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Typhoon effects on super-tall buildings

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Abstract

Full-scale measurement is considered to be the most reliable method for evaluating wind effects on buildings and structures. This paper presents selected results of wind characteristics and structural responses measured from four super-tall buildings, The Center (350 m high, 79 floors) in Hong Kong, Di Wang Tower (384 m high, 78 floors) in Shenzhen, CITIC Plaza Tower (391 m high, 80 floors) in Guangzhou and Jin Mao Building (421 m high, 88 floors) in Shanghai, during the passages of three typhoons. The field data such as wind speed, wind direction and acceleration responses, etc., were continuously measured from the super-tall buildings during the typhoons. Detailed analysis of the field data was conducted to investigate the characteristics of typhoon-generated wind and wind-induced vibrations of these super-tall buildings under typhoon conditions. The dynamic characteristics of the tall buildings were determined from the field measurements and comparisons with those calculated from the finite element (FE) models of the structures were made. Furthermore, the full-scale measurements were compared with wind tunnel results to evaluate the accuracy of the model test results and the adequacy of the techniques used in the wind tunnel tests. The results presented in this paper are expected to be of considerable interest and of use to researchers and professionals involved in designing super-tall buildings.

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1. Introduction

Recently, many super-tall buildings (building height >300 m) have been or are being built throughout the world. As the building height increases, the sensitivity of super-tall buildings to dynamic excitations, such as strong wind has increased. Consequently, these structures have become more wind sensitive, and wind loads generally control the design of such tall buildings. This has resulted in a greater emphasis on understanding the structural behavior of super-tall buildings under strong wind action. While most current codes are generally applicable to the structural design of common tall buildings, they are not guaranteed to fully cover the design of super-tall buildings. It is thus necessary to conduct comprehensive investigations of wind effects on super-tall buildings. It has been recognized that the most reliable evaluations of dynamic characteristics and wind

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effects are obtained from measurements of a prototype building. Monitoring the performance of super-tall buildings with different structural systems under harsh typhoon conditions can provide important validation of design procedures and examine structural behavior of super-tall buildings. With the development of data acquisition techniques during the last two decades, a number of full-scale measurements of wind effects on tall buildings have been made throughout the world (e.g., Refs. [1,2]), including the extensive measurement programs on four Chicago tall buildings currently being undertaken by Notre Dame University and the University of Western Ontario [3] and on several super-tall buildings in Hong Kong and Mainland China conducting by Li et al. [4–7], Xu et al. [8] and Campbell et al. [9]. However, it has been widely recognized in wind engineering community that the chance to conduct full-scale measurements is quite rare, and obtained data are very important and valuable. Thus, there is a need to carry out further research works on this topic.

This paper presents some selected field measurement results of wind effects on four super-tall buildings, The Center (350 m high, 79 floors) in Hong Kong, Di Wang Tower (DWT) (384 m high, 78 floors) in Shenzhen, CITIC Plaza Tower (CPT) (391 m high, 80 floors) in Guangzhou and Jin Mao Building (JMB) (421 m high, 88 floors) in Shanghai, during the passages of three typhoons. The field data such as wind speed, wind direction and acceleration responses, etc., were continuously measured from the four super-tall buildings during the typhoons. Detailed analysis of the field data and comparative study are conducted to investigate the characteristics of typhoon-generated wind and wind-induced vibrations of these super-tall buildings under typhoon conditions.

The Center is located in the central districts of Hong Kong Island, which has an approximately square planform, is a steel structure. The Center is situated very close to the coast in a typhoon-prone region, and as such the super-tall building may be subjected to severe wind forces under typhoon conditions. DWT is located in downtown Shenzhen City, China, about 2 km away from the nearest Hong Kong border. The structural system includes steel and reinforced concrete core wall and perimeter steel frame coupled with outrigger trusses at four levels. The aspect ratio of height to transverse width is about 9, which means that it largely exceeds the relevant criteria laid down in the current design codes and standards in China. This makes a detailed study of wind effects on this slender building particularly important and necessary. CPT, located in the central district of Guangzhou, about 120 km away from the Hong Kong border, is the tallest reinforced concrete building in the world. The basic planform of the building is essentially a square. The JMB with 88-storeies located in Pudong New Area, Shanghai, has a height of 421 m and is the highest tall building in Mainland China. It is a steel and concrete composite structure with building's plan form very close to a square shape. The observations of wind velocity atop the super-tall buildings can provide very useful information on the characteristics of typhoon-generated wind over typical urban areas. Monitoring the performance of the super-tall buildings with different structural systems provides an excellent opportunity to investigate their dynamic characteristics and wind-induced vibrations for validation of design procedures and assurance of acceptable behavior. The four super-tall buildings among the highest in the world, located in the southeast coastal region of China which is one of the regions most seriously impacted by typhoons in the world, are idea test beds for investigating typhoon effects on super-tall buildings.

Determination of structural dynamic characteristics is necessary in the design of tall buildings, since natural frequencies, mode shapes and damping ratios are basic data for wind or seismic-induced response analysis. Several analytical and numerical methods are available for evaluating the natural frequencies and mode shapes of a structure in design stage. However, as yet there is no widely accepted method available for estimating damping ratios of a structure prior to construction. It has been recognized that damping is a nonlinear parameter, and may increase with increasing amplitude [4,5,10,11]. However, literature review reveals that the information on amplitude-dependent damping contained in the literature mostly concerns normal tall buildings in the vicinity of 40 stories or shorter. Thus, there is a serious scarcity of damping data for tall buildings taller than 40 stories, especially for super-tall buildings under typhoon conditions. In this study, the amplitude-dependent damping ratios of the four super-tall buildings are determined by the random decrement technique based on the measurements of wind-induced responses.

In general, it is difficult to reproduce the exact field conditions such as incident turbulence and terrain characteristics in wind tunnel tests. A direct comparison of model test results to full-scale measurements is always desirable, not only to evaluate the accuracy of the model test results and the adequacy of the techniques used in wind tunnel tests, but also to provide better understanding of the physics. The full-scale measurements of typhoon effects on the four super-tall buildings provided an excellent opportunity to compare the real structural performance with wind tunnel test results for the purposes mentioned above. In fact, such comparison has seldom been made for super-tall buildings under typhoon conditions.

The full-scale measurements by themselves can provide useful information on typhoon-generated wind characteristics over typical urban terrains and the wind-induced response of the super-tall buildings. Furthermore, the field measurements are also very useful to examine the adequacy of the computational models of the structures and the accuracy of wind tunnel test results. The objective of this study is to further the understanding of wind effects on super-tall buildings and the behavior of such structures under typhoon conditions in order to apply that knowledge to design.

2. Full-scale measurements of wind effects on the four super-tall buildings

2.1. The instrumented super-tall buildings

The Center (TC) in Hong Kong, DWT in Shenzhen, CPT in Guangzhou and JMB in Shanghai, as shown in Fig. 1, have been or are being monitored in an attempt to obtain reliable field data that represent real life wind loads on and wind-induced vibrations of the super-tall buildings. Measurements of data from these buildings include wind speeds, wind directions, acceleration and displacement responses, etc. This is currently one of the largest experiments in the world for studying wind effects on full-scale structures, which can provide a fundamental improvement of knowledge in structural dynamic characteristics, wind–structure interaction, wind climate, wind field modelling and design wind loads for Hong Kong, Shenzhen, Guangzhou, and Shanghai.

Accelerometers were installed at several selected floors in each instrumented tall building. The measurements from the accelerometers mounted at the top floor along two orthogonal main axes (directions 1 and 2, as defined in Fig. 1) in each instrumented tall building are analyzed and presented in this paper. The accelerometers provide measurements of vibrations of the buildings. These measurements were continuously acquired, amplified, and pass filtered at 10 Hz before being digitized at 20 Hz. Both propeller anemometers and ultrasonic anemometers were installed on the masts atop DWT and CPT with the height of 345 and 350 m from ground and 22.5 and 18 m above the roofs of DWT and CPT, respectively. The local wind regime around JMB was monitored by an anemometer installed atop a tall building near the JMB. The height of the location of the anemometer was about 220 m from ground level. The location of the anemometer was calibrated in a wind tunnel test to be described later. In addition, the wind speed data recorded by two rotating cup anemometers installed at elevation of about 350 m above ground level on the 75th floor of Central Plaza (near TC) in Hong Kong Island by the Hong Kong Observatory Department were adopted in the analysis of wind speed data.

These anemometers produce analog output voltages proportional to the wind speed and wind direction, which provided outputs sampled at 20 Hz. In order to reduce the interference effects from the masts, the anemometers were installed at a steel cantilever with 2–4 m away from the mast centers atop DWT and CPT. Acceleration responses, wind speed, and wind direction were measured simultaneously for each of the instrumented tall buildings during typhoons. It should be mentioned that there are relatively few full-scale studies of this type being undertaken, although more and more tall buildings are being designed and constructed. Significant field data has been measured from the instrumented tall buildings in Hong Kong, Shenzhen, Guangzhou and Shanghai over the last several years, including the measurements made during the passage of several typhoons such as Typhoon Imbudo, Typhoon Dujuan, and Typhoon Rananim. Data analysis has been conducted based on these field measurements to provide useful information on wind effects on, structural dynamic characteristics and wind-induced responses of the instrumented tall buildings.

2.2. Typhoon-generated wind characteristics

This paper presents some selected results of wind effects on TC, DWT, and CPT during the passages of Typhoon Imbudo and Typhoon Dujuan as well as on JMB during Typhoon Rananim. As reported by the Hong Kong Observatory [12], Imbudo developed as a tropical depression about 730 km southwest of Guam

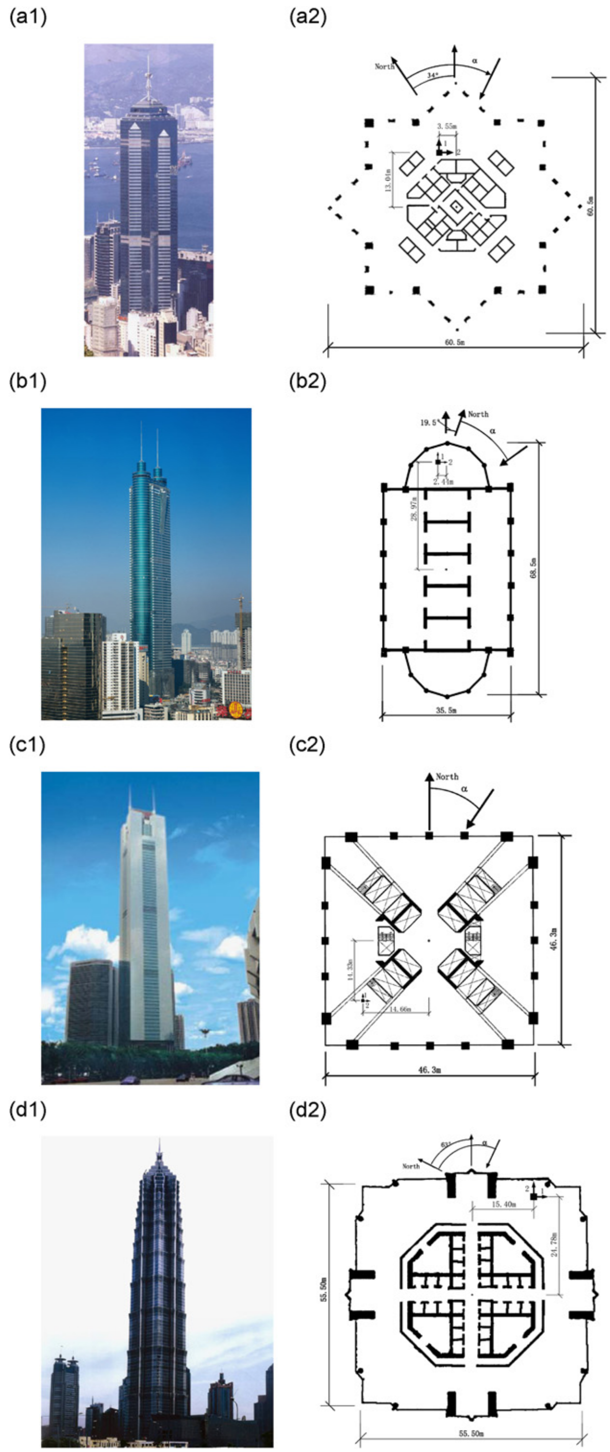

Fig. 1. Pictures of the instrumented super-tall buildings, locations and orientations of the installed accelerometers (marked by 1 and 2): (a1) picture of The Center (in Hong Kong, 350 m high); (a2) top view and locations of accelerometers; (b1) picture of Di Wang Tower (in Shenzhen, 384 m high); (b2) top view and locations of the accelerometers; (c1) picture of Citic Plaza Tower in Guangzhou, 391 m high); (c2) top view and locations of the accelerometers; (d1) picture of the Jin Mao Tower (in Shanghai, 421 m high); and (d2) top view and locations of the accelerometers.

on 17 July 2003. It became a severe tropical storm on 19 July and further strengthened into a typhoon the next day with a maximum wind speed reaching about 185 km/h near its center on 21 July. Imbudo entered the South China Sea on the night of 22 July and continued to move west-northwestwards towards the South China coast. On the morning of 24 July, it made landfall near Yangjiang of western Guangdong. Imbudo weakened into a tropical storm over land on the morning of 25 July and dissipated in Guangxi the same day.

Dujuan entered the South China Sea on the early morning of 2 September, 2003 and moved westwards towards the coast of Guangdong. While crossing the northern part of the South China Sea, it exhibited a double eye wall structure. On the night of 2 September, Dujuan skirted the north of Hong Kong and hit Shenzhen, as shown Fig. 2. It then continued to move westwards crossing Guangdong. Dujuan weakened rapidly into a tropical storm on the morning of 3 September. Dujuan was regarded as the strongest typhoon to hit the Pearl River Delta region since 1979.

As reported by Shanghai Typhoon Research Institute [13], Rananim developed as a tropical depression over the western North Pacific on 8 August 2004, about 1100 km east-northeast of Manila. It intensified over water on the East China Sea and attained typhoon strength on 11 August. Rananim made landfall in Wenzhou on the night of 12 August and dissipated over land the next day. Rananim was regarded as the strongest typhoon struck the eastern coastline of Mainland China in the last several decades.

When Typhoon Dujuan approached Hong Kong on 2 September 2003, typhoon signal no. 10 was hoisted in Hong Kong for the first time since 1999. Fig. 3 shows the hourly mean wind speed and wind direction, which were recorded atop Central Plaza by the Hong Kong Observatory Department during Typhoon Dujuan. Typhoon signal no. 8 was hoisted on 23 July 2003 as Typhoon Imbudo struck Hong Kong. Fig. 4 plot the variations of hourly mean wind speed and wind direction during the passage of Typhoon Imbudo, which were also recorded by the Hong Kong Observatory Department at the same measurement station in Hong Kong Island. The maximum hourly mean wind speeds were found to be 28.4 and 21.7 m/s during Typhoon Dujuan and Typhoon Imbudo, respectively. It is observed from Figs. 3(b) and 4(b) that there was a significant variation of wind direction as the strongest storms during Typhoon Dujuan or Typhoon Imbudo passed the measurement station.

Turbulence intensity and gust factor are important parameters for determining design wind loads on buildings and structures. When typhoons make landfall, several changes occur in their characteristics, particularly to the turbulence intensity and gust factor. This fact makes a field measurement on the turbulence intensity and gust factor during typhoons of particular interest.

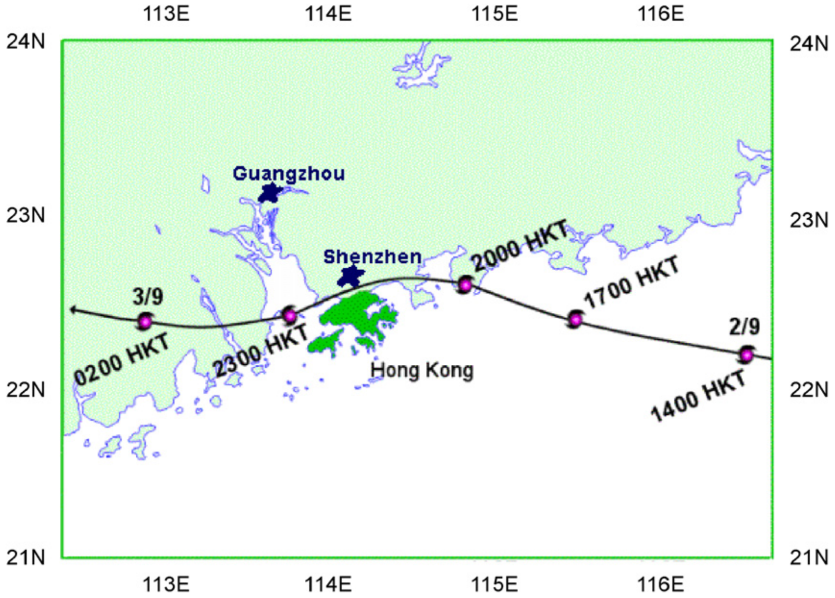

Fig. 2. Moving track of Typhoon Dujuan.

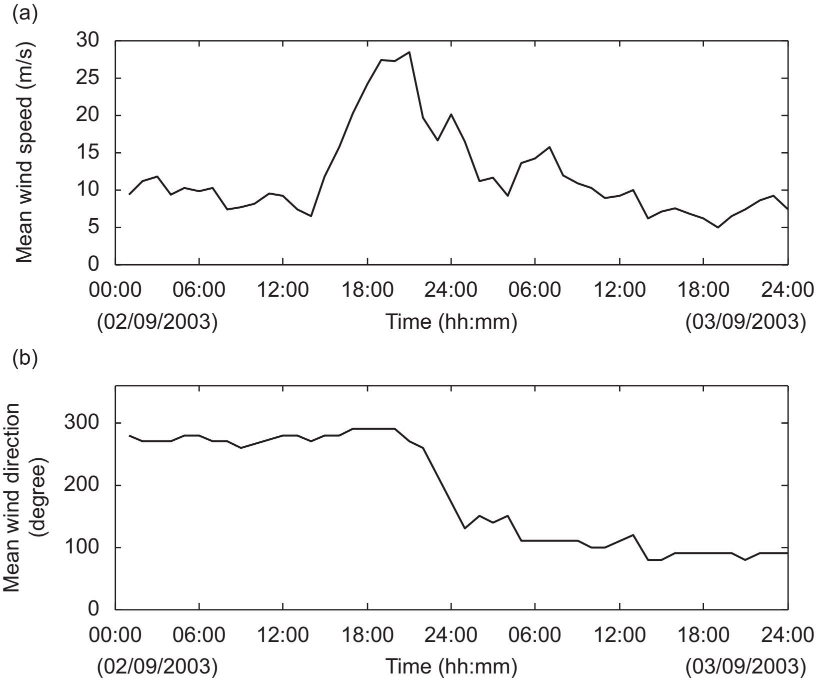

Fig. 3. Hourly mean wind speed and direction recorded in Hong Kong during Typhoon Dujuan.

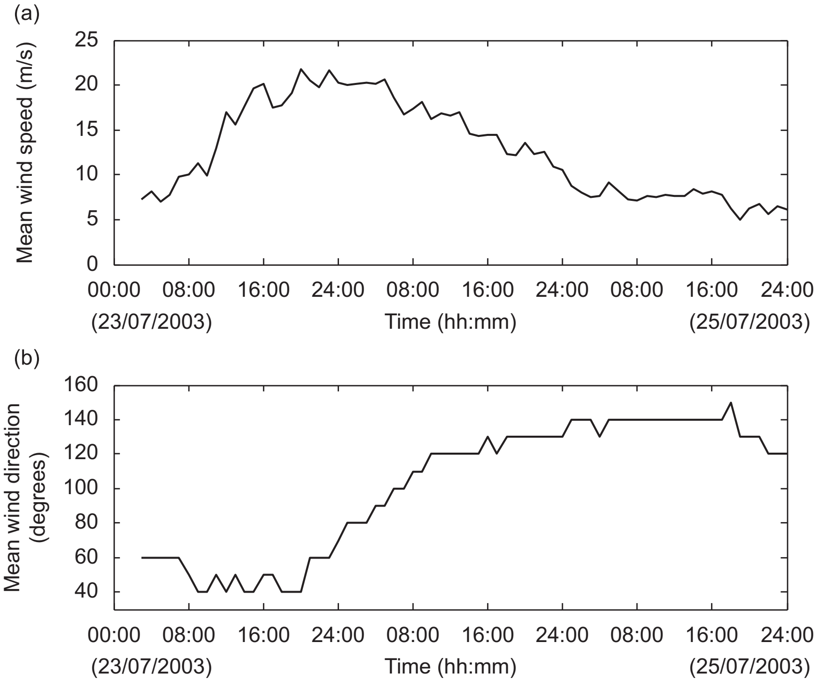

Fig. 4. Hourly mean wind speed and direction recorded in Hong Kong during Typhoon Imbudo.

Through analysis of the measured data, the turbulence intensity I_i ($i = u,v,w$ where u indicates the component in longitudinal direction, v denotes the component in lateral direction and w represents the component in vertical direction) and the gust factor G_i ($i = u,v,w$) defined by the following equations are determined:

$$I_i = \frac{\sigma_i}{\bar{V}} \quad (i = u, v, w), \tag{1}$$

$$\begin{aligned} G_u(t_g) &= 1 + \frac{\max\left(\overline{u(t_g)}\right)}{\bar{V}}, \\ G_v(t_g) &= \frac{\max\left(\overline{v(t_g)}\right)}{\bar{V}}, \\ G_w(t_g) &= \frac{\max\left(\overline{w(t_g)}\right)}{\bar{V}}, \end{aligned} \tag{2}$$

where $\bar{V}$ is the measured mean of the resultant wind speed with 10 min duration in horizontal plane, which is also the mean of the longitudinal wind speed; $\sigma_i, (i = u, v, w)$ are the standard deviation of wind speed components (within 10 min) in the longitudinal, lateral and vertical direction, respectively; t_g is the duration of gust, in this paper, $t_g = 3\,\mathrm{s}$; $\overline{u(t_g)}$, $\overline{v(t_g)}$ and $\overline{w(t_g)}$, are the longitudinal, lateral and vertical mean wind speeds with 3 s duration, respectively.

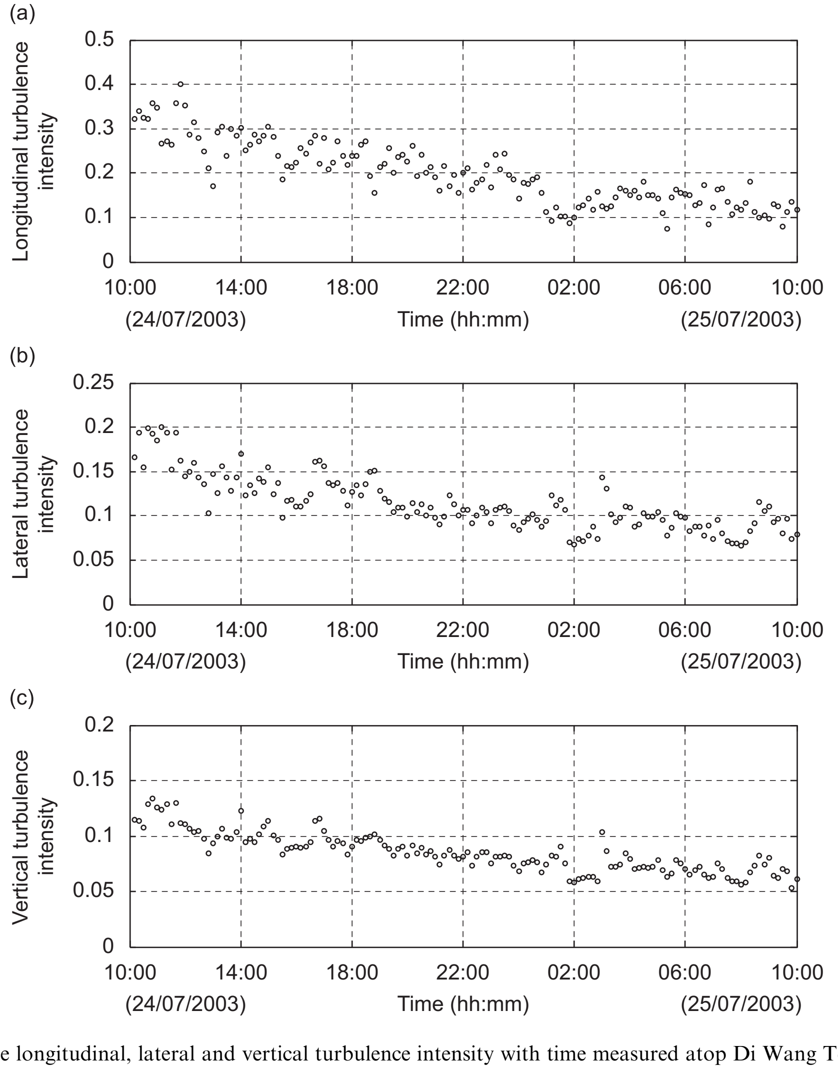

Fig. 5. Variation of the longitudinal, lateral and vertical turbulence intensity with time measured atop Di Wang Tower during Typhoon Imbudo.

Fig. 5 shows the variations of the longitudinal, lateral, and vertical turbulence intensities with time in each 10 min period, which were measured atop DWT in Shenzhen during the passage of Typhoon Imbudo. The averaged longitudinal, lateral, and vertical turbulence intensities atop the tall building (at height of 345 m from ground level) are 0.196, 0.112, and 0.084, respectively, during the typhoon. The ratio among the three components of turbulence intensity is 1:0.57:0.43.

Fig. 6 presents the variations of the longitudinal, lateral, and vertical gust factors with time in each 10 min period, which were also measured from DWT during the passage of Typhoon Imbudo. The average longitudinal, lateral, and vertical gust factors are 2.05, 0.49, and 0.11, respectively, during the typhoon. The ratio among the three components of the gust factor is 1:0.24:0.05. It was observed from the field measurements that the gust factor values decreased with the increase of mean wind speed and approached to constant as the wind speed became larger.

Fig. 7 demonstrates the variation of the longitudinal turbulence intensity with mean wind speed atop DWT during Typhoon Dujuan. There is an obvious tendency for the longitudinal turbulence intensity to decrease with the increase of mean wind speed.

The wind flow in the boundary layer of the Earth is highly turbulent, and the wind loads acting on buildings and structures are significantly influenced by the approaching turbulent flow characteristics. The turbulence

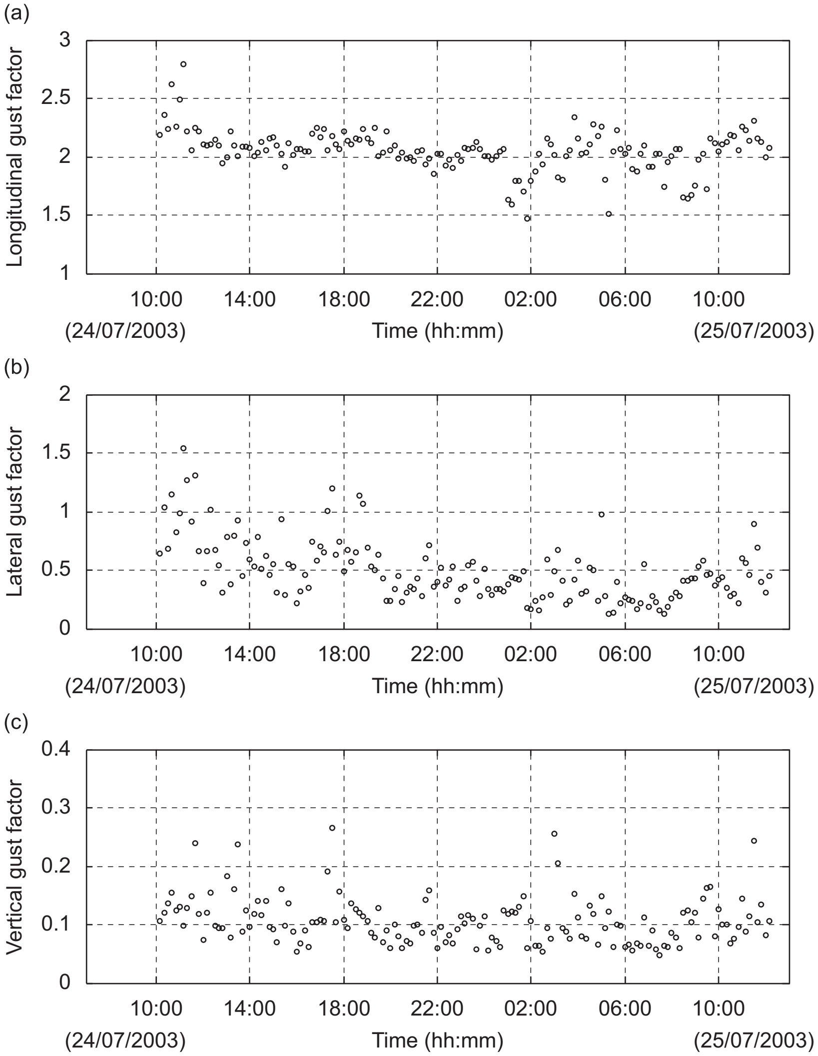

Fig. 6. Variations of the longitudinal, lateral and vertical gust factor with time measured atop Di Wang Tower during Typhoon Imbudo.

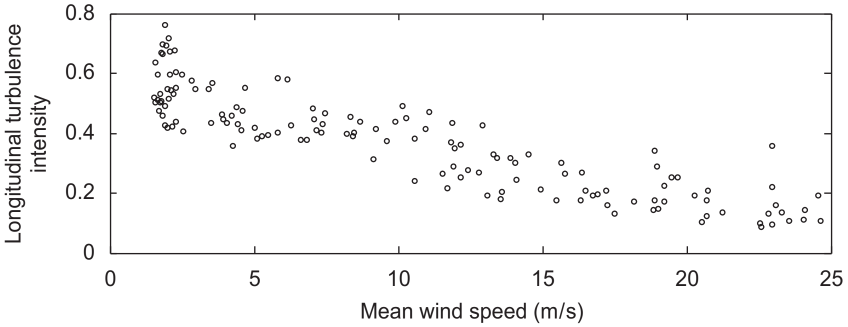

Fig. 7. 10-min mean wind speed vs. the longitudinal turbulence intensity measured atop Di Wang Tower during Typhoon Dujuan.

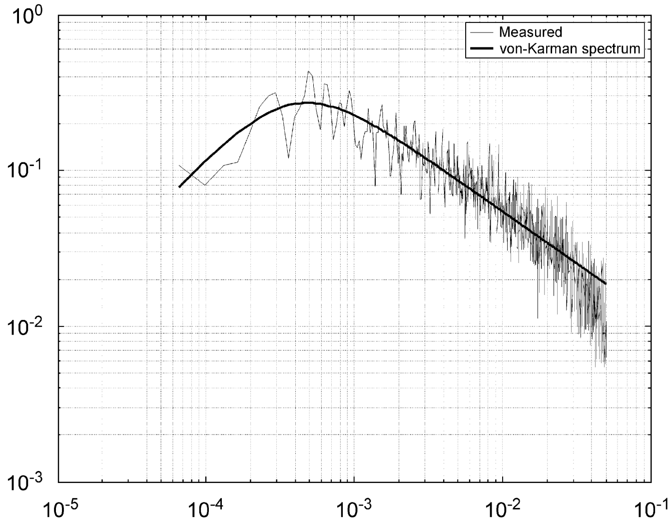

Fig. 8. Power spectrum density of wind speed atop Di Wang Tower during Typhoon Dujuan.

characteristics of natural wind are usually identified by two parameters: turbulence intensity and turbulence scale. The longitudinal turbulence integral scale, L_x, is defined in several ways. It is often interpreted as the wavelength corresponding to the maximum of the normalized spectral density of wind speed. The von-Karman spectrum is one that is usually used to fit measured spectra for estimation of the longitudinal integral length scale using L_x as the fitting parameter. This method has the advantage of fitting the whole spectrum rather than only the position of the peak. The von-Karman spectrum has the from of

$$\frac{fS_v(f)}{\sigma_v^2}=\frac{4L_xf/\bar{U}}{[1+70.7(L_xf/\bar{U})^2]^{5/6}}, \tag{3}$$

where $S_v(f)$ is the power spectrum of wind speed; f is the frequency (Hz); $\bar{U}$ is the mean of the longitudinal wind speed; and σ_v is the standard deviation of fluctuating velocity.

Figs. 8 and 9 show the normalized spectra of wind speed measured atop DWT and JMB, which were obtained based on the measured data with a long sample (10-h) during Typhoon Dujuan and Typhoon Rananim, respectively. Using the least-square method to estimate the fitting parameter, L_x, the von-Karman spectrum is also presented in these figures for comparison purposes. It can be seen that the shapes of the power spectral density of wind speed agree fairly well with the von-Karman spectrum, suggesting that the von-Karman-type spectrum is able to describe the energy distribution fairly well for wind speed above typical urban areas. From the spectra shown in Figs. 8 and 9, the overall mean values of the longitudinal turbulence

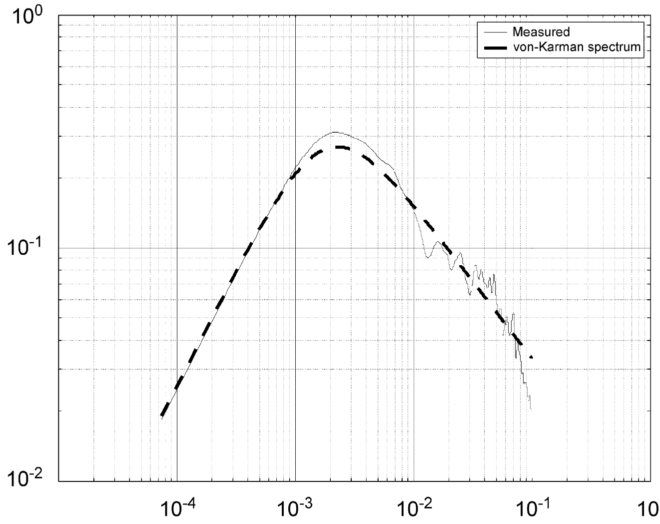

Fig. 9. Power spectrum density of wind speed atop the Jin Mao Building during Typhoon Rananim.

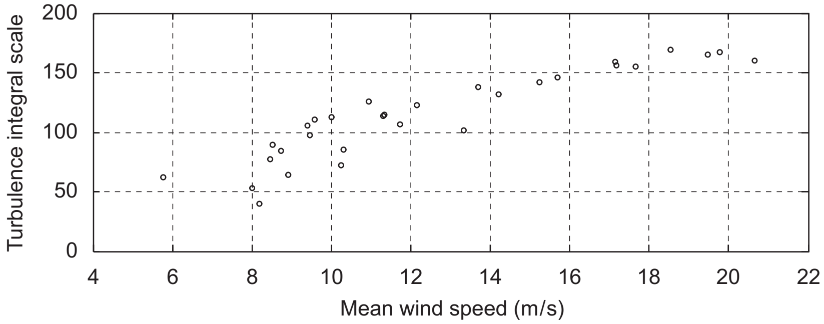

Fig. 10. Longitudinal turbulence integral scale measured atop Di Wang Tower during Typhoon Imbudo.

integral scale determined based on the data measured atop DWT and JMB during the 10-h record period are 136 and 65 m, respectively.

Fig. 10 shows the variation of longitudinal turbulence integral scale with mean wind speed. The turbulence scale was estimated by fitting the power spectra of wind speed from each 1-h record measured from DWT during Typhoon Imbudo. It was found that the turbulence integral scale was very small when the mean wind speed was less than 8 m/s. It is evident that there is a tendency for the turbulence integral scale to increase with mean wind speed. The mean turbulence integral scale is 117 m for the total 44-h recording period.

The field measurements reveal that in the atmospheric boundary layer the longitudinal turbulence integral scale exhibited considerable variations from site to site. The variations were also significant for the measurements made in different typhoons at the same measurement site. The longitudinal turbulence integral scales were observed to vary between 30 and 550 m at elevations of 330–400 m above the city centers of Hong Kong, Shenzhen and Shanghai during the passages of the three typhoons. According to the field measurement results, it was estimated that the ratio of longitudinal turbulence integral scale to building characteristic length for typical super-tall buildings in the atmospheric boundary layer may be more than 10. However, this ratio simulated in wind tunnels is usually of the order of unity. As reported by Li and Melbourne [14,15], longitudinal turbulence integral scale has a significant effect on the estimation of peak and fluctuating wind pressures on building models. Fig. 10 shows that the variation of longitudinal turbulence integral scale during a typhoon was quite large. Thus, it is clear that there exists a source of uncertainty involved in wind tunnel modeling which needs to be further investigated. There is a need to investigate how the characteristics of wind actions and wind-induced vibrations of tall buildings in large turbulence scale wind flows.

2.3. Wind-induced vibrations

The results of spectral analysis of acceleration response measured from the four instrumented super-tall buildings are shown in Figs. 11–14. These spectra were obtained from a direct analysis of the accelerometer output data measured during the typhoons. The spectral analysis results show that the wind-induced responses of these super-tall buildings were all primarily in the two fundamental sway modes of vibration, but higher modes were also clearly present. Table 1 lists the natural frequencies of the tall buildings along the two main orthogonal axes (directions 1 and 2, as illustrated in Fig. 1), which were determined based on the spectra shown in Figs. 11–14. In addition, the natural frequencies from the computational models of the buildings are also presented in the table for comparison purposes. The computational models of the buildings (TC, DWT, and CPT) were established based on the structural design drawings or the information on the mass and stiffness of the buildings provided by the structural designers, while the calculated natural frequencies of JMB listed in Table 1 were found from Gu and Jiang [16]. It was found from Table 1 that there are significant differences between the calculated and measured natural frequencies for the first three modes of TC, CPT and JMB. Except JMB, the measured results are all larger than the calculated ones. It is maintained that the differences between the calculated and measured natural frequencies are attributable to several reasons, including that the effective mass values of these buildings are less than those assumed at the design stage or/and the effective stiffness values of the buildings are higher than those determined at the design stage due to the contribution of non-structural components. Since natural frequencies are very important parameters in structural dynamic analysis of tall buildings, the results presented in Table 1 clearly suggested that there is a need for structural engineers to further improve the accuracy of determining such parameters at design stages.

Figs. 15–18 show the relationship between the standard deviations (averaged over 10 min period) of the measured acceleration response at the top floors of the four tall buildings and the mean wind speed equivalent atop the buildings, in which the measurements were made from TC (during Typhoon Dujuan), DWT and CPT (during Typhoon Imbudo) and JMB (during Typhoon Rananim).

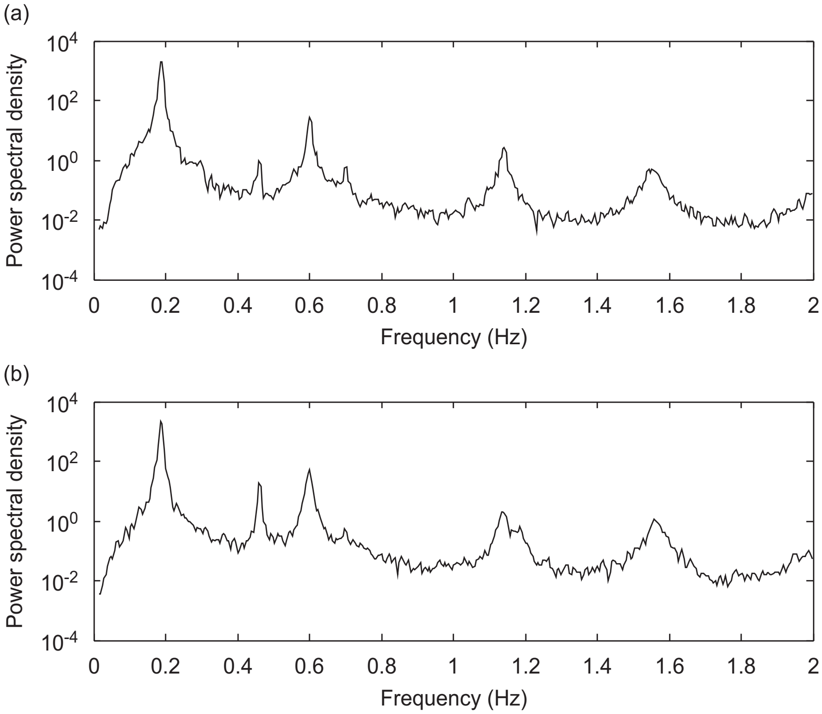

Fig. 11. Power spectral density of acceleration responses for The Center: (a) direction 1 and (b) direction 2.

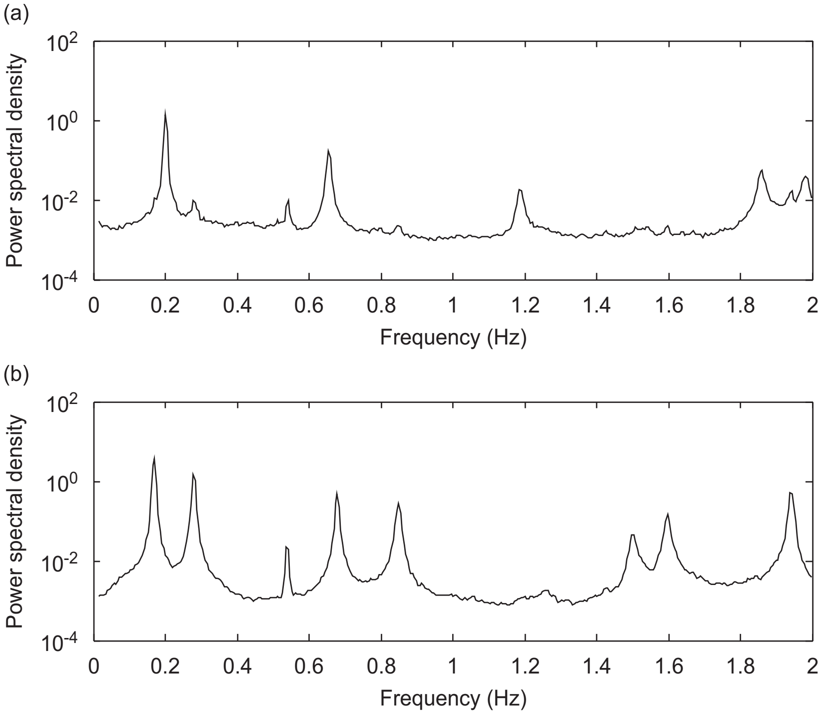

Fig. 12. Power spectral density of acceleration responses for Di-Wang Tower: (a) direction 1 and (b) direction 2.

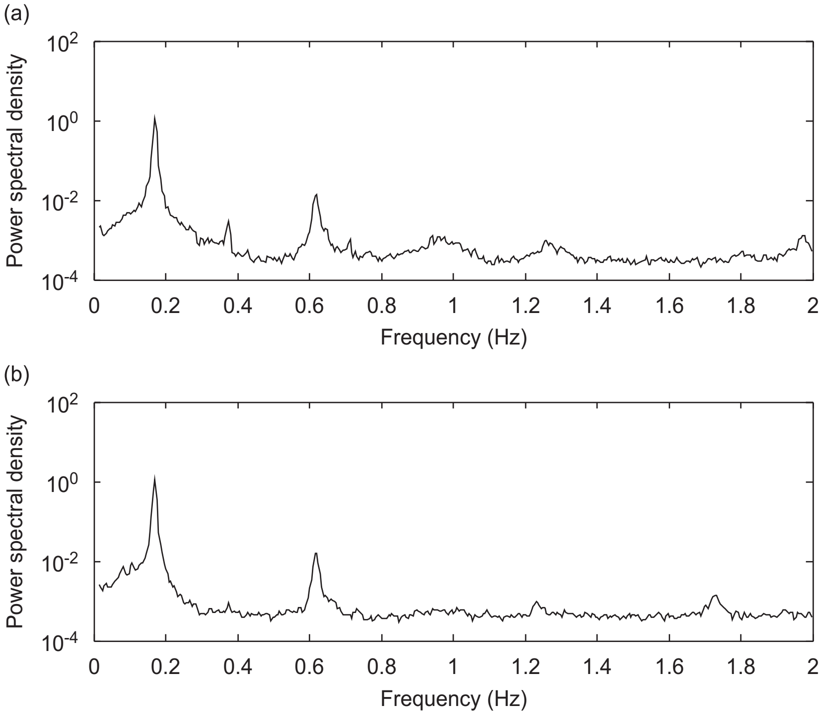

Fig. 13. Power spectral density of acceleration responses for Citic Plaza Tower: (a) direction 1 and (b) direction 2.

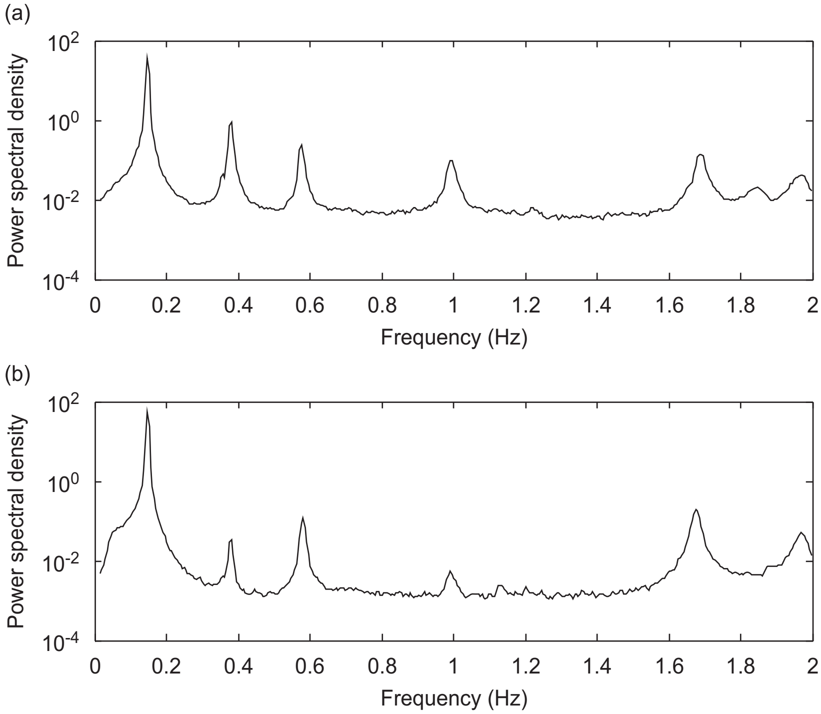

Fig. 14. Power spectral density of acceleration responses for the Jin Mao Building: (a) direction 1 and (b) direction 2.

Table 1
Comparison of the measured natural frequencies of the four buildings and computational results

Building	Mode order	Results of the measurements (Hz)	Computational results (Hz)	Difference[a] (%)	Mode
The Center	1st	0.186	0.167	11.37	Direction 1
	2nd	0.186	0.167	11.37	Direction 2
	3rd	0.459	0.417	10.07	Torsion
Di Wang Tower	1st	0.173	0.168	2.98	Direction 1
	2nd	0.208	0.181	14.92	Direction 2
	3rd	0.293	0.286	2.45	Torsion
CITIC Plaza Tower	1st	0.171	0.124	37.90	Direction 1
	2nd	0.171	0.124	37.90	Direction 2
	3rd	0.371	0.273	35.90	Torsion
Jin Mao Building	1st	0.147	0.162	−10.6	Direction 1
	2nd	0.147	0.162	−10.6	Direction 2
	3rd	0.576	0.664	−15.2	Torsion

[a] Difference = (measured−calculated)/measured.

For the data presented in Figs. 15–18, the regression curves of acceleration responses for each direction in the four super-tall buildings are expressed by the following unified equation:

$$\sigma_A = a_1 \bar{V}^{a_2} \quad \text{(milli-g)}, \tag{4}$$

where parameter a_1 and a_2 for the four buildings are listed in Table 2.

It appears that both components of acceleration in each instrumented building increased monotonically with mean wind speed during the passage of the typhoons, as shown in Figs. 15–18. The measured data show

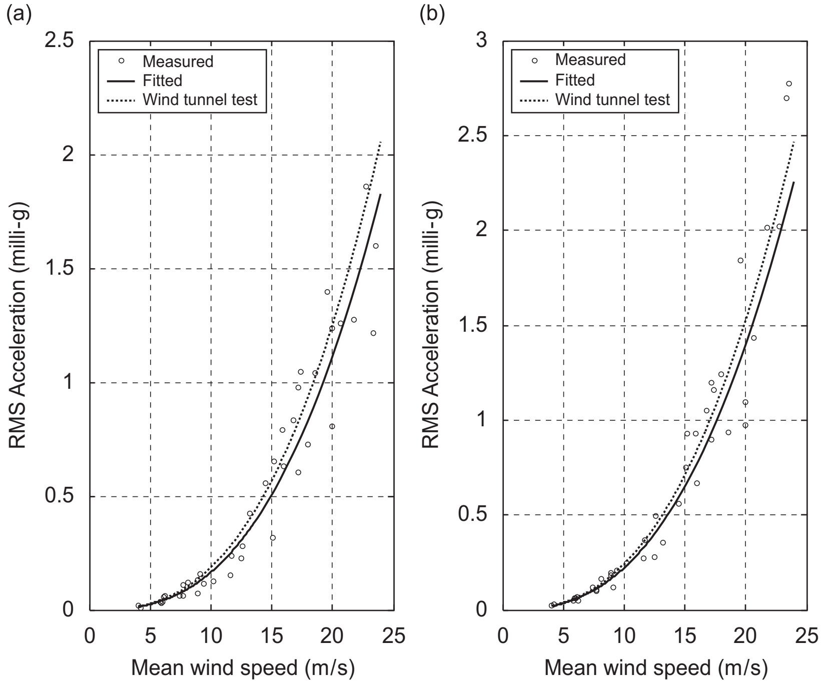

Fig. 15. Relation between wind speed and acceleration responses and comparison with the wind tunnel test data for the Center, the field measurements were made during Typhoon Dujuan at the approaching wind direction of $\alpha = 270°$, as defined in Fig. 1: (a) direction 1 and (b) direction 2.

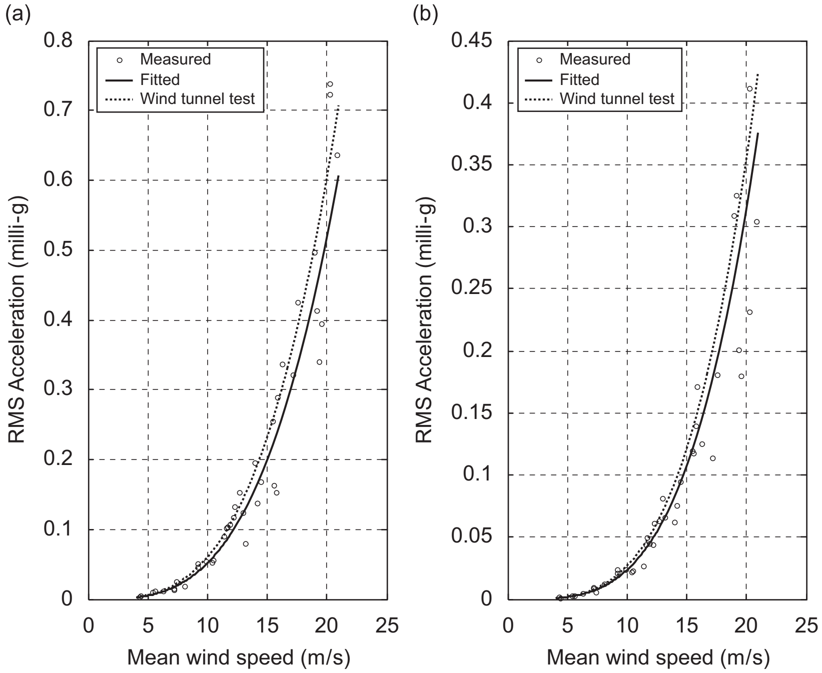

Fig. 16. Relation between wind speed and acceleration responses and comparison with the wind tunnel test data for Di Wang Tower, the field measurements were made during Typhoon Imbudo at the approaching wind direction of $\alpha = 135°$: (a) direction 1 and (b) direction 2.

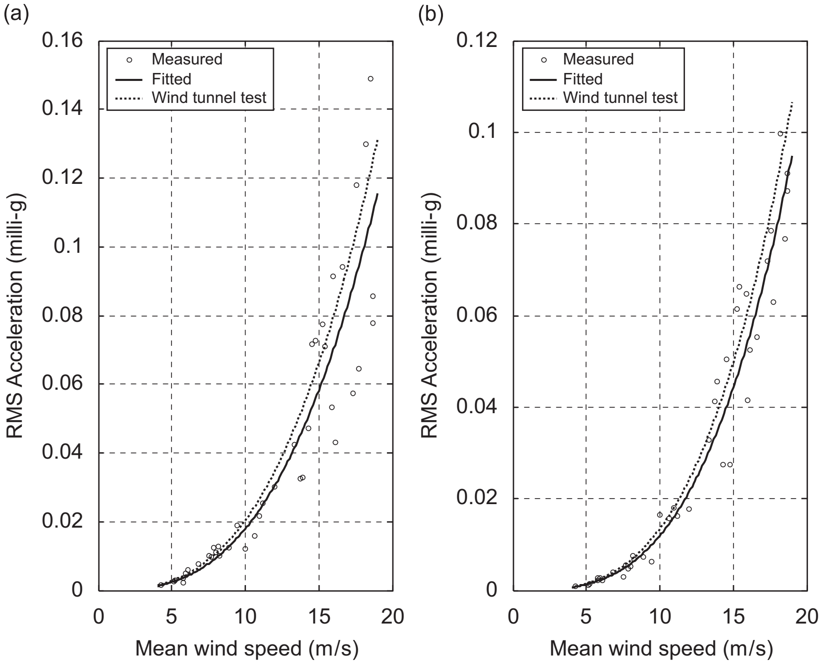

Fig. 17. Relation between wind speed and acceleration responses and comparison with the wind tunnel test data for Citic Plaza Tower, the field measurements were made during Typhoon Imbudo at the approaching wind direction of $\alpha = 140^\circ$: (a) direction 1 and (b) direction 2.

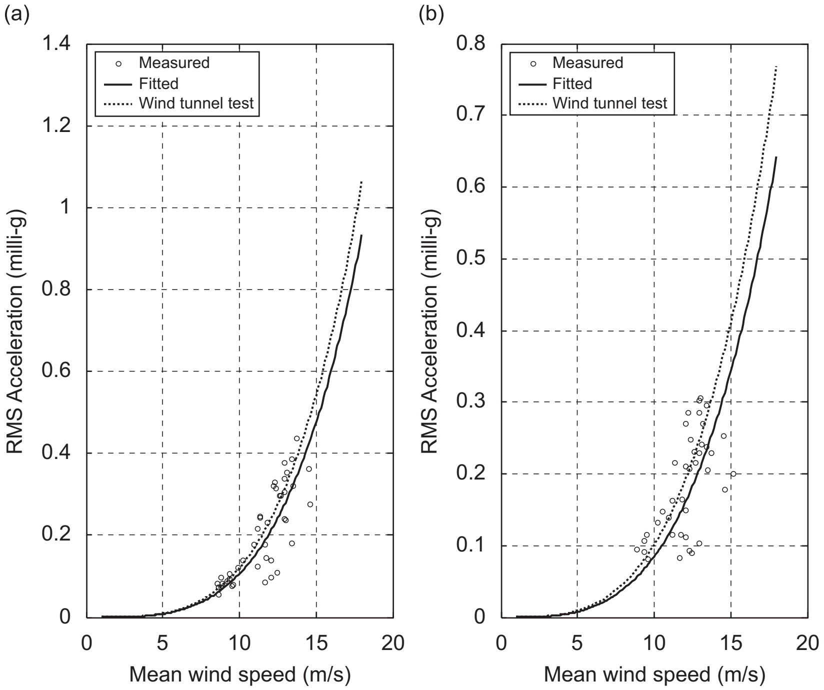

Fig. 18. Relation between wind speed and acceleration responses and comparison with the wind tunnel test data for Jin Mao Building, the field measurements were made during Typhoon Rananim at the approaching wind direction of $\alpha = 105^\circ$: (a) direction 1 and (b) direction 2.

Table 2
Parameters for the regression curves of the four buildings

		a_1	a_2
The center	Direction 1	3.02×10^{-4}	2.74
	Direction 2	4.97×10^{-4}	2.65
Di Wang Tower	Direction 1	2.55×10^{-5}	3.31
	Direction 2	4.53×10^{-6}	3.72
CITIC Plaza Tower	Direction 1	2.26×10^{-5}	2.90
	Direction 2	7.03×10^{-6}	3.23
Jin Mao Building	Direction 1	2.11×10^{-5}	3.70
	Direction 2	3.00×10^{-5}	3.45

Table 3
The maximum acceleration responses of the four buildings during the typhoons (milli-g)

Buildings	Typhoons	Max. instantaneous acceleration		Max. 10-min rms of acceleration	
		Direction 1	Direction 2	Direction 1	Direction 2
The center	Dujuan	5.46	6.16	1.81	2.78
Di Wang tower	Imbudo	2.65	4.40	0.42	0.73
CITIC plaza tower	Imbudo	0.62	0.43	0.15	0.10
Jin Mao building	Rananim	1.12	1.54	0.40	0.50

that the standard deviations of acceleration responses at the top floors of the four super-tall buildings were proportional to the wind speed equivalent atop the buildings raised to a power of 2.65–3.72.

For modern flexible tall buildings, such as the four instrumented super-tall buildings, serviceability issues are of paramount importance and occupant comfort is a major concern in the design. It has been widely accepted that building acceleration is the most appropriate response component for establishing checking procedure for structural serviceability requirements under wind action. A number of proposals and regulations for limitation of wind-induced vibration have been suggested [7,17,18]. Several codes, for example, the National Building Code of Canada (NBCA) [19] suggests acceptable levels of accelerations as a serviceability requirement, which recommends that a tentative maximum acceleration limitation of 1–3 percent of gravity (10–30 milli-g) once every 10 years as a guideline for comfort of occupants and the lower value might be considered appropriate for apartment buildings, the higher value for office buildings. ISO 6897 [20] suggests 5 milli-g rms acceleration criterion for a 6-year return period for building structures. Table 3 presents the peak instantaneous accelerations and the maximum 10-min standard deviations of acceleration responses along the two orthogonal axes of the four super-tall buildings during the typhoons. It is observed from Table 3 that although the vibration magnitudes of the four buildings were significant different during Typhoons Dujuan, Imbudo, and Rananim, the peak acceleration responses measured at the top floors in the four buildings during the typhoons were all below the serviceability criteria for occupancy comfort. Considering that TC is the most sensitive wind excited structure among the four super-tall buildings and Typhoon Dujuan has been the strongest typhoon to hit Hong Kong since 1999, it can be concluded that the four super-tall buildings would appear to satisfactorily meet the occupancy comfort criteria under typhoon conditions.

2.4. Comparison with the wind tunnel measurements

It is very useful to compare model test results with actual performance for the purposes of improving the modeling techniques in wind tunnel tests. However, such comparison is scarce and has rarely been made for super-tall buildings under typhoon conditions.

Wind tunnel tests for TC were conducted in the boundary layer wind tunnel at Monash University, Australia before the building was constructed. The wind-induced vibration of TC was investigated through the aeroelastic model tests [21]. By examining the wind velocity data measured during Typhoon Dujuan, it was found that the wind direction corresponding to the strongest wind speed period during the typhoon mainly varied around 270°. This implies that the wind direction during this period can be regarded as a constant (270°). Fig. 15 shows the comparison between the full-scale measurements and the model test results at different wind speeds for this azimuth sector. In Fig. 15, the wind tunnel data were extracted from Cheung et al. [21] and the field data were measured during the passage of Typhoon Dujuan. The smooth curves presented in Figs. 15–18 were obtained by curve fitting to the field measurement and wind tunnel test results by using Eq. (4), while the parameter a_2 takes the same value for the field and model measurements for each instrumented building and the parameter a_1 is a variable to fit the two sets of data (field measurements and wind tunnel results). It can be seen from Fig. 15 that the model test results are in good agreement with the field measurements, even though the wind tunnel results are larger than the measured responses by 12.6% and 9.3% in directions 1 and 2, respectively.

Wind tunnel tests for DWT were conducted in the Boundary Layer Wind Tunnel Laboratory at University of Western Ontario through force balance model tests [22]. Fig. 16 shows the comparison between the full-scale measurements during Typhoon Imbudo and the model test results at different wind speeds for wind direction around 135°. The agreement between the two sets of data are satisfactory for this case, and it is found that the measured responses are smaller than the wind tunnel test data by 16.5% and 13.0% in directions 1 and 2, respectively.

Wind tunnel tests for CPT, which was also conducted at Monash University at its design stage in 1993, including the determination of overall wind loads and dynamic responses of the super-tall building through aeroelastic model tests [23]. Fig. 17 shows the comparison between the full-scale measurements during Typhoon Imbudo and the model test results at different wind speeds for the wind direction around 140°. It can be seen from Fig. 17 that basically, the agreement between the two sets of data is satisfactory, although the measured responses are smaller than the wind tunnel responses by 13.7% and 12.4% in directions 1 and 2, respectively.

Although Ho et al. [24] and Gu et al. [25] conducted wind tunnel experiments to determine wind effects on the JMB for design purposes, in order to make meaningful comparison of model test results with the structural actual performance monitored during Typhoon Rananim in August 2004, a new wind tunnel test with properly modeling of the real existing surrounding conditions such as those in 2004 was conducted in this study through a force balance model test. The models of the wind tunnel test at a geometric scale of 1:500 reproduced all major existing surrounding buildings within a full-scale radius of approximately 600 m from the JMB. The location of the anemometer installed atop a tall building near JMB was also calibrated in the wind tunnel test. This is an essential part for comparing the model test results with the field measurements. Fig. 18 shows the comparison between the wind tunnel test results and the field measurements of wind effects on the JMB during Typhoon Rananim. It was found that the wind tunnel results are larger than the field measurements by 11.8% and 19.1% in directions 1 and 2, respectively.

Table 4 summarizes the comparison results mentioned above, which demonstrates that there were some differences between the field measurements and the model test results. However, considering that there were many uncertainties in the wind tunnel tests such as properly modeling of incident turbulence properties, terrain characteristics and Reynolds number as well as reasonably estimation of structural damping ratio, etc., the agreement between the field measurements and the model test data is satisfactory at least for engineering applications, thus illustrating that wind tunnel tests can provide satisfactory predictions of wind-induced vibrations of super-tall buildings under typhoon conditions.

2.5. *Damping characteristics of the super-tall buildings*

The measured acceleration data can be used to obtain the dynamic characteristics of the super-tall buildings (damping, natural frequencies, etc.). The random decrement technique was employed to evaluate the damping in these buildings based on the field measurements. In order to obtain the damping ratio of each mode, the measured signals of acceleration responses were band-pass filtered before processing the random decrement to

Table 4
Differences between the field measurements and the wind tunnel tests results (rms responses)

		Difference[a] (%)
The center	Direction 1	12.58
	Direction 2	9.26
Di Wang tower	Direction 1	16.47
	Direction 2	13.04
CITIC plaza tower	Direction 1	13.72
	Direction 2	12.36
Jin Mao building	Direction 1	11.76
	Direction 2	19.07

[a] Difference = (wind tunnel data−measured data)/measured data.

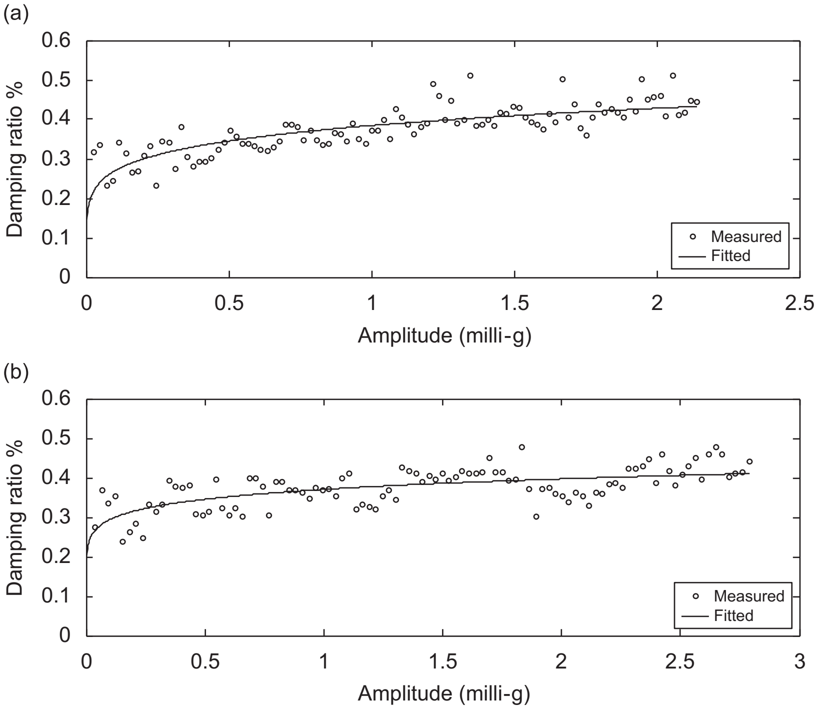

Fig. 19. Variation of damping ratio with vibration amplitude for The Center during Typhoon Dujuan: (a) direction 1 and (b) direction 2.

remove the components not concerned. The damping curves (damping against amplitude) of the first sway mode in directions 1 and 2 of the four super-tall buildings were evaluated from the measured acceleration data under typhoon conditions, as shown in Figs. 19–22, which comprise both structural damping and aerodynamic damping.

Fig. 19 shows the amplitude-dependent damping characteristics of TC, which were determined based on the acceleration data measured during the passage of Typhoon Dujuan. Figs. 20 and 21 present the damping data from DWT and CPT during Typhoon Imbodu. The damping results measured from JMB during Typhoon Rananim are presented in Fig. 22. Information on amplitude-dependent damping obtained from the four buildings should be very useful since similar measurements are still very limited for such high-rise structures under typhoon conditions. The damping curves shown in these figures except Fig. 22(b) clearly demonstrate the nonlinear energy dissipation characteristics of the buildings. It is clear that the damping increases with increase in amplitude during typhoons.

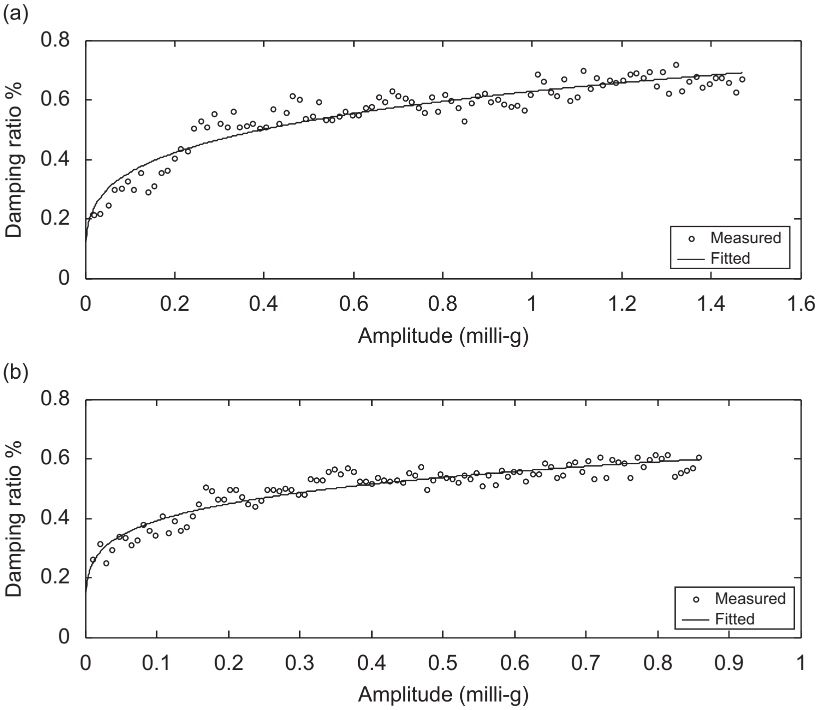

Fig. 20. Variation of damping ratio with vibration amplitude for Di Wang Tower during Typhoon Imbudo: (a) direction 1 and (b) direction 2.

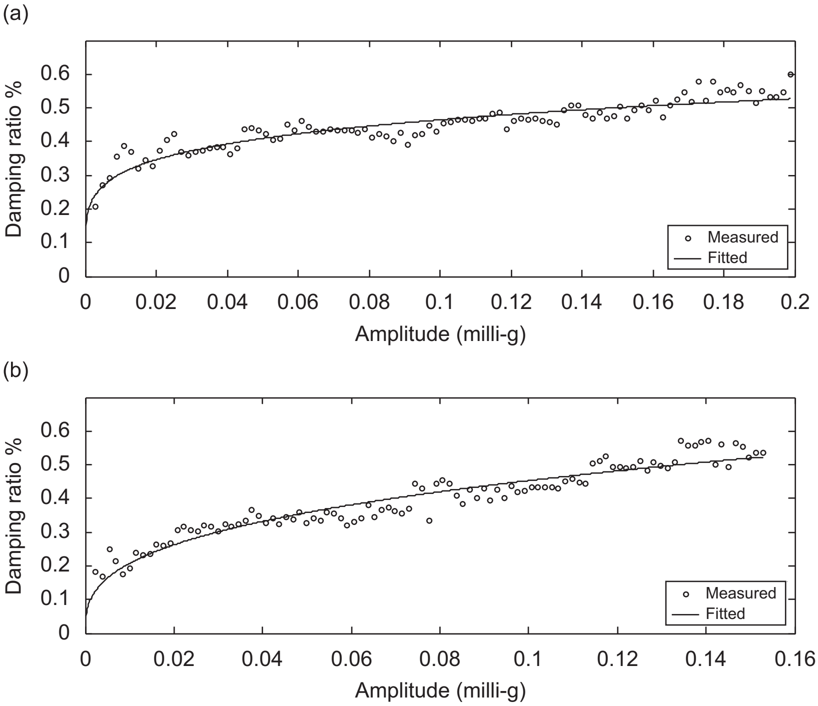

Fig. 21. Variation of damping ratio with vibration amplitude for CITIC Plaza Tower during Typhoon Imbodu: (a) direction 1 and (b) direction 2.

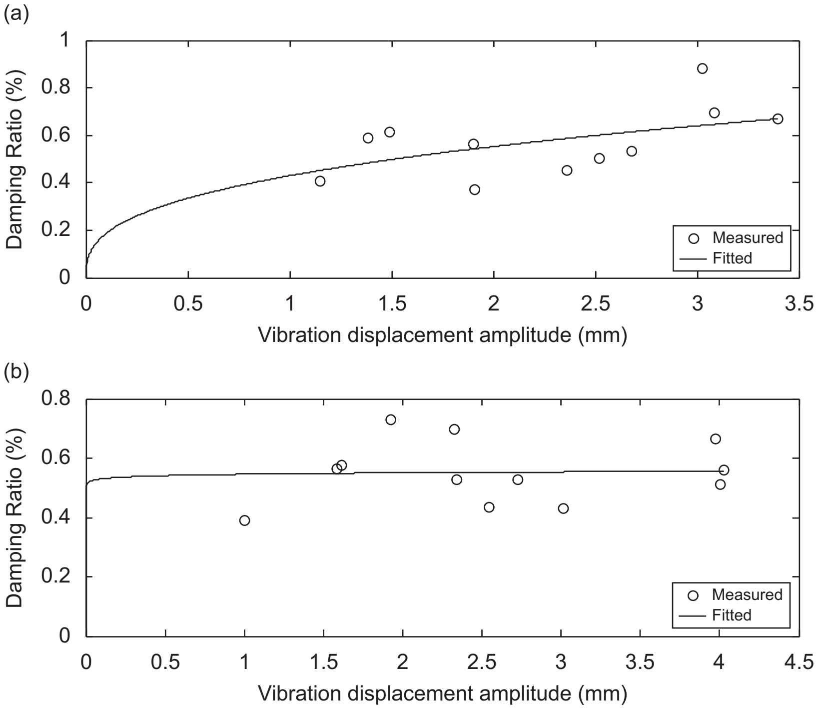

Fig. 22. Variation of damping ratio with vibration amplitude for Jin Mao Building during Typhoon Rananim: (a) direction 1 and (b) direction 2.

The measured acceleration responses were also used to evaluate the damping values of the four buildings without taking into account of vibration amplitudes. The overall damping ratios along the two orthogonal directions in these buildings were determined using the random decrement technique based on the field data measured during the typhoons, which were found to be in the range of 0.5–1.0%. As yet, there is no widely accepted method available for evaluating damping ratios of buildings prior to construction. In the wind tunnel tests at the design stage, structural damping ratios were usually assumed to be 1%, 1.5%, 2%, and 2.5% for the estimations of wind-induced responses of the super-tall buildings. From Figs. 19–22 and the overall damping ratios mentioned above, it appears that the assumptions may overestimate the damping ratios of these buildings at least as far as amplitude appropriate to the serviceability criterion for these buildings is concerned.

3. Concluding remarks

This paper presents some selected results measured from four super-tall buildings located in Hong Kong, Shenzhen, Guangzhou, and Shanghai during the passages of three typhoons. Detailed analysis of the field data was conducted to investigate the characteristics of typhoon-generated wind and wind-induced vibrations of these super-tall buildings under typhoon conditions. Furthermore, the full-scale measurements were compared with the calculated natural frequencies of the structures and the wind tunnel results to evaluate the accuracy of the numerical modelling and the model test results. Some conclusions are summarized as follows:

(1) The von-Karman-type spectrum was found to be able to describe the energy distribution fairly well for the wind speed above typical urban areas. It was observed that there was a tendency for turbulence integral scale to increase with mean wind speed. The longitudinal turbulence integral scale estimated by fitting the von-Karman-type spectrum varied in the range between 30 and 550 m at elevations of 330–400 m above the city centers of Hong Kong, Shenzhen, and Shanghai during the passages of the three typhoons. The values of longitudinal turbulence integral scale estimated from 10-h records were found to be 136 and 65 m in

Shenzhen and Shanghai, respectively. The larger variation of the measured longitudinal turbulence integral scale indicates that there exists a source of uncertainty involved in wind tunnel modeling, which needs to be further investigated.

(2) It was found from the field measurements that the average longitudinal, lateral, and vertical turbulence intensities atop DWT (at height of 345 m from ground level) were 0.196, 0.112, and 0.084, respectively, during Typhoon Imbudo. The ratio among the three components was 1:0.57:0.43. There was an obvious tendency for the longitudinal turbulence intensity to decrease with the increase of mean wind speed. The average longitudinal, lateral, and vertical gust factors atop DWT during the passage of Typhoon Imbudo were 2.05, 0.49, and 0.11, respectively. The ratio among the three components of the gust factor is 1:0.24:0.05. It was observed from the field measurements that the gust factor values decreased with the increase of mean wind speed and approached to constant as the wind speed became larger.

(3) Wind-induced acceleration responses of the four super-tall buildings were found to be monotonically increasing with wind speed measured atop the buildings. The measured data show that the standard deviations of acceleration responses at the top floors of the four buildings were proportional to the wind speed equivalent atop the buildings raised to a power of 2.65–3.72. It was observed that although the vibration magnitudes of the four buildings were significantly different, the peak acceleration responses measured atop the buildings during the three typhoons including Typhoon Dujuan were all below the serviceability criteria for occupancy comfort. Thus, it was concluded from the field measurement results that the four super-tall buildings which are among the highest buildings in the world would appear to satisfactorily meet the occupancy comfort criteria during typhoons.

(4) The acceleration responses measured from the four super-tall buildings have been compared with the wind tunnel test results. The measured acceleration data were consistent with those obtained in the model tests, although the model test results were generally conservative. The differences between the field measurements and the wind tunnel data were in the range of 9.3–19.1% for the four super-tall buildings, thus verifying the accuracy of the model test results and illustrating that wind tunnel tests can provide satisfactory predictions of wind-induced vibrations of super-tall buildings under typhoon conditions.

(5) The measured damping ratios demonstrated obvious amplitude-dependent characteristics and increased with increasing amplitude. The overall damping ratios along the two orthogonal directions in these buildings were also determined using the random decrement technique based on the field data measured during the typhoons, which were found to be in the range of 0.5–1.0%. The evaluated damping values indicated that the fundamental modal damping ratios of the four super-tall buildings were similar, even though these buildings were constructed with different types of structural systems. The measurement results implied that damping values of 0.5–1.0% of critical appeared reasonable for wind-resistant design of super-tall buildings for serviceability consideration.

(6) The measured natural frequencies of the first several modes of the four super buildings were compared with those determined from the computational (finite element (FE)) models. There were significant differences between the measured and calculated natural frequencies. It was maintained that such differences were attributable to several reasons, including that the effective mass values of the buildings may be less than those assumed at the design stage, or/and the effective stiffness values of the buildings were higher than those determined at the design stage due to contribution of non-structural components. As a result, the measured natural frequencies were larger than those calculated except the JMB. Since natural frequencies are very important parameters in structural dynamic analysis of tall buildings, there is a need for structural engineers to accurately determine such parameters at design stages.

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