi Building and the arrangement of instrumentations. Bai-Shi building has a rectangular cross-section. The longer side is on the E-W direction, denoted as X-axis. The shorter side is on the N-S direction, denoted as Y-axis. On the north side roof of the building is a mechanical room. Four anemometers were installed at the corners of the south side roof and the roof of the mechanical room on the north side. At least one of anemometers could take wind speed measurement without interference of the building itself. Gill/WindSonic bi-axial ultrasonic anemometer was used in this project; it has velocity range of 0-60 m/s, ±2% accuracy and the digital output rate at 4 Hz. Four PMD/EA-120 uni-axial accelerometers were installed at the geometric center and the corner of the building roof in both X and Y direction, in order to measure the accelerations in both lateral and torsional directions as well. The accelerometer has range of ±2g, 0.8μg resolution and frequency response of DC-50 Hz. Since the expected building response in an average typhoon is relatively small for a 30-story building and it would be difficult to obtain building's displacement from the accelerometer measurements, a high resolution bi-axial velocity sensor was installed at the geometric center of the building roof to measure the building velocity in both X and Y directions. It is a PMD/EP-105 seismometer with high sensitivity (2000V/m/s) and good frequency response of 0.033-50 Hz. It can be used for obtaining the displacement by performing integration, or for verification with the results from the accelerometers. During each typhoon, all sensor measurements were continuously recorded for 24 hours at sampling frequency of 20 Hz.

RESLUTS OF FIELD MEASUREMENTS AND IDENTIFICATION OF STRUCTURAL PROPERTIES

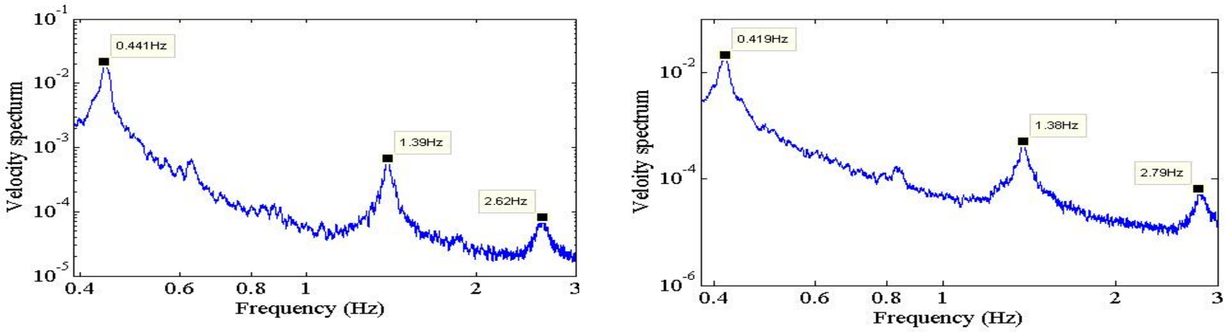
Shown in Figure 3(a) and 3(b) are typical building response time histories at building roof. Since the velocity sensors have better resolution, Results presented in this paper are mostly from the velocity sensor measurements. Prior to analyzing the field data, the orientation of the seismometer was adjusted so that the crosstalk between the two orthogonal axes would be at minimum. All the velocity data were numerically integrated to obtain the building displacement time history. Then, these displacement data were processed for the structural identification or wind induced response. Since both the Fourier analysis for frequency identification and Random Decrement procedure for damping identification are based on the assumption of stationary random process, the stationarity of the field data was checked. The reverse arrangements test (Bendat & Piersol, 1986) was applied to all recorded one-hour field data to determine the stationarity (Chen and Xu, 2004). To properly executing the reverse arrangement test, minimum of 10 segments are needed. Since the record length of each segment is set to be 10 minutes, two consecutive one-hour wind speed records were test together. Each one-hour record was considered stationary if it passes the test combining with either one of the two neighboring one-hour records. Among the 72 one-hour full scale data measured during the 3 typhoons, approximately 90% could pass the stationarity test. For the time being, only those one-hour records that passed stationary test were used in the subsequent data analyses.



(a) X-axis (b) Y-axis

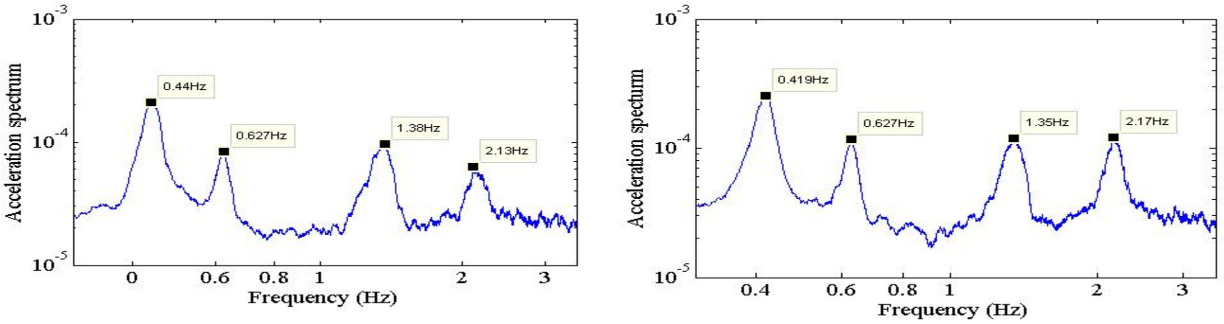
Figure 3: time histories of velocity response at center of building roof

The power spectral analyses were performed on the building response time histories. The duration for each data-processing segment is 12000x0.05 seconds = 600 seconds. Shown in Figure 4(a) and (b) are the power spectral densities of the velocity response at the center of the building roof. As observed from Figure 4(a), the natural frequencies of the first three modes in the X (strong axis) direction are 0.44, 1.39 and 2.62 Hz, respectively. The natural frequencies of the first three modes in the Y (weak axis) direction, shown in Figure 4(b), are 0.42, 1.38 and 2.79Hz, respectively. The torsional natural frequency can be identified from the spectra of the acceleration response measured at building corner. The first two natural frequencies in the torsional direction are 0.63 and 2.15 Hz, as can be identified from the spectrum of the acceleration at the corner as shown in Figure 5. It has been found that the natural frequencies obtained from all records are very consistent. All these measured measure natural frequencies will be used later on to calibrate the FEM model of this building.



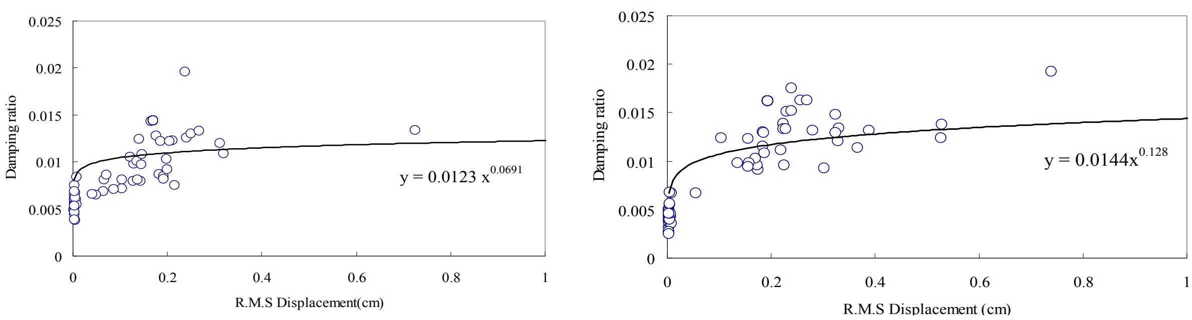
(a) X-axis (b) Y-axis

Figure 4: Building velocity response spectra at center



(a) X-axis (b)Y-axis

Figure 5: Building acceleration response spectra at corner.



(a) X-axis (b) Y-axis

Figure 6: Damping ratio as function of building

The building's velocity responses measured at center were also use to identify structural damping. Structural damping was identified by the random decrement method. The RD threshold was set at 1.0

standard deviation of the velocity response; the number of segment was kept greater than 1000. Shown in Figure 6(a) and 6(b) were damping ratio plotted as a function of the root-mean-square (RMS) value of the displacement response. As observed from Figure 6, at small amplitude, damping ratio is heavily dependent on the structural response; however, when the normalized structural RMS response is greater than 0.1 cm, the damping ratio of both x and y axes show some randomness, nevertheless they approach a stable value at roughly 1.2 % and 1.4 %, respectively. Similar damping ratio versus amplitude relationship was reported by other researchers in their field monitoring works (Fang et.al., 1999, Li and Wu 2007). The damping ratio for the torsional direction is yet to be determined.

Shown in Figure 7 is a typical trajectory of Bai-Shi Building's dynamic displacement during typhoon. The elliptic trajectory with an inclination toward 60° suggests certain degree of correlation between wind induced building response in x and y axes. This correlation is likely due to the correlated wind loads of the two horizontal axes that were caused by the inclined wind direction. Shown in Figure 8 & 9 are the 10-minute averaged RMS displacement responses at building roof as the function of wind speed. Data collected during different typhoons are all in fairly good proportion to the square of wind speed. The proportional coefficients for the displacement in X and Y axes during typhoon Haitang are 0.0421 and 0.0625, respectively. The proportional coefficients for the displacement in X and Y axes during

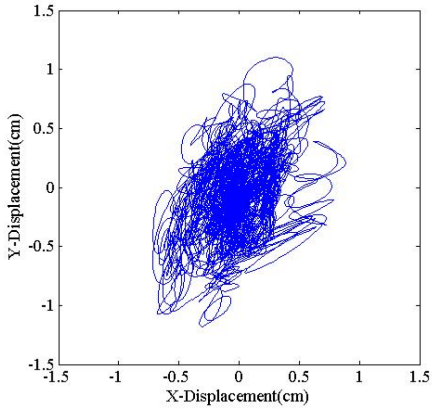
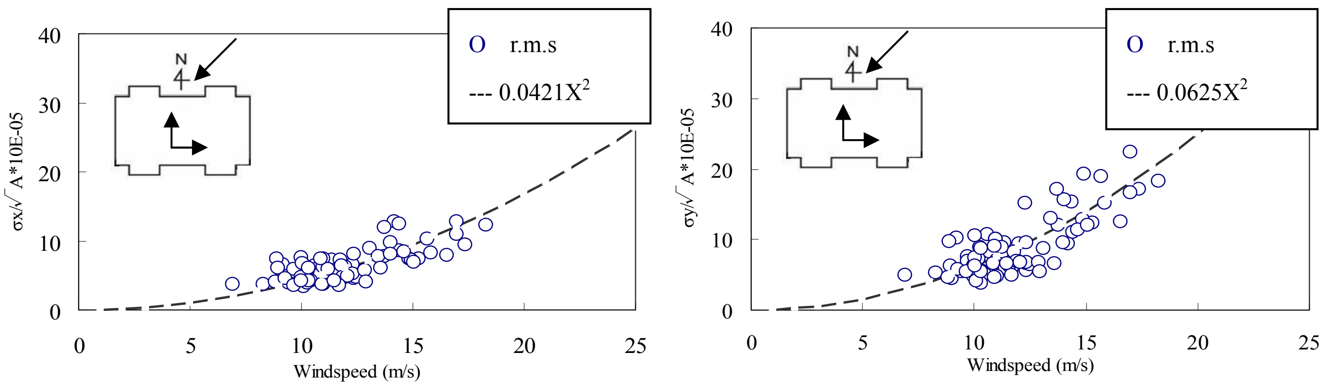


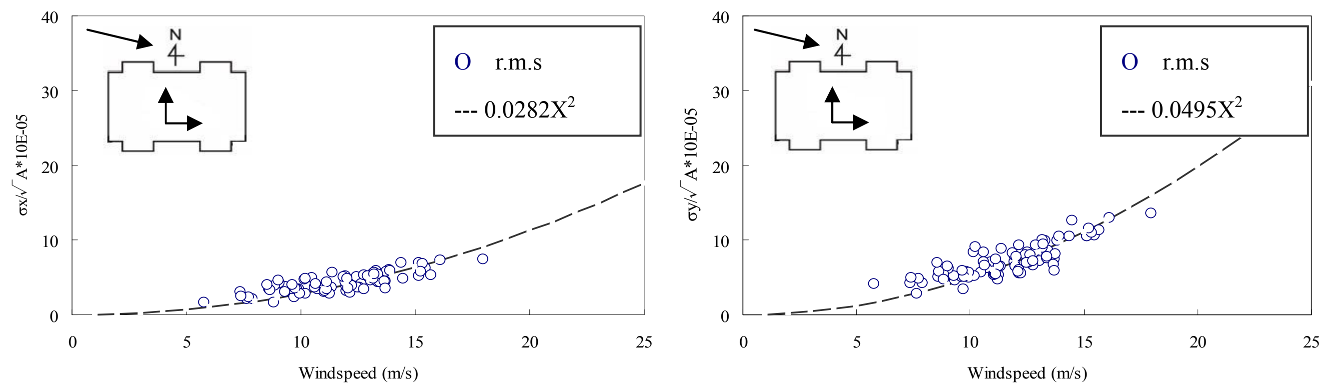
Figure 7: Typical trajectory of displacement



(a) X-axis

(b) Y-axis

Figure8: RMS displacement of Bai-Shi Builidng during Haitang Typhoon (2005/7).



(a) X-axis

(b) Y-axis

Figure 9: RMS displacement of Bai-Shi Builidng during Matsa Typhoon (2005/8)

typhoon Matsa are 0.0282 and 0.0495, respectively. The difference in the proportional coefficients is due to the significant difference in wind directions. All structural response data will be used later to be compared with the wind tunnel test.

The probability density functions of the building responses were calculated each 10-minute data segment and compared with the standard Gaussian distribution. Shown in Figure 10 are typical PDF of the building responses in two horizontal axes. The field measured building response appears to symmetric bell-like distribution but with less scatter than the Gaussian variates. Shown in Figure 11 are the plots of kurtosis coefficients of the building motion as function of the response amplitude. The skewness coefficient appears to be independent of response level and have an averaged value close to 0.0. The kurtosis coefficient, on the other hand, appears to be more scattered at small amplitude and gradually converge as response amplitude increases. The averaged value is 3.58 and 3.71 for X-axis and Y-axis response which are noticeably deviated from the 3.0 for Gaussian variate. This probability characteristic could be observed in all three typhoons. Similar result can be found in earlier field monitoring report (Li et al., 2003).

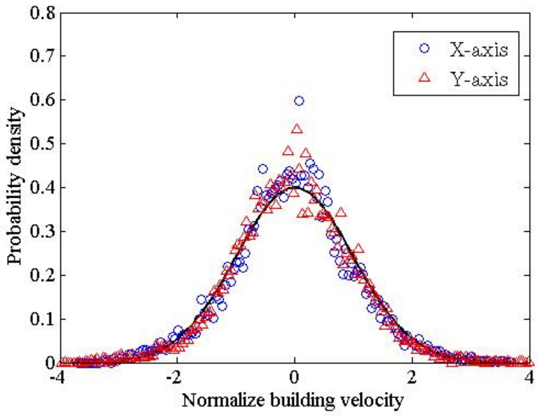


Figure 10: Probability density of building response

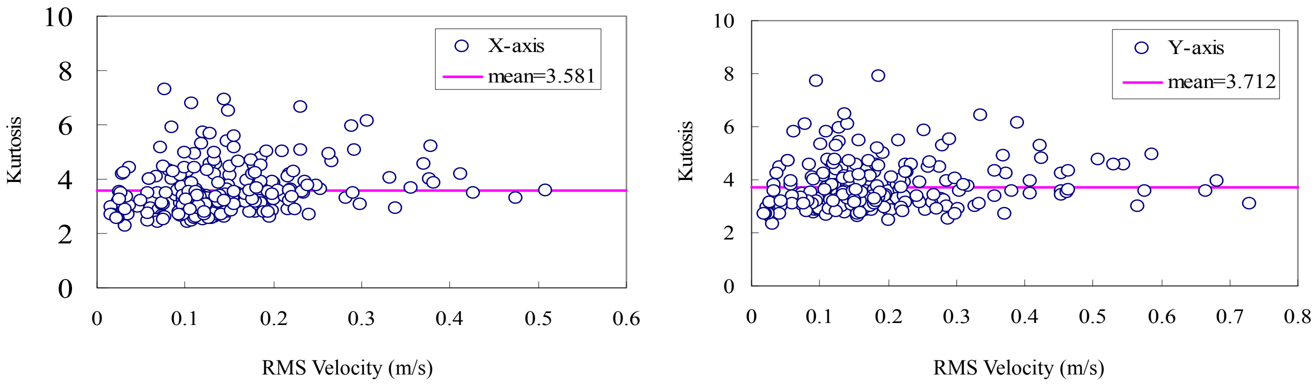


Figure 11: Building response Kurtosis coefficient as function of RMS amplitude

FINITE ELEMENT MODEL OF BAI-SHI BUILDING

A Finite Element Method (FEM) model of Bai-Shi Building was built for later predictions on the wind induced building responses. The structural system consists of steel frame with diagonal bracing in both axes and concrete floors. Commercial software, MIDAS, was used to build the FEM model and the subsequent dynamic analyses. Total of 4084 frame elements and rigid diaphragm for the floor were used to model the shear building system as shown in Figure 12. All member sections of the frame system were built based on the original

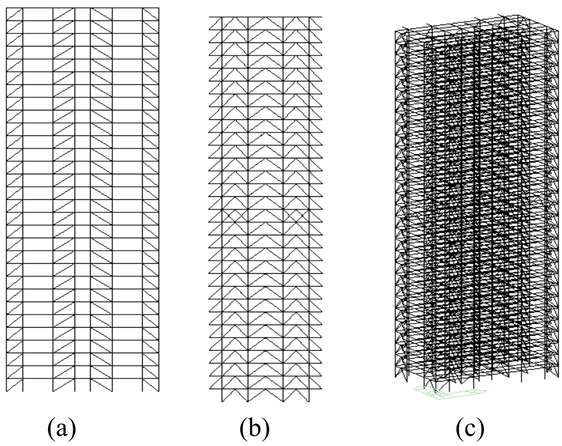


Figure 12: 30 story steel frame FEM model
(a) front view; (b) side view; (c) 3D view

construction blueprint. The geometric size and material properties are listed in Table 1. Thicker floor thickness at roof representing in-situ equipments and the mechanical room were added at the building roof. The thickness of concrete floor which representing dead loads plus live loads was treated as a variable during modeling process to meet the dynamic characteristics of field measurement results. Shown in Table 2 are the comparisons of the structural frequencies between field measurements and FEM model. The first six dominant frequencies of vibration modes agree quite well with the field measurement results. The error percentage of the first mode frequencies in X, Y, RZ axes are 0.2%, 0.5% and 3.1% respectively. The error percentage of the second mode frequencies in X, Y, RZ axes are higher but still reasonable at 4.7%, 8.6% and 7.7% respectively.

Table 1 Geometric size and material properties of FEM model

Geometric size (unit : m)		Material Properties	
Height×Width×Depth	103.1×35.4×26.8	Steel	A572-50 ($E=2.05\times10^{10}$ kgf/m^2)
Story Height	3.4 (4.5 for roof)	Concrete	Grade 2500 (ρ=2403 kgf/m^3)
Floor thickness	0.215 (0.4 for roof)		

Table 2 Comparisons of structural frequencies of field measurements and FEM model

Mode	Axis	Frequencies (Hz)		Error(%)
		Field Measurement	FEM	
1	Y	0.42	0.422	0.5%
2	X	0.44	0.441	0.2%
3	RZ	0.63	0.610	3.1%
4	Y	1.38	1.261	8.6%
5	X	1.39	1.324	4.7%
6	RZ	2.15	1.981	7.7%
7	Y	2.79	2.434	12.8%
8	X	2.62	2.510	4.2%

WIND TUNNEL TEST AND COMPARISONS

1) Wind tunnel test

A wind tunnel testing program was carried out parallel to the Bai-Shi Building monitoring project. The aerodynamic test and the results are presented in this paper. A 1/400 scale pressure model instrumented with 224 pressure taps was tested in a simulated turbulent boundary layer. Instantaneous wind pressures were simultaneously measured through ZOC pressure scanner system and the wind loads were subsequently calculated for later structural spectral analysis and time domain analysis. In order to make meaningful comparison between field measurements and wind tunnel results, the field data were carefully examined and field measurements of wind direction around 40° were selected for this comparison. Shown in Figure 13 is the layout of the wind tunnel test section. In addition to the usual detail modeling of the surrounding buildings within the wind tunnel turn table (corresponding to 360 m radius in full scale), the upstream buildings and streets extending up to 4000 m upstream were carefully modeled, turbulent boundary layer devices for suburban terrain (α=0.25) were used at entrance of test section. In such arrangement, at least the lower part of the turbulent boundary layer that covers the height of target building was generated by the genuine terrain in stead of the artificial boundary layer generating device. The boundary layer characteristics were measured at the monitoring site by removing the target building to avoid interference. Shown in Figure 14 are the mean velocity and turbulence intensity profiles. The measured power law exponential α=0.44 which is significantly higher than the presumed α=0.25~0.3 for this part of Taipei city that consists of mostly 5~10 story buildings. This unexpected high velocity gradient is probably due to a row of closely spaced 10~15 story buildings along a main street that cut though test section at roughly 4.3 km upstream and at 40° angle. These buildings act like a barrier wall that causes a down stream wake and the unusual velocity gradient.

Shown in Figure 15 is a set of typical base shear force time histories in the two horizontal axes.

Figure 13: Wind tunnel model arrangement

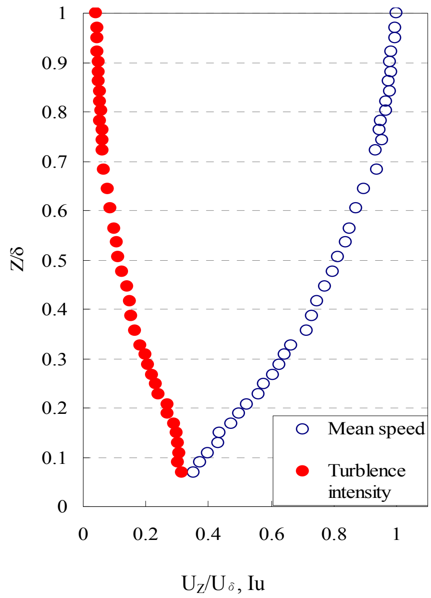


Figure 14: Mean velocity and turbulence intensity profile

The Y-axis wind load exhibits slightly larger RMS values than the X-axis wind load. It is partly due to the fact that Bai-Shi Building is wider in Y-axis; the other possible reason is that there exists a neighboring building interference in the X-axis. The wind load spectra of the two horizontal axes are plotted and shown in Figure 16, in which wind load spectra of both axes are similar and exhibit broad bandwidth nature, whereas wind load in Y axis has higher energy contains in the lower frequency region.

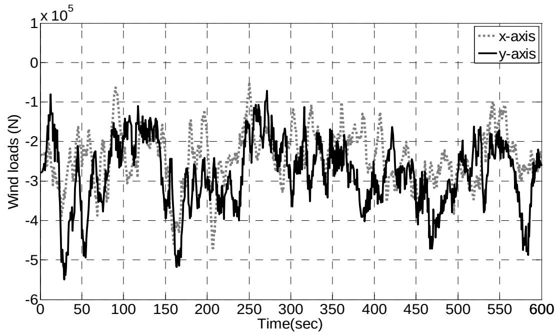


Figure 15: Wind loads based on wind tunnel simulation.

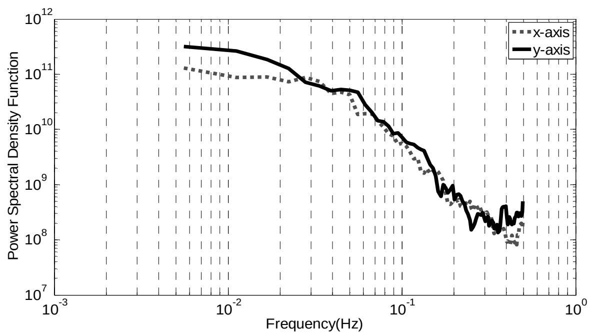
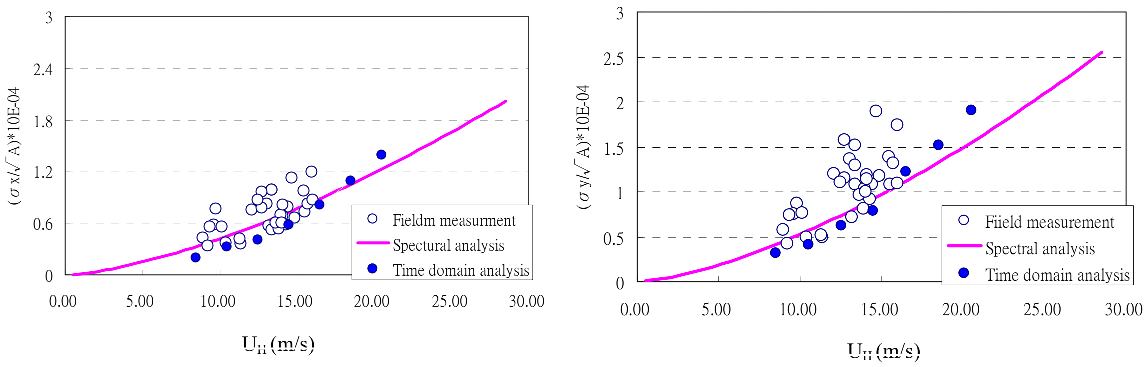


Figure 16: Wind Load spectra for FEM model

2) Comparison predicted building response and field measurement

The wind induced structural responses of Bai-Shi Building were calculated through both frequency domain and time domain analyses. Both structural prediction procedures are based on the wind loads from the wind tunnel test and structural properties of the FEM model which have calibrated with respect to the field measurements. The frequency domain analysis is the conventional single degree of freedom spectral analysis, in which both the structural modal coupling and wind load coupling are excluded. In the time domain analysis, a segment of time histories of wind loads measured from the wind tunnel test, which corresponds to 10-minute duration in full scale, were transformed into nodal loads and applied to the FEM model. In order to make proper comparison with the spectral analysis the magnitude of wind load time history was adjusted so that the RMS value would be same as the one-hour average used in the spectral analysis. Newmark-β direct integration was used. Damping ratios are assumed to be 1.3% for the first mode and 1.2% for the second mode to calculate the coefficients of Rayleigh damping. Shown in Figure 17 (a) and (b) are the comparisons of calculated displacement responses at building height to the field measurements. The calculated building response by either spectral analysis or time domain analysis for both x and y axes are close to but slightly less than the field measurements. Figure 17 also exhibits some minor difference between the results from the spectral and direct integration analyses. At very low wind speed the single d.o.f spectral analysis produces higher building response than the time domain calculation. However, as wind speed increases, the results from time domain analysis gradually surpass the spectral analysis outcomes. The source of this deviation between two methods is to be determined. It could be combination of inherent random error in



(a) X-axis (b) Y-axis

Figure 17: Comparisons of building response prediction with field measurement.

the wind load time history, round-off error in nodal wind load interpretation, structural coupling and aerodynamic coupling effects.

CONCLUDING REMARKS

A 30-story building located in Taipei City was instrumented and monitored during 2005-2006 typhoon seasons. Based on the field data the building natural frequencies and damping ratios were identified. Damping ratio is heavily dependent on the structural response at small amplitude, and approaches stable value at 1.2 ~ 1.4 %. The probability density of the building response exhibits symmetric bell-like distribution but with less scatter than the Gaussian variate. The averaged kurtosis coefficient is at 3.58 and 3.71 for responses in two horizontal axes. Furthermore, FEM model of the target building was built and calibrated with respect to field data. Natural frequencies of the lowest horizontal and torsional modes agree well with field data. Aerodynamic wind tunnel tests of the target building were performed in a well simulated wind tunnel environment. The building responses were then calculated by both spectral analysis and direct time domain integration methods. The building responses based on wind tunnel test show good agreement with field measurements.

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