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Full-scale monitoring of typhoon effects on super tall buildings

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Abstract

This paper presents the field measurement results of wind characteristics and structural responses of two super tall buildings, Central Plaza Tower (374 m, 78 floors) in Hong Kong and Di Wang Tower (384 m, 78 floors) in Shenzhen during the passage of Typhoon Sally. The field data such as wind speeds, wind directions and acceleration responses were simultaneously and continuously measured from the tall buildings during the typhoon. Detailed analysis of the field data and comparative study were conducted to investigate the characteristics of typhoon-generated wind over the two cities and wind-induced vibrations of the two super tall buildings under typhoon condition. The dynamic characteristics of the buildings were determined on the basis of the field measurements and comparisons with those calculated from the computational models of the buildings were made. The damping ratios of the buildings were estimated and the amplitude-dependent damping characteristics are presented and discussed. Furthermore, the full-scale measurements were compared with the wind tunnel results to evaluate the accuracy of the model test results and the adequacy of the techniques used in wind tunnel tests.
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Keywords: Wind effect; Vibration; Tall building; Typhoon; Full-scale measurements; Wind tunnel test

1. Introduction

Recently, many super tall buildings have been or are being built in the world. While the current codes for structural design cover tall buildings, they are not guaranteed to cover the design of super tall buildings. It is thus necessary to investigate wind effects on super tall buildings. It has been recognized that the most reliable evaluations of dynamic characteristics and wind 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 behaviour of super tall buildings. However, reliable field measurement of wind effects on super tall buildings (building height > 300 m) is still very limited; in particular, field measurement of wind and structural responses of super tall buildings under typhoon conditions has rarely been conducted in the past.

Central Plaza Tower (called CPT in this paper) has a height of approximately 374 m and 78 storeys. Fig. 1(a) shows a photo of CPT. It is currently the second tallest structure in Hong Kong and the tallest reinforced concrete building in

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the world. The building has an approximately triangular plan form with recessed corners as shown in Fig. 1(b). The plan form of the building is shown in Fig. 1(b). The total weight of CPT is about 7.3×10^5 tons. This tall building is located in Wanchai North commercial district in the heart of Hong Kong's business center. The site of the building is very close to the seashore and on the lee slope of extremely hilly terrain in a typhoon active area. There are a number of tall buildings around CPT. Meanwhile, because of the height and the slenderness of the tower, the main concern at the design stage was the potential wind-induced vortex shedding response (Ho and Surry, 1989). Obviously, the best way to investigate this issue is through field measurements.

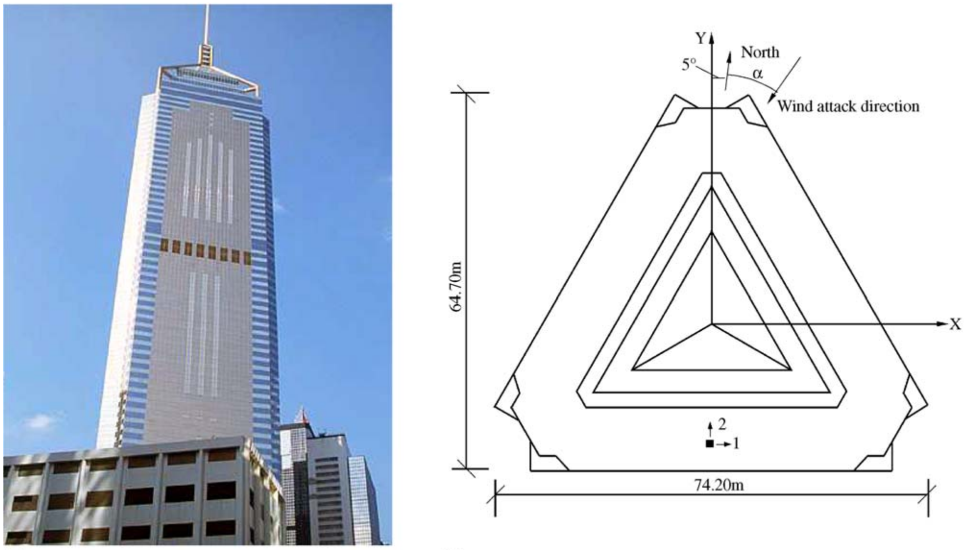
Di Wang Tower (called DWT in this paper) is located northwest of downtown Shenzhen, Guangdong province, China, about 1.3 km away from the nearest Hong Kong border, including a 68-storey main office tower, plus 11-storey facility and refuge floors as well as top tower structures. Totally, the main structure of the tall building has 79 storeys and is about 325 m high from the ground. There are two 59 m high masts erected on the roof of the tower. The height from the ground to the top of the masts is about 384 m. Fig. 2(a) shows a photo of the tall building. DWT is surrounded by a number of buildings including a tall building with a height of more than 100 m located on the west side of DWT. There are small hills about 3 km away in the south from DWT. The total weight of the building is about 2.1×10^5 tons. DWT was the tallest structure in mainland China when it was built several years ago, and now it is the third highest. The structural system utilizes both steel and reinforced concrete (SRC), including core wall systems and perimeter steel frame coupled by outrigger trusses at four levels. The basic plan form of the tower is essentially rectangular with two semicircles of 12.5 m radius at its two sides, as shown in Fig. 2(b). The length of the main building in direction 1 (longitudinal) and the width in direction 2 (transverse) is 68.55 m and 35.5 m, respectively. Therefore, the aspect ratio between height and transverse width is about 9, which has largely exceeded the criteria in the current design codes and standards in China, such as "The Standard of Structural Design against Earthquake" (GB 50011-2001). This implies that this tall building is a flexible and slender structure. Therefore, there is a need for investigating its structural performance under typhoon conditions.

Hong Kong and Shenzhen are located at the edge of the most active typhoon generating area in the world. These super tall buildings may be susceptible to severe vibration induced by typhoons. However, neither of the tall buildings with such exceptional heights uses dissipation devices such as tuned mass dampers or sloshing dampers for suppression of wind-induced vibrations. All these facts make a field study of wind effects on the super tall buildings under typhoon conditions of particular importance.

This paper presents some selected results obtained from the simultaneous field measurements of wind effects on CPT and DWT during the passage of Typhoon Sally during 8–10 September 1996. The field data, such as wind speeds, wind directions and acceleration responses were simultaneously and continuously measured from these super tall buildings during the typhoon. Detailed analysis of the field data and comparative study were conducted to investigate the characteristics of typhoon-generated wind over the two cities and wind-induced vibrations of the super tall buildings under typhoon conditions.

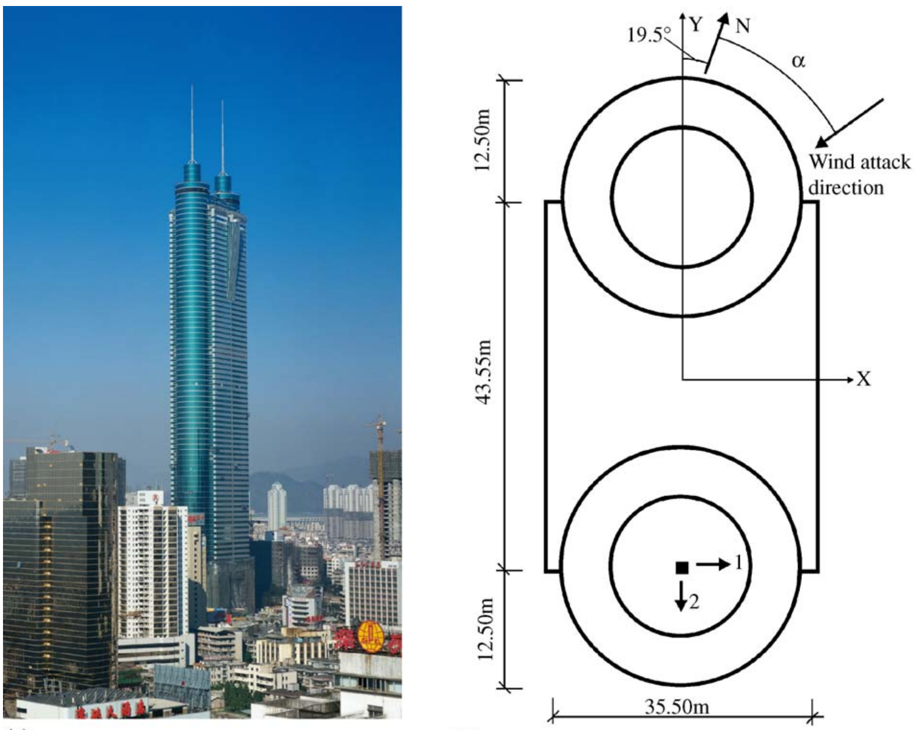
Determination of structural dynamic characteristics is necessary in the design of tall buildings, since natural frequencies, mode shapes and damping ratios are basic data for wind and seismic response analysis. Several analytical and numerical methods are available for evaluating the natural frequencies and mode shapes of a tall building in design stage. However, as yet there is no widely accepted method available for estimating damping ratios of a structure prior to construction. Reliable evaluations of structural damping can be obtained from experimental measurements of a prototype building only. In general, the dynamic response of a structural system is greatly affected by the amount of damping exhibited by each mode of vibration. The importance of damping is becoming increasingly significant as modern tall buildings are becoming taller and more flexible. Previous studies (Hart and Vasudevian, 1975; Jeary, 1986; Tamura et al., 1993; Tamura and Suganuma, 1996; Li et al., 1998, 2000; Fang et al., 1999) show that damping is a nonlinear parameter, and may increase with increasing amplitude. However, our literature review reveals that the information on amplitude-dependent damping contained in the literature mostly concerns mid-rise buildings in the vicinity of 40 storeys or shorter. Thus, there is a serious scarcity of damping data for super tall buildings. In this paper, the amplitude-dependent damping ratios of the two super tall buildings are evaluated by the Random Decrement Technique based on the measurement 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 a better understanding of the physics. So, it is very useful to compare model test results with actual performance to improve the modelling techniques in wind tunnel tests. The full-scale measurements from the two tall buildings provide an excellent opportunity to compare the real structural performance with the wind tunnel test results. In fact, such a comparison has rarely been made for super tall buildings under typhoon conditions.



(a) (b)

Fig. 1. Central Plaza Tower: (a) photo of CPT and (b) top view of CPT, definition of wind attack direction and arrangements of accelerometers.



(a) (b)

Fig. 2. Di Wang Tower: (a) photo of DWT and (b) top view of DWT, definition of wind attack direction and arrangements of accelerometers.

The main objective of this study is to further the understanding of wind effects on super tall buildings and the behaviour of such buildings under typhoon conditions in order to apply that knowledge to design.

2. Instrumentation

Two accelerometers were installed orthogonally at the elevation of the 73rd floor of CPT to measure the acceleration responses, as shown in Fig. 1(b). Two rotating cup-type anemometers were installed on the 75th floor of the building by the Hong Kong Observatory Department for the purpose of measuring wind velocity. However, these mechanical cup-type anemometers are too slow to offer the frequency resolution of 20 Hz that we need for the study of turbulence characteristics. For this reason, two Gill-propeller-type anemometers were installed on the masts erected on top of a super tall building near CPT (approximately at an elevation of 350 m from ground) to provide detailed information on typhoon-generated wind characteristics over the central district of Hong Kong Island. At the same time, the data outputs of mean wind speed and direction recorded by the Hong Kong Observatory Department on the 73rd floor in CPT were also analysed for the purposes of calibrating the wind velocity recorded by the Gill-propeller-type anemometers.

Two accelerometers were placed orthogonally on the floor, corresponding to the height of 298 m of DWT, to provide measurement of the accelerations, as shown in Fig. 2(b). Two Gill-propeller-type anemometers were installed on each of the masts located at the top of the building at a height of 347.5 m from the ground and 22.5 m above the roof of the building to provide detailed information on the local wind regime.

Acceleration responses from the two tall buildings were continuously acquired and digitized at 20 Hz and were amplified and low-pass filtered at 10 Hz before digitization. The installed anemometers produced analogue output voltages proportional to the wind speed and wind direction, which were synchronized with the response of the accelerometers sampled at 20 Hz. The data outputs included acceleration responses, wind speeds and wind directions. In order to reduce the interference effects from the masts, each anemometer was installed on a steel cantilever, 2–4 m away from the mast centers. After considering the wind attack angles and the alignment of the two anemometers installed in each instrumented building, the wind speed data measured from the anemometer with less interference effects from the masts were adopted in the present data analysis.

3. Typhoon Sally

As reported by the Hong Kong Observatory Department (1996), Typhoon Sally developed as a tropical depression about 1300 km east of Manila on the 5th September 1996. Moving west–northwestwards, it intensified over water and attained typhoon strength on the 7th September. Typhoon Sally entered the South China Sea the next morning and moved rapidly towards the coast of western Guangdong province, PR China. After traversing the Leizhou Peninsula and Guangxi Province on 9th September, Sally moved into northern Vietnam and dissipated over land the next day. Fig. 3 shows the route of Typhoon Sally. Sally was an unusually fast moving typhoon. Sally's 24-hourly speed of 38 km/h over the northern part of the South China Sea making it one of the fastest typhoons in the region during the last century. The maximum hourly mean wind speed and the gust speed recorded at Waglan Island and Cheung Chau by Hong Kong Observatory Department are shown in Table 1.

4. Characteristics of typhoon-generated wind

The data simultaneously recorded from the instrumented tall buildings from 10 p.m. on 8th September to 2 a.m. on 10th September during the passage of Typhoon Sally were adopted for investigating the characteristics of typhoon-generated wind over the two neighbouring cities, Hong Kong and Shenzhen.

4.1. Wind speed and direction

Fig. 4 shows the mean wind speed and wind direction averaged over 10 min, which were measured atop a super tall building near CPT and atop DWT. It was found that the characteristics of the mean wind speed and wind direction in both sites were similar, even though the buildings are located in two different cities with about 35 km distance between the two measurement sites. The maximum instantaneous wind speeds measured near CPT and atop DWT in the record

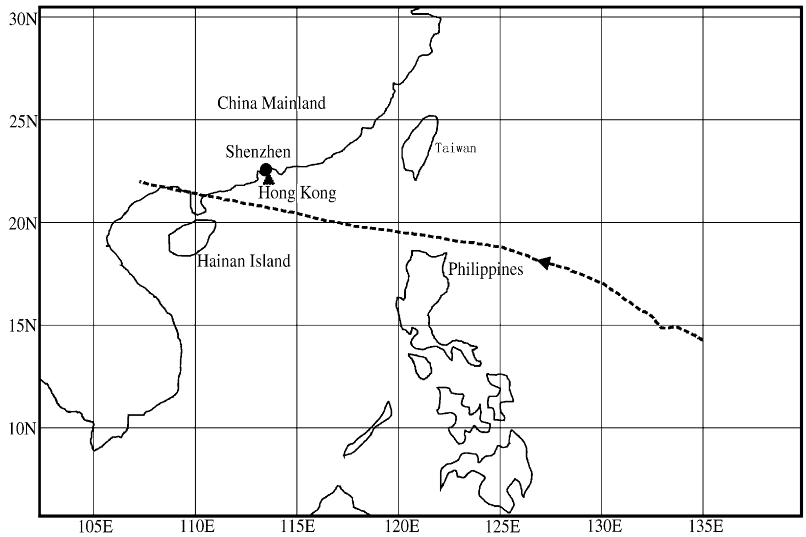


Fig. 3. Route of Typhoon Sally (Hong Kong Observatory Department, 1996).

Table 1
The maximum hourly mean wind speed and the gust speed recorded at Waglan Island and Cheung Chau by Hong Kong Observatory Department

Station	Position		Head of anemometer above MSL (m)	Maximum gust		Maximum hourly wind	
	Latitude N	Longitude E		Direction	Speed(m/s)	Direction	Speed(m/s)
Waglan Island	22°11′	114°18′	82	E	38.9	E	26.7
Cheung Chau	22°12′	113°56′	92	ESE	37.5	ESE	24.4

of Typhoon Sally were 29.6 and 33.5 m/s, respectively. The maximal 10-min mean wind speeds measured in Hong Kong and Shenzhen were 18.9 and 22.4 m/s, respectively. These results illustrate that the strength of Typhoon Sally was moderate, since it did not hit Hong Kong and Shenzhen directly, as shown in Fig. 3. The 10-min mean wind direction measured at the measurement site in Hong Kong varied in the range of 66–135°. From 2:00 to 18:00 on 9th September, after a significant transition of wind direction, the variation of wind direction was small, and the mean wind direction during the 16-h record period was 122°. Meanwhile, the 10-min mean wind direction measured atop DWT varied in the range of 42–120°. From 2:00 to 18:00 on 9th September, the wind direction relatively stabilized, and the mean wind direction during the 16-h record period was 98°.

4.2. Power spectral density and turbulence scale of wind

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 characteristics of natural wind are usually identified by two parameters: turbulence intensity and turbulence scale. One of the most widely used scales is the integral length scale, L_x, which is defined in several ways. It is often interpreted as the wavelength corresponding to the maximum of the normalized spectral density of wind speed. If this approach is adopted, then the turbulence integral scale can be estimated from the power spectrum of the velocity fluctuations. The von Karman velocity spectrum is one that is usually used to fit the measured spectra for estimation of the integral scale using L_x as the fitting parameter. This method has the advantage of fitting the whole spectrum, rather than only the

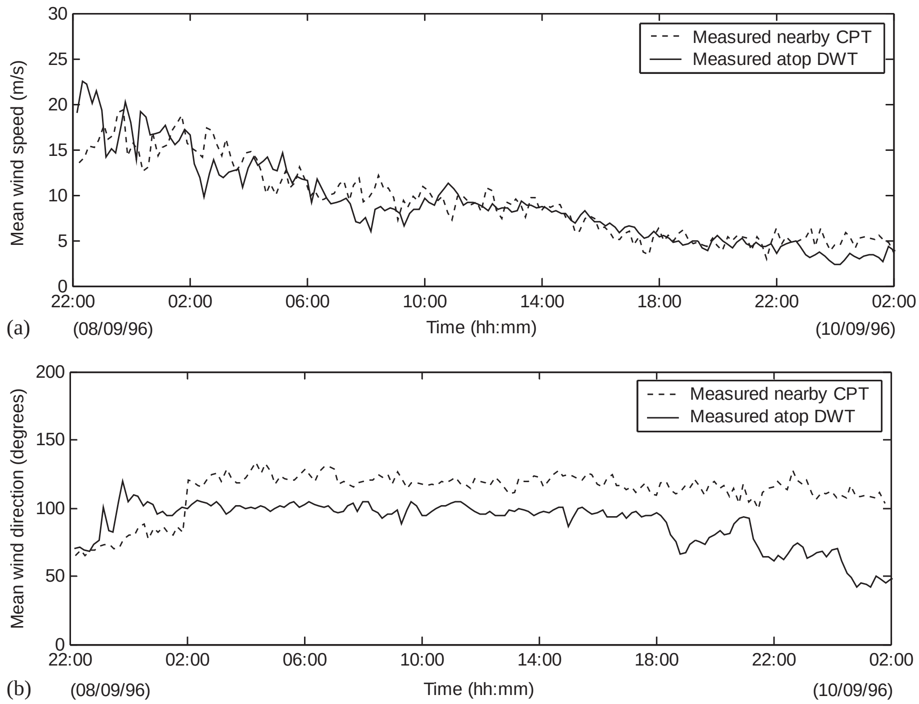


Fig. 4. 10-min mean wind speed and direction measured during the passage of Typhoon Sally.

position of the peak. The von Karman spectrum has the form of

$$\frac{fS_v(f)}{\sigma_v^2} = \frac{4L_x f/\bar{V}}{[1 + 70.7(L_x f/\bar{V})^2]^{5/6}}; \tag{1}$$

$S_v(f)$ is the power spectrum of wind speed, f is the frequency (Hz), and σ_v is the standard deviation of fluctuating velocity. $\overline{V}$ is mean wind speed.

Figs. 5 shows the normalized spectra of wind speed for CPT and DWT, which were obtained based on the measured data with a long sample (28 h) during Typhoon Sally. The spectra estimated using the von Karman spectrum are also presented 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 the wind speed above Hong Kong island and the central district of Shenzhen.

Fig. 6 shows the longitudinal and lateral turbulence integral scale of wind measured near CPT during the Typhoon. The turbulence integral scale was estimated by fitting the power spectra of wind speed from each 1-h record. The mean value of the longitudinal turbulence scale was 112 m. It can be seen from Fig. 6(a) that the longitudinal turbulence integral scale increases with the mean wind speed. Fig. 6(b) shows that there is also a tendency of the lateral turbulence integral scale increasing with the mean wind speed. Fig. 7 shows the longitudinal and lateral turbulence integral scale of wind measured atop DWT. The mean value of the longitudinal turbulence integral scale was 134 m. It is also found that there is a tendency for the longitudinal turbulence integral scale to increase with the mean wind speed, but the tendency of the lateral turbulence integral scale increasing with the mean wind speed was not as clear as that shown in Fig. 6(b), in particular in the low wind speed range.

Vickery (1975) commented that the range of the ratio of turbulence integral scale to building characteristic length for tall buildings in the atmospheric boundary layer would be in the range of 3–10. For slender structures the ratio may be more than 20. For guyed masts this ratio may reach values of the order of 100 and even higher for elements of these structures. However, this ratio simulated in wind tunnels is usually of the order of unity. As reported by Li and Melbourne (1995, 1999), turbulence integral scale has a significant effect on the estimation of peak and fluctuating wind pressures on building models. Figs. 6 and 7 show that the variations of turbulence integral scale during a typhoon passage were quite large. Thus, it is clear that there exists a source of uncertainty involved in wind tunnel modelling which needs to be further investigated.

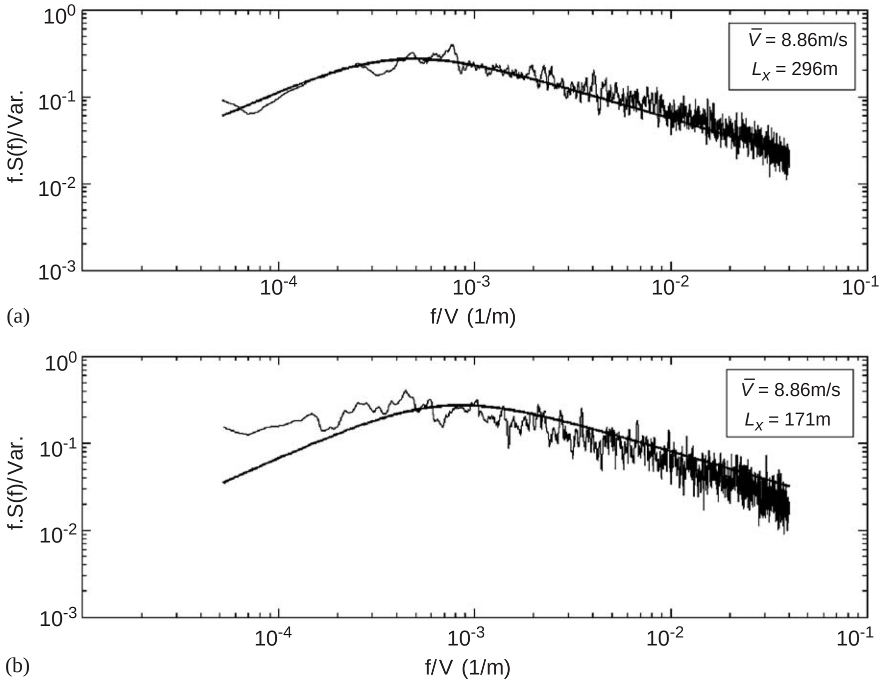


Fig. 5. Power spectrum density of wind speed measured during the passage of Typhoon Sally.

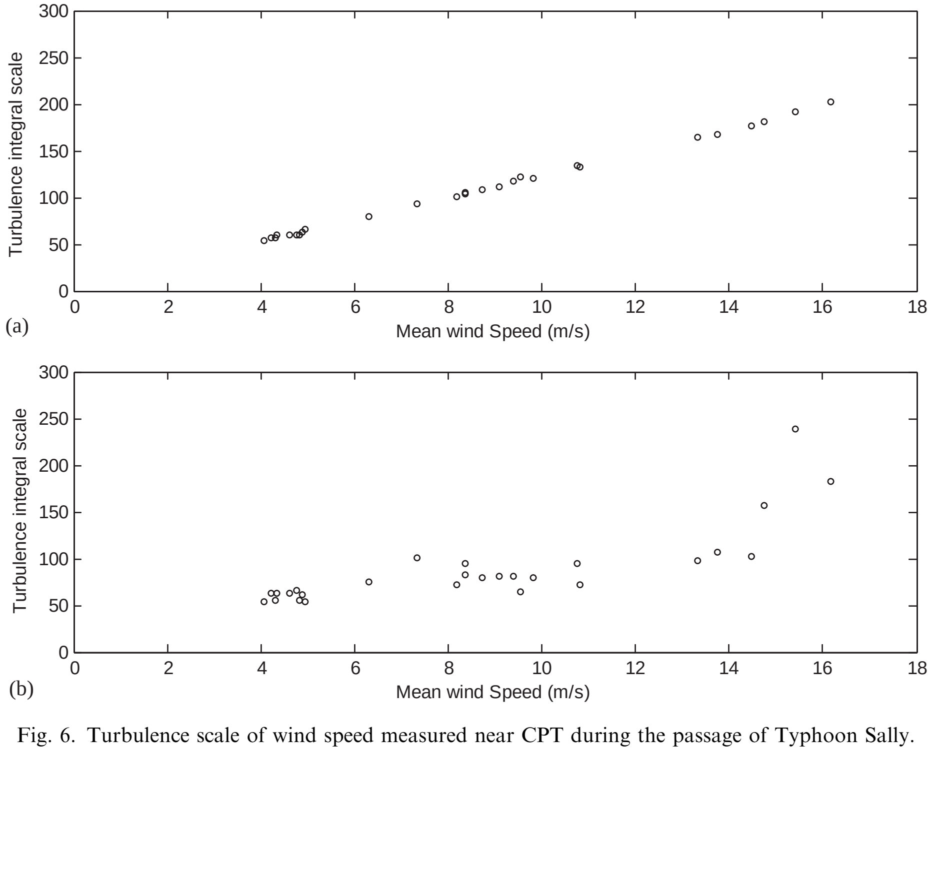


Fig. 6. Turbulence scale of wind speed measured near CPT during the passage of Typhoon Sally.

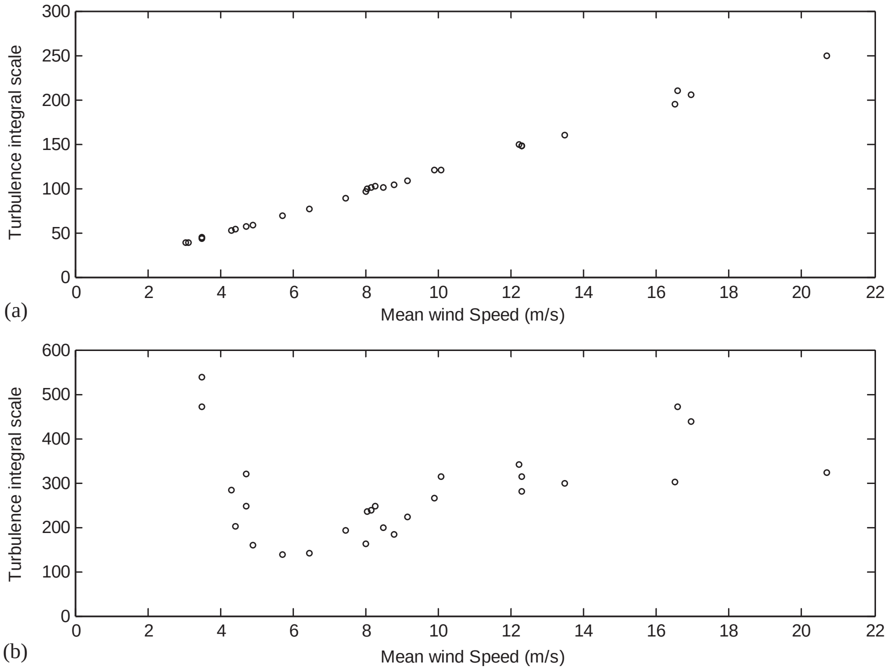


Fig. 7. Turbulence scale of wind speed measured atop DWT during the passage of Typhoon Sally.

4.3. Turbulence intensity and gust factor

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

$$G_u(t_g) = 1 + \frac{\max\left(\overline{u(t_g)}\right)}{\bar{V}},\qquad G_v(t_g) = \frac{\max\left(\overline{v(t_g)}\right)}{\bar{V}}, \tag{2}$$

$$I_i = \frac{\sigma_i}{\bar{V}} \qquad (i = u, v), \tag{3}$$

where $\overline{V}$ is the measured mean wind speed with 10 min duration; t_g is the duration of gust, in this paper, $t_g = 3\,s$; $\overline{u(t_g)}$ and $\overline{v(t_g)}$ are the longitudinal and lateral mean wind speed, respectively, with 3 s duration; $\sigma_i, (i = u.v)$ are the standard deviations of wind speed components within 10 min.

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 of the turbulence intensity and gust factor during typhoons of particular interest.

Fig. 8 shows the variation of turbulence intensities of 10-min duration measured near CPT with recording time. The average values of the longitudinal and lateral turbulence intensities, when the main wind speed was more than 10 m/s during Typhoon Sally, are 0.216 and 0.206, respectively. On the other hand, our previous measurements revealed that the averaged longitudinal turbulence intensity measured near CPT during the passage of Typhoon Sibyl on 3rd October 1995 is 0.225. In the Draft of the Code of Practice on Wind Effects Hong Kong-1996 issued by the Buildings Department of Hong Kong, turbulence intensity with a constant 0.15 is recommended for height more than 205 m in the urban area of Hong Kong. Obviously, the measured turbulence intensity is much larger than the recommended one. It is found from the measurements that there is a tendency for the longitudinal and lateral turbulence intensities to decrease with increasing mean wind speed.

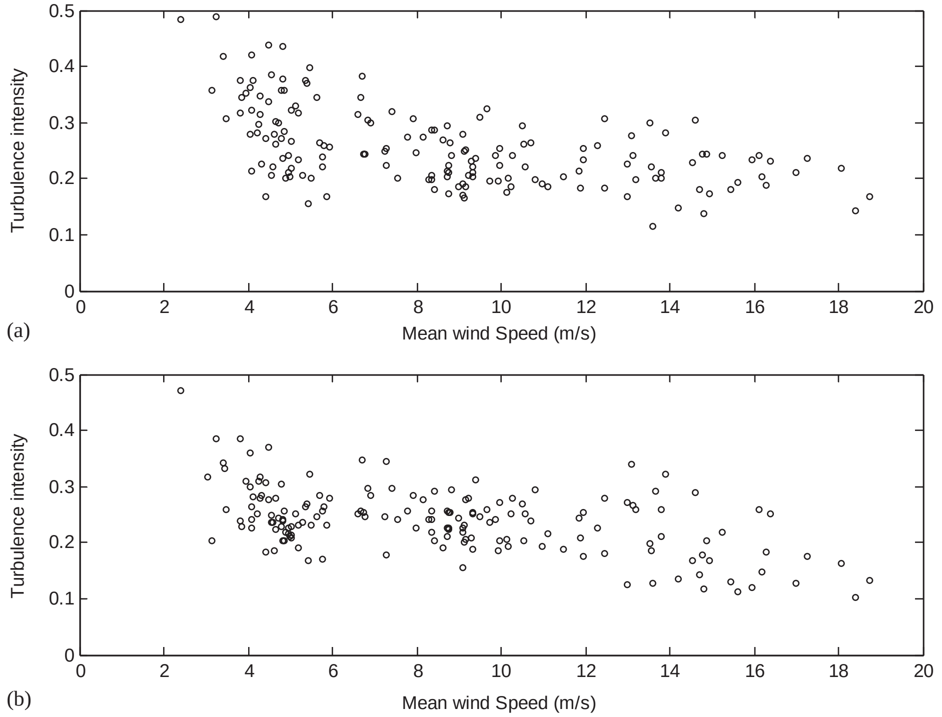


Fig. 8. Turbulence intensity of wind speed measured near CPT during the passage of Typhoon Sally.

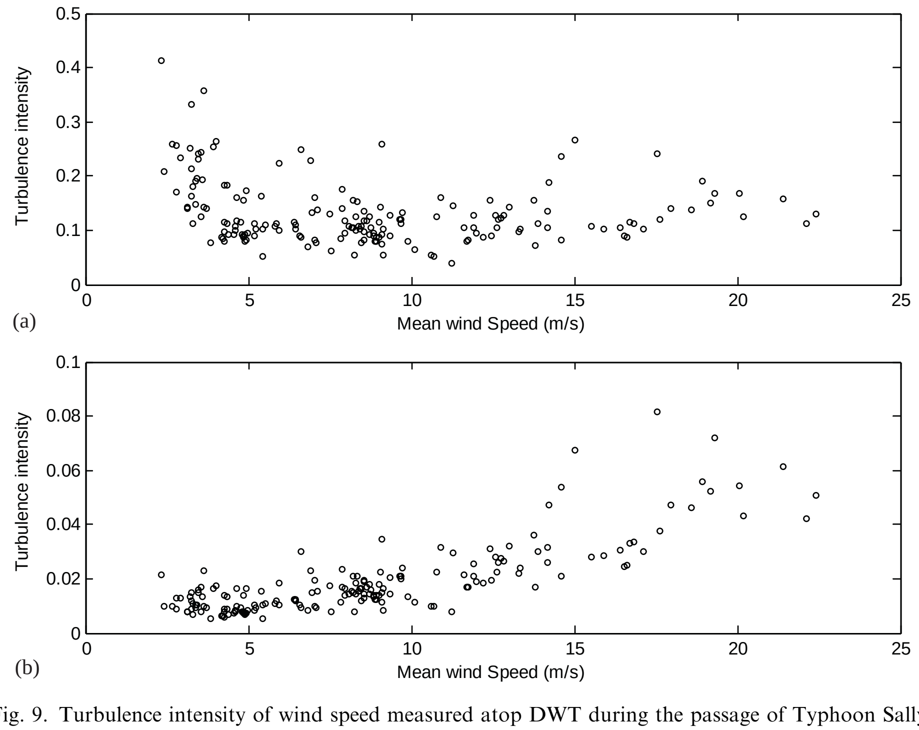


Fig. 9. Turbulence intensity of wind speed measured atop DWT during the passage of Typhoon Sally.

Fig. 9 demonstrates the characteristics of turbulence intensities of 10-min duration measured atop DWT. The average values of the longitudinal and lateral turbulence intensity when the mean wind speed was more than 10 m/s during Typhoon Sally are 0.123 and 0.033, respectively. The measurements near CPT and atop DWT shown in Figs. 8 and 9 all demonstrate that the longitudinal turbulence intensity approaches a constant as the wind speed increases. However, the distribution of the lateral turbulence intensity versus wind speed, as shown in Fig. 8(b) for CPT, is totally different from that shown in Fig. 9(b) for DWT.

Fig. 10 shows the variation of gust factor measured near CPT with recording time. The mean values of the longitudinal and lateral gust factor are 1.61 and 0.659, respectively. In the case of Typhoon Sibyl the averaged value of the longitudinal gust factor in a 24-h record is 1.64. The corresponding gust factor determined using the procedure in the Draft of the Code of Practice on Wind Effects Hong Kong-1996 is 1.56, which is in good agreement with the measured values. Fig. 11 demonstrates the characteristics of gust factor measured atop DWT. The mean values of the longitudinal and lateral gust factor are 1.31 and 0.057, respectively. It can be seen from Fig. 10(a) and 11(a) that the longitudinal gust factor decreases with the increase of mean wind speed and approaches a constant as the wind speed becomes larger. However, Figs. 10(b) and 11(b) show a contrary tendency for the variation of the lateral gust factor with mean wind speeds for these two buildings.

From the results presented above, it is found that the turbulence characteristics measured near CPT during Typhoon Sally and Typhoon Sibyl are similar, at least for the longitudinal components. However, there are significant differences for wind characteristics; in particular, the lateral components, measured at similar heights above the central districts of Hong Kong and Shenzhen during Typhoon Sally. Values of turbulence intensity and gust factor measured in Hong Kong are larger than those obtained in Shenzhen, i.e., the level of fluctuation of wind is higher in Hong Kong. This may be attributed to the existence of many tall buildings and a mountain near CPT, thus illustrating that wind characteristics strongly depend on terrain conditions.

5. Wind-induced vibrations

5.1. Structural dynamic characteristics and spectral analysis of the responses

The results of spectral analysis of acceleration response measured from CPT and DWT are shown in Figs. 12 and 13. These spectra were obtained from a direct analysis of the accelerometer output data that were measured simultaneously from the two buildings. The spectral analysis results show that the wind-induced responses of these buildings were all primarily in the two fundamental sway modes of vibration, but higher modes were also clearly present. As mentioned previously, two accelerometers were placed orthorgonally at the top floor in each instrumented building. However, two accelerometers were not enough for studying wind-induced response characteristics. Additional accelerometers were also installed on the top floors. For example, two accelerometers that were parallel to the orthogonally placed accelerometers were installed on the top floor in each instrumented building to obtain torsional vibration information for these buildings. All these accelerometers provided measures of the two translational accelerations and the rotational accelerations for each instrumented building. Fig. 14(a) and (b) give a typical example of an angular acceleration time history measured from DWT and its spectrum which clearly show the torsional modes. Table 2 lists the natural frequencies of the first three modes of the two buildings determined from the measured spectra and those calculated from the computational models of the two buildings. The computational models of the buildings were established based on the structural design drawings or the information on the mass and stiffness of the buildings provided by the structural designers. It was found from Table 2 that there are about 2.9–17.8% differences between the calculated and measured natural frequencies for the first two fundamental sway modes of the two buildings. 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 the buildings are less than those assumed at the design stage, or the effective stiffness values of the buildings are higher than those determined at the design stage due to the contribution of nonstructural components. As a result, the measured natural frequencies for the two fundamental sway modes of the two super tall buildings are larger than those calculated.

5.2. Wind-induced vibration

Figs. 15 and 16 show the relationship between the standard deviations of the measured acceleration response averaged over 10 min period and the measured mean wind speed.

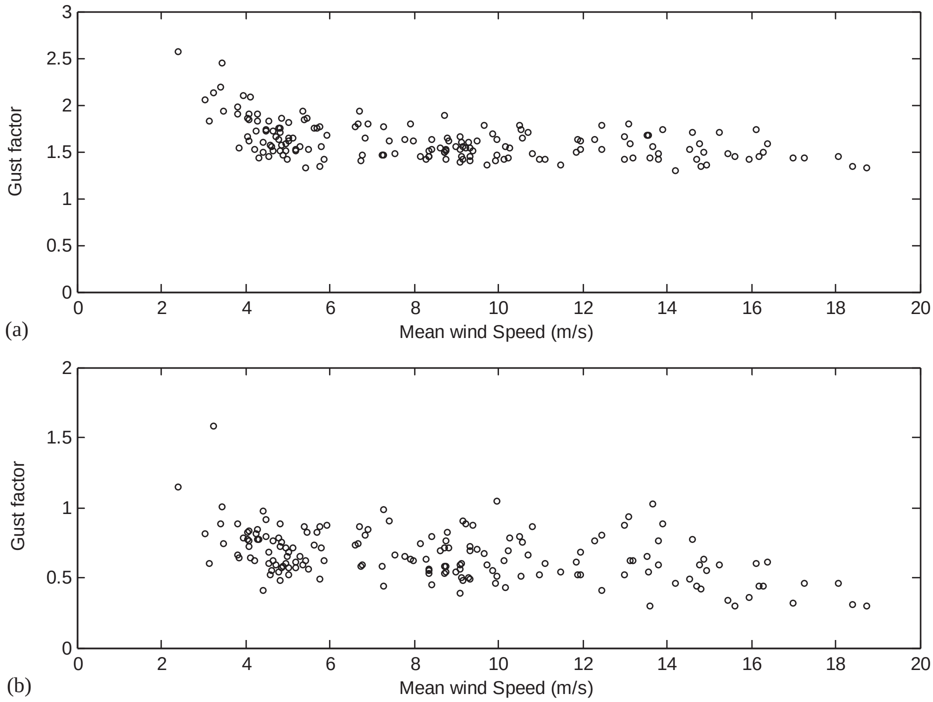


Fig. 10. Gust factor versus wind speed measured near CPT during the passage of Typhoon Sally.

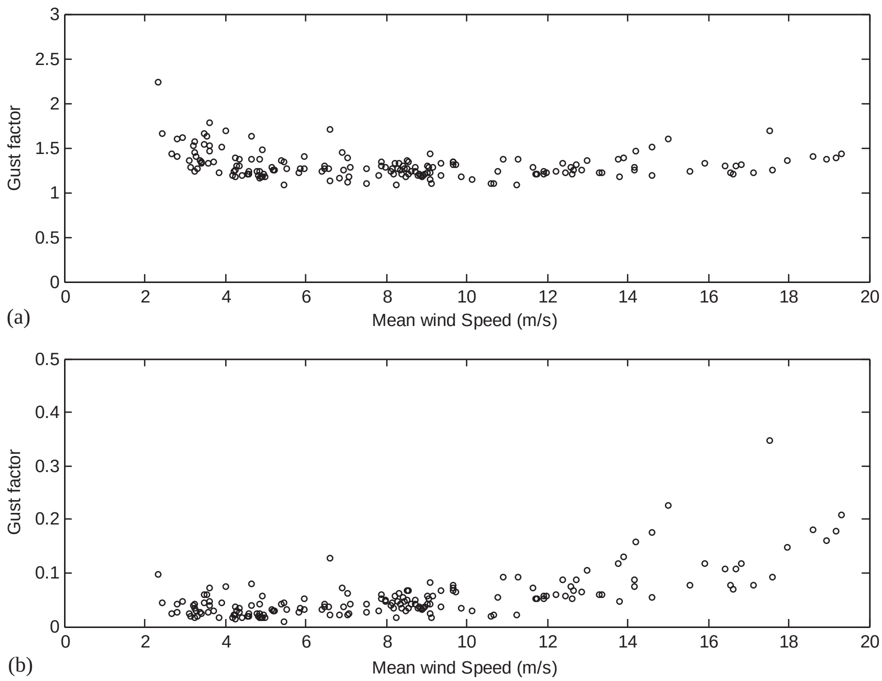


Fig. 11. Gust factor versus wind speed measured near CPT during the passage of Typhoon Sally.

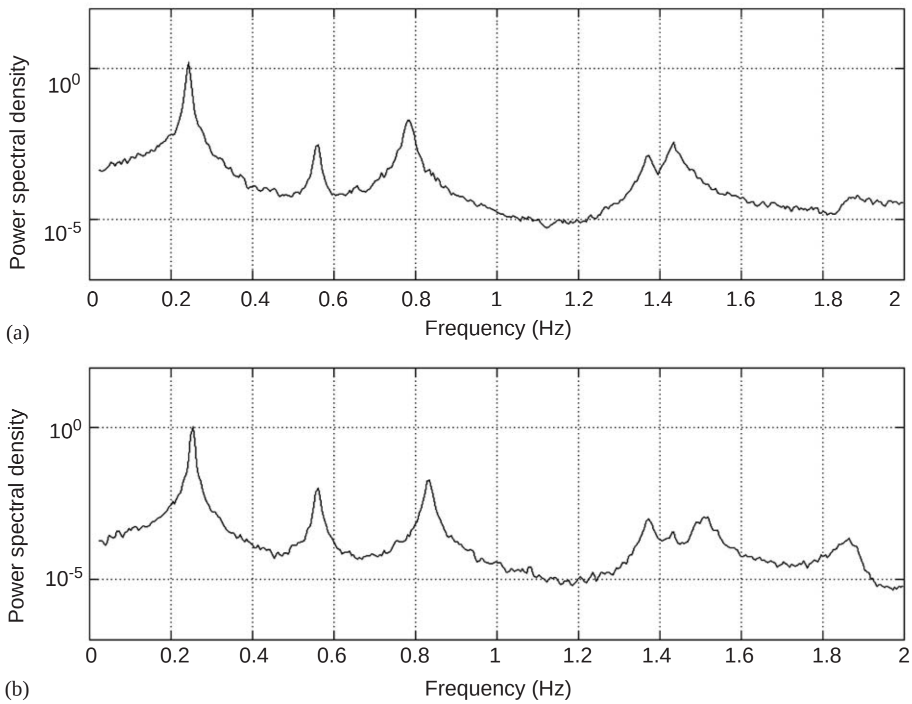


Fig. 12. Power spectrum density of acceleration of CPT.

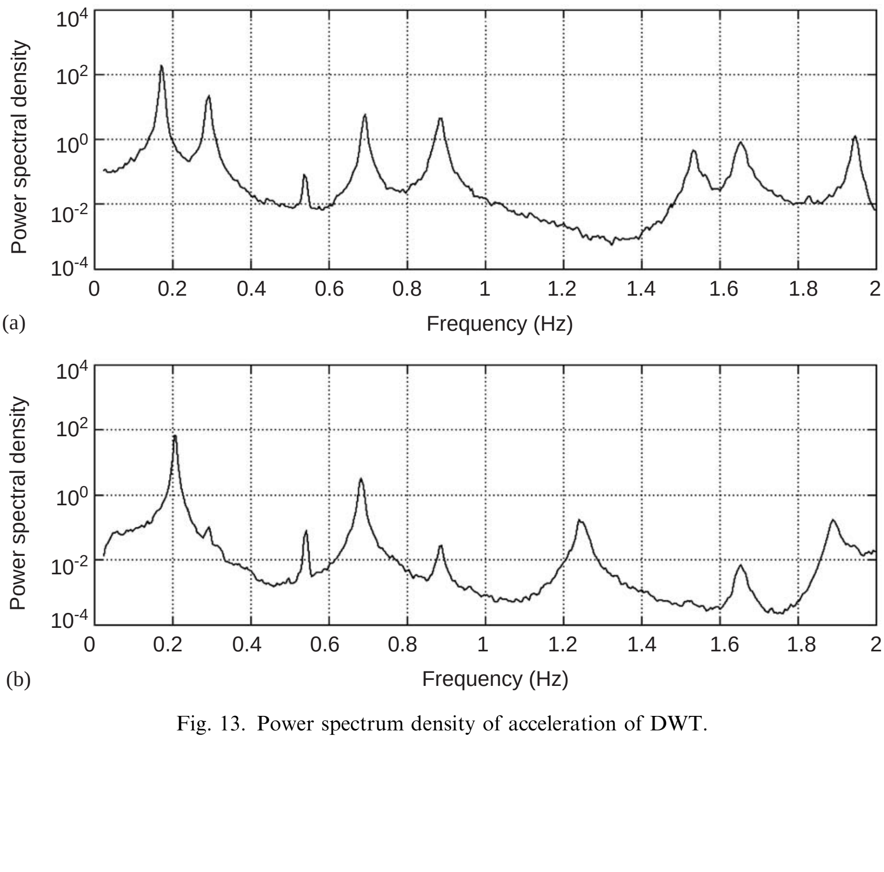


Fig. 13. Power spectrum density of acceleration of DWT.

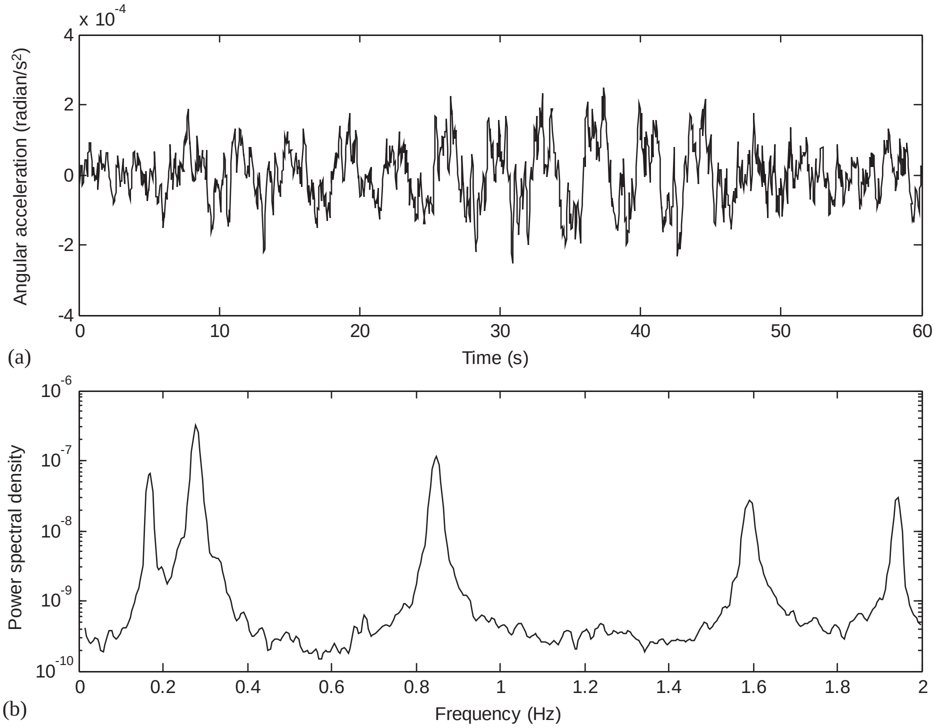


Fig. 14. Angular acceleration time history measured from DWT and its spectrum.

Table 2
Natural frequencies (Hz) of the two buildings

	Frequencies (Mode 1, sway)			Frequencies (Mode 2, sway)			Frequencies (Mode 3, torsion)		
	Measured	Calculated	Difference (%)[a]	Measured	Calculated	Difference (%)[a]	Measured	Calculated	Difference (%)[a]
CPT	0.244	0.206	15.6	0.253	0.208	17.8	0.557	0.606	−8.08
DWT	0.173	0.168	2.9	0.208	0.181	13.0	0.293	0.286	2.45

[a]Difference = (Measured-Calculated)/Measured.

For the data presented in Figs. 15 and 16, the regression curves of acceleration responses for each direction in the two super tall buildings are expressed by the following equation:

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

where the parameters a_1 and a_2 for the two buildings are listed in Table 3.

It appears that both components of acceleration in each instrumented building increased monotonically with mean wind speed during the passage of Typhoon Sally. The measured data showed that the standard deviations of acceleration responses are proportional to the wind speed equivalent at the top of the buildings raised to a power of 3.10–3.72.

For modern flexible tall buildings, such as the two instrumented 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. Some codes, for example, the National Building Code of Canada (NBCA) (1991) suggests acceptable levels of accelerations as a serviceability requirement, which recommends that a tentative maximum

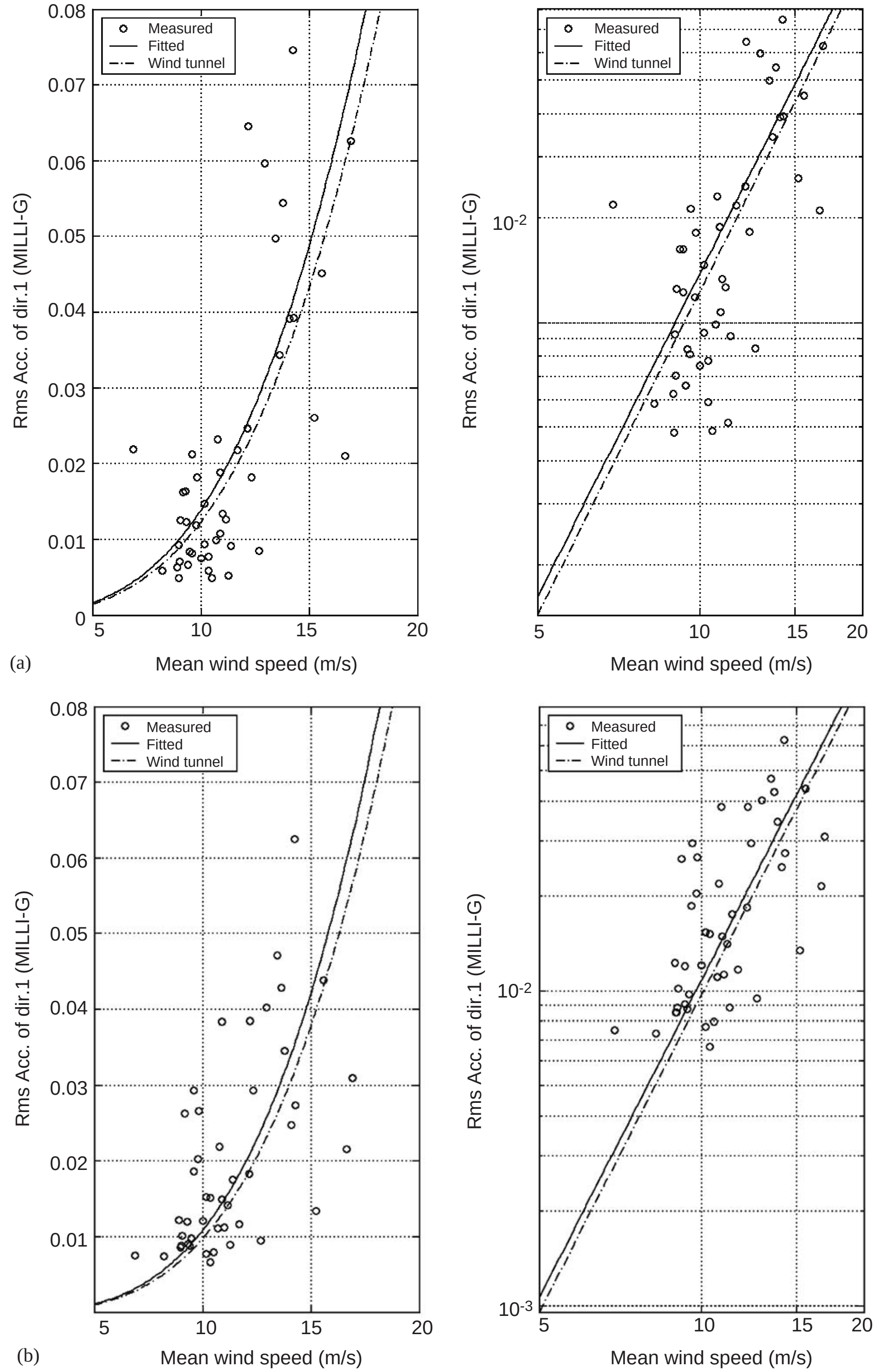


Fig. 15. Relation between wind speed and acceleration responses and comparison with the wind tunnel test data for CPT: (a) Direction 1 and (b) Direction 2.

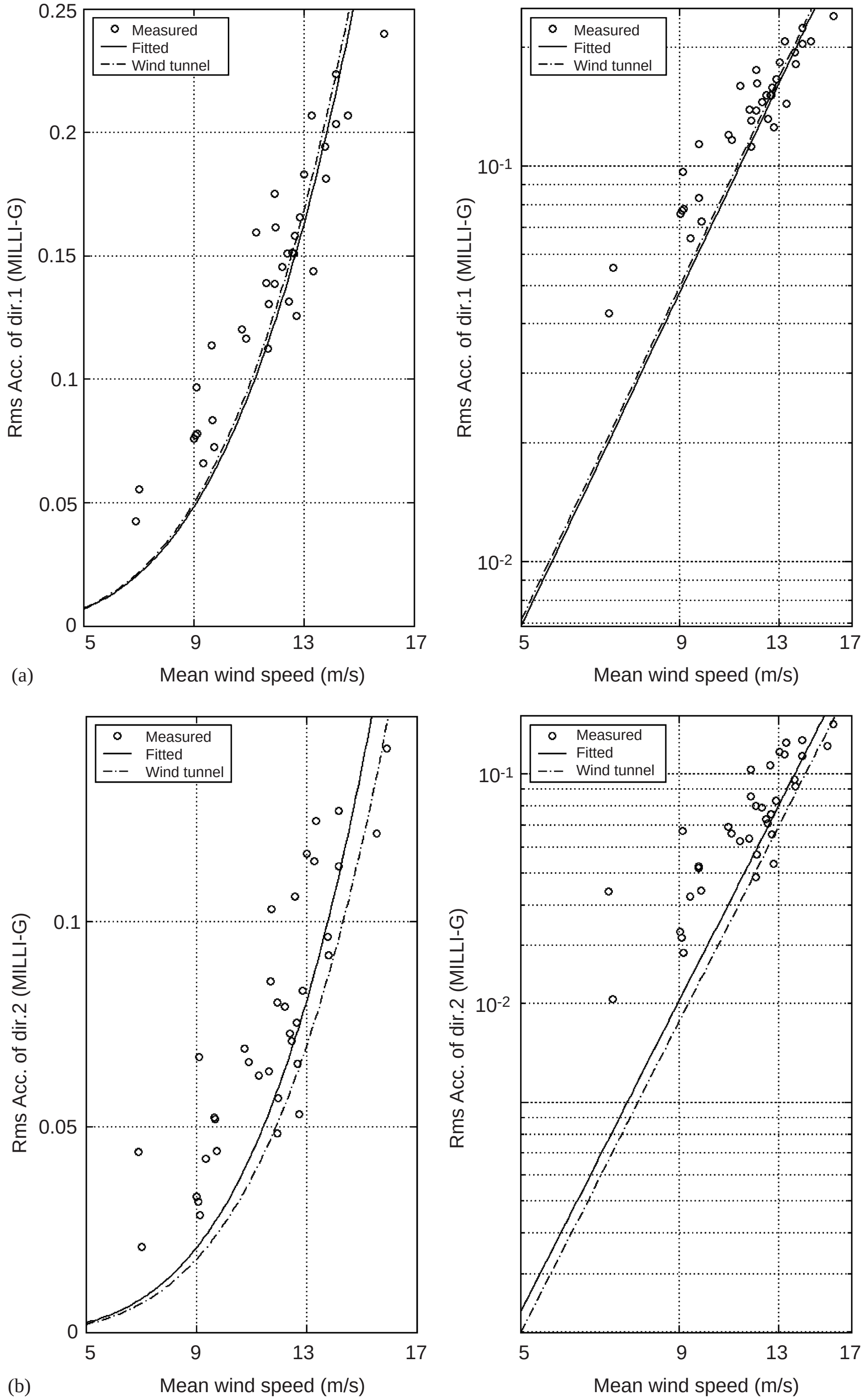


Fig. 16. Relation between wind speed and acceleration responses and comparison with the wind tunnel test data for DWT: (a) Channel 1 and (b) Channel 2.

Table 3
Parameters for the regression curves of the two buildings

		a_1	a_2
CPT	Direction 1	1.10×10^{-5}	3.10
	Direction 2	4.84×10^{-6}	3.35
DWT	Direction 1	2.85×10^{-5}	3.31
	Direction 2	4.83×10^{-6}	3.72

Table 4
Maximum accelerations of the two buildings during Typhoon Sally (milli-g)

	Max. instantaneous acceleration		Max. 10-min r.m.s. of acceleration	
	Direction 1	Direction 2	Direction 1	Direction 2
CPT	0.30	0.21	0.07	0.06
DWT	1.50	1.31	0.78	0.58

acceleration limitation of 1–3 percent of gravity once every 10 years as a guideline for comfort of occupants, and that the lower value might be considered appropriate for apartment buildings, while the higher value for office buildings. ISO 6897 suggests 5 milli-g r.m.s. acceleration criterion for a 6-year return period for building structures. The return period of the maximum wind speed observed during Typhoon Sally was estimated to be about 1–2 years. Table 4 presents the peak accelerations and the maximum 10-min standard deviations of acceleration responses along the two orthogonal directions in the two buildings during Typhoon Sally. It was observed that although the vibration magnitudes of the two buildings are significantly different, the peak acceleration responses measured atop the buildings during Typhoon Sally were all below the serviceability criteria for occupancy comfort. To evaluate the serviceability of the buildings more properly, it is needed to consider the relationship among the resultant acceleration responses and the mean wind speeds as well as the occupancy comfort criteria with different return periods. The simplest way to combine the accelerations from two way motions is to take the square root of the sum of the squares. Fig. 17(a) and (b) present the forecasting resultant acceleration responses of the two buildings, which were obtained based on the field measurements. Meanwhile, the serviceability criteria for return periods of 6 years (ISO 6897) and 10 years (NBCA) are also plotted in the figures for comparison purposes. The NBCA criterion of r.m.s. acceleration was determined from the maximum acceleration criterion divided by a peak factor of 3.5. The wind speeds with the return periods (6 and 10 years) marked in the figures were obtained from the local wind codes of Hong Kong and the structural design standard of China. It can be observed from Fig. 17 that the two super tall buildings would appear to satisfactorily meet the occupancy comfort ISO6897 criterion and the Canadian criterion for different return periods.

6. Comparison with wind tunnel measurements

It is very useful to compare model test results with actual performance for the purposes of improving the modelling techniques in wind tunnel tests. In fact, such comparisons are scarce and have rarely been made for super tall buildings under typhoon conditions.

6.1. CPT

Wind tunnel tests for CPT were conducted in the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario (UWO) in 1989 for wind-resistant design purposes. The wind engineering study carried out included

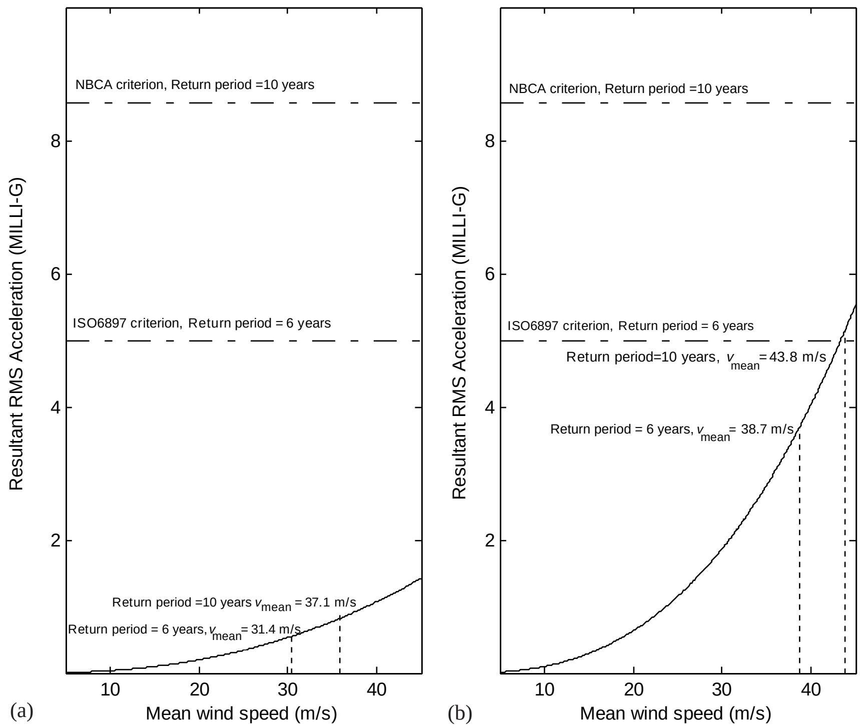


Fig. 17. Comparison of the resultant acceleration responses predicted based on the field measurements and the serviceability criteria of ISO6897 and NBCA.

the determination of overall wind loads and dynamic responses of this building through force balance model tests. As introduced by Ho and Surry (1989), the force balance wind tunnel tests were carried out at a geometric scale of 1:500. Measurements were made of the mean and dynamic components of the model forces at the foundation level of the building. The model of the wind tunnel tests reproduced the topography and all major buildings around the project site. The two translational accelerations and the rotational accelerations near the top of the building (at a full-scale height of 298 m above the foundation level) were determined based on the wind tunnel tests. Ho and Surry (1989) gave a detailed introduction about the wind tunnel tests.

By examining the wind velocity data measured at the measurement site in Hong Kong, it was found that the wind direction mainly varied around 115–125° with the mean wind direction of 121° during 2–10 a.m. on 9th September. This implies that the wind direction during this period can be regarded as constant (121°). Fig. 15 shows the comparison between the full-scale measurements and the model test results at different wind speeds for the wind direction around 121°. In Fig. 15, the wind tunnel data were extracted from Ho and Surry (1989) and the field data were measured during Typhoon Sally. The smooth curves shown in Fig. 15 were obtained by curve fitting to the field measurements and the wind tunnel test results. It can be seen from Fig. 15 that basically, the agreement between the two sets of data is satisfactory, although the measured responses are larger than the wind tunnel responses by 12.5% and 11.5% in directions 1 and 2, respectively.

6.2. DWT

Wind tunnel tests for DWT were conducted in the Boundary Layer Wind Tunnel Laboratory at UWO in 1993 through force balance model tests. As introduced by Crooks et al. (1993), the force balance wind tunnel tests were carried out at a geometric scale of 1:400. Measurements were made of the mean and dynamic components of the model forces at the foundation level of the building. The model of the wind tunnel tests reproduced the topography and all major buildings around the project site. Based on the model test results and the statistical analysis of the local wind climate, predictions were made of peak accelerations and standard deviations of accelerations etc. at a full-scale height of 307.5 m above ground.

By examining the measured wind velocity data, it was found that the wind direction measured atop DWT during Typhoon Sally mainly varied in the range of 95–105° with a mean wind direction of 98° during 2–10 a.m. on 9th September. This implies that the wind directions during this period can be approximately regarded as constant (98°). Fig. 16 shows the comparison between the full-scale measurements and the model test results at different wind speeds for this azimuthal sector. In Fig. 16, the wind tunnel data were extracted from Crooks et al. (1993) and the field data were measured during the passage of Typhoon Sally. Obviously, the agreement between the two sets of data is quite satisfactory for this case, and it was found that the measured responses were smaller than the wind tunnel test data by 4.5% and 4.0% in direction 1 and 2, respectively, verifying the accuracy of the model test results and illustrating that wind tunnel tests can provide accurate predictions of wind-induced vibrations of super tall buildings under typhoon conditions.

7. Damping characteristics of the super tall buildings

The measured acceleration data can be used to obtain the dynamic characteristics of the buildings (damping, natural frequencies, etc.). The modified random decrement technique that was developed by the authors was employed to evaluate the damping in these building based on the field measurements during Typhoon Sally. As commented by Li et al. (2003), the random decrement technique represents a quick and practical method for establishing the nonlinear damping characteristics. As discussed previously, the wind-induced responses of the two super tall buildings were primarily in the two fundamental sway modes of vibration, but higher modes were also present. 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 remove the components not concerned. The damping curves (damping against amplitude) of the first sway mode in each direction of the two buildings are evaluated from the measured acceleration data, as shown in Figs. 18 and 19, which comprise both structural damping and aerodynamic damping.

Figs. 18 and 19 show the amplitude-dependent damping characteristics of the two buildings. Information on amplitude-dependent damping obtained from the two buildings should be very useful, since similar measurements are still very limited for such super tall buildings under typhoon conditions. The damping curves shown in these figures clearly demonstrate the nonlinear energy dissipation characteristics of the buildings. It is clear that the damping increases with increase in amplitude during Typhoon Sally. Figs. 18 and 19 also present the variation of aerodynamic damping and structural damping against structural acceleration amplitude. The aerodynamic damping values of these buildings were determined based on the method introduced in Holmes (2001). It is evident from the results presented in Figs. 18 and 19 that both the structural damping and aerodynamic damping of the two buildings all slightly increase with increasing amplitude.

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 assumed to be 1%, 1.5%, 2% and 2.5% for the estimation of wind-induced responses of the two buildings. From Figs. 18 and 19, it appears that these assumptions may overestimate the damping ratios of these buildings, at least as far as an amplitude appropriate to the serviceability criterion for these buildings is concerned, since the damping curves presented in these figures were measured under moderate wind conditions.

The measured acceleration responses were also used to evaluate the damping values of CPT and DWT without taking into account of vibration amplitudes. Such results are summarized in Table 5. 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 Typhoon Sally, which were found to be in the range of 0.51–0.59%. The corresponding damping values determined by the spectrally based half-power bandwidth method varied in the range of 0.80–1.13% for the two buildings. It is clear that the damping values estimated by the random decrement technique are smaller than those evaluated by the half-power bandwidth method, suggesting that damping estimates depend upon the damping evaluation methods. It was discussed by Li et al. (2003) that the random decrement technique usually provides more realistic damping estimates. Obviously, the accuracy of the spectrally based method is dependent on the spectral resolution.

The damping values evaluated by the random decrement technique indicate that the fundamental modal damping ratios of the two super tall buildings are very similar, even though the two buildings were constructed with different types of structural systems and subjected to different levels of vibration amplitudes. Considering that damping ratios cannot be predicted precisely prior to construction, it is suggested that damping values of 0.5% of the critical appear reasonable for wind-resistant design of super tall buildings for serviceability considerations, which aligns with the lower values of the present field measurements.

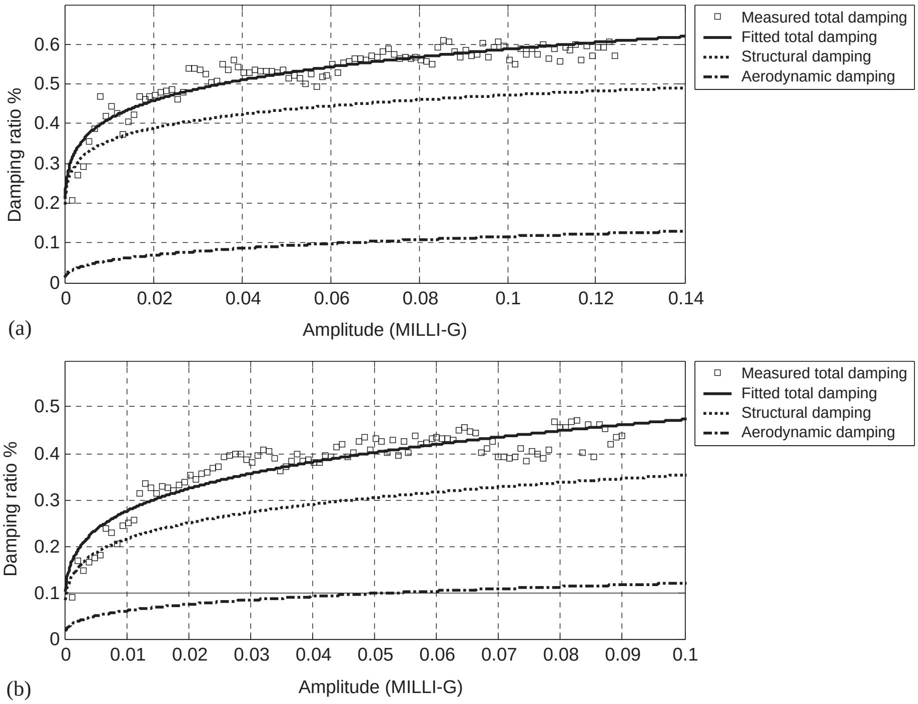


Fig. 18. Variation of damping ratio with vibration amplitude for CPT.

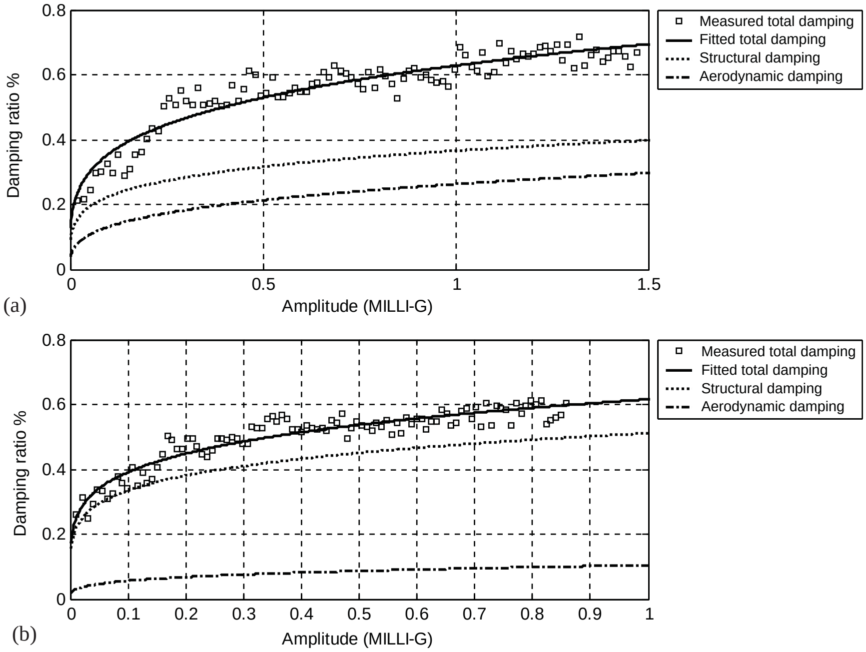


Fig. 19. Variation of damping ratio with vibration amplitude for DWT.

Table 5
Damping ratios of CPT and DWT (during Typhoon Sally)

		Random decrement (%)	Half-power spectrum (%)
CPT	Direction 1	0.59	1.13
	Direction 2	0.51	0.82
DWT	Direction 1	0.58	1.06
	Direction 2	0.57	0.88

8. Conclusions

This paper presents the simultaneous measured results from two super tall buildings located in Hong Kong and Shenzhen during the passage of Typhoon Sally; 28-hour data recorded simultaneously and continuously from the two tall buildings were analyzed to investigate wind effects on the buildings. Comparative study on the characteristics of typhoon-generated wind above the two cities and the performance of the tall buildings with different structural systems under typhoon conditions was presented. Some conclusions are summarized as follows.

(i) The von Karman-type spectrum was found to be able to describe the energy distribution fairly well for the wind speed above Hong Kong Island and the central district of Shenzhen. It was found that there is a tendency for the longitudinal-turbulence integral scale to increase with mean wind speed in both Hong Kong and Shenzhen. The longitudinal-turbulence integral scale estimated by fitting the von Karman-type spectrum varied in the range from 50 to 200 m in Hong Kong, and was in the range of 40–250 m in Shenzhen during the passage of Typhoon Sally. The values of longitudinal-turbulence integral scale estimated from the 28-h records were found to be 112 and 134 m in Hong Kong and Shenzhen, respectively. The larger variation of the measured longitudinal- and lateral-turbulence integral scales indicates that there exists a source of uncertainty involved in wind tunnel modelling which needs to be further investigated.

(ii) It was found from the field measurements that the turbulence characteristics measured in Hong Kong during Typhoon Sally and Typhoon Sibyl were similar. However, significant differences existed for wind characteristics measured at similar heights above the central districts of Hong Kong and Shenzhen during Typhoon Sally. Values of turbulence intensity and gust factor measured in Hong Kong were larger than those obtained in Shenzhen. The average values of the longitudinal turbulence intensity and gust factor measured in Hong Kong during Typhoon Sally when the main wind speed was more than 10 m/s were 0.216 and 1.61, respectively. The corresponding results recorded atop DWT in Shenzhen were 0.123 and 1.31. These results indicated that the level of fluctuation of wind was higher in Hong Kong. This may be attributed to the existence of many tall buildings and a mountain near CPT, thus illustrating that wind characteristics strongly depend on terrain conditions. Both the turbulence intensity and the gust factor were found to decrease with an increase in mean wind speed and approach to constants as the wind speed increases.

(iii) The measured natural frequencies of the two fundamental sway modes of the two buildings were compared with those determined from the computational models. There were about 2.9–17.8% differences between the measured and calculated natural frequencies for the two fundamental sway modes. It was maintained that such differences are attributable to several reasons, including that the effective mass values of the buildings may be less than those assumed at the design stage or the effective stiffness values of the buildings were higher than those determined at the design stage due to the contribution of nonstructural components. As a result, the measured natural frequencies for the two fundamental sway modes were larger than those calculated.

(iv) Wind-induced acceleration responses of the two super tall buildings were found to be monotonically increasing with the measured wind speeds. The measured data show that the standard deviations of acceleration responses were proportional to the wind speed equivalent at the top of the buildings raised to a power of 3.10–3.72. It was observed that, although the vibration magnitudes of the two buildings were significant different, the peak acceleration responses measured atop the buildings during Typhoon Sally were all below the serviceability criteria for occupancy comfort. Thus, from the field measurements and further predictions, the two super tall buildings would appear to satisfactorily meet the occupancy comfort criteria specified in ISO6897 and NBCA for different return periods.

(v) The field measured acceleration responses have been compared with the wind tunnel test results. The measured acceleration data were consistent with those obtained in the model tests. The differences between the field measurements and the wind tunnel data were in the range of 4.0–12.5% for the two super tall buildings, thus verifying the accuracy of the model test results and illustrating that wind tunnel tests can provide accurate predictions of wind-induced vibrations of super tall buildings under typhoon conditions.

(vi) The measured damping ratios demonstrate obvious amplitude-dependent characteristics and increases with increasing amplitude during Typhoon Sally. 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 Typhoon Sally, which were found to be in the range of 0.51–0.59%. The evaluated damping values indicated that the fundamental modal damping ratios of the two super tall buildings were very similar, even though the two buildings were constructed with different types of structural systems and subjected to different levels of vibration amplitudes during the typhoon. The measurement results showed that damping values of 0.5% of the critical appear reasonable for wind-resistant design of super tall buildings for serviceability consideration.

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References

Crooks, G., Isyumov, N., Edey, R.T., Davenport, A.G., 1993. A study of overall wind-induced loads and responses for the Di Wang Tower, Shenzhen, PRC. Research Report BLWT-SS26-1993, Boundary Layer Wind Tunnel Laboratory. The University of Western Ontario, Canada.

Draft of the Code of Practice on Wind Effects Hong Kong-1996, Buildings Department of Hong Kong, 1996.

Fang, J.Q., Li, Q.S., Jeary, A.P., Liu, D.K., 1999. Damping in tall buildings: its evaluation and probabilistic characteristics. The Structural Design of Tall Buildings 8, 145–153.

Hart, G.C., Vasudevian, R., 1975. Earthquake design of buildings: damping. ASCE Journal of Structural Division 101 (ST1), 11–30.

Ho, T.C.E., Surry, D., 1989. A study of wind effects for the proposed harbor road development, Hong Kong. Research Report BLWT-SS44-1989, Boundary Layer Wind Tunnel Laboratory. The University of Western Ontario, Canada.

Holmes, J.D., 2001. Wind Loading of Structures. Spon Press, London.

Hong Kong Observatory Department, 1996. "Tropical cyclone in 1996".

Jeary, A.P., 1986. Damping in tall buildings, a mechanism and a predictor. Earthquake Engineering and Structural Dynamics 14, 750–773.

Li, Q.S., Melbourne, W.H., 1995. An experimental investigation of the effects of free-stream turbulence on streamwise surface pressures in separated and reattaching flows. Journal Wind Engineering and Industrial Aerodynamics 51–52, 313–323.

Li, Q.S., Fang, J.Q., Jeary, A.P., Wong, C.K., 1998. Full scale measurement of wind effects on tall buildings. Journal of Wind Engineering and Industrial Aerodynamics 74-76, 741–750.

Li, Q.S., Melbourne, W.H., 1999. The effects of large scale turbulence on pressure fluctuations in separated and reattaching flows. Journal of Wind Engineering and Industrial Aerodynamics 83, 159–169.

Li, Q.S., Liu, D.K., Fang, J.Q., Jeary, A.P., Wong, C.K., 2000. Damping in buildings: its neural network and AR model. Engineering Structures 22, 1216–1223.

Li, Q.S., Yang, K., Wong, C.K., Jeary, A.P., 2003. The effect of amplitude-dependent damping on wind-induced vibrations of a super tall building. Journal of Wind Engineering and Industrial Aerodynamics 91, 1175–1198.

National Building Code of Canada, 1991. National Research Council. Ottawa, Canada.

Tamura, Y., Suganuma, S., 1996. Evaluation of amplitude-dependent damping and natural frequency of buildings during strong winds. Journal of Wind Engineering and Industrial Aerodynamics 59, 115–130.

Tamura, Y., Shimada, K., Hibi, K., 1993. Wind response of a tower (typhoon observation at the nagasaki huis ten bosch domtoren). Journal of Wind Engineering and Industrial Aerodynamics 50, 309–318.

Vickery, B.J., 1975. Discussion of section 4—dynamic response II. Proceedings of the Fourth International Conference on Wind Effects on Buildings & Structures. Cambridge University Press, Cambridge, pp. 389–395.