Dynamic Behaviour of Two Tall Residential Buildings during Two Typhoons

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1.0 INTRODUCTION

Hong Kong has a high population density, accommodating 6,803,000 residents in its 1,103 square kilometres [1]. A significant portion of this land is difficult to build upon, however, leading to extreme statistics, such as 50,820 people per square kilometre throughout the Kwun Tong district [2]. Maintaining such high population densities is only possible through the construction of tall buildings both for commercial and residential purposes. As a consequence, Hong Kong has 52 of the tallest 100 residential buildings in the world, most of which were built within the last five years [3].

To aid in the future safe design of tall buildings, it is useful to verify the full-scale dynamic performance of the structural design during extreme loading conditions. In pursuit of this goal, two full-scale residential buildings were monitored, which are the subject of this paper. Building *C* and Building *E* are located within a built-up terrain, are 218m and 206m tall, and have almost identical plan form as illustrated in Figure 1.

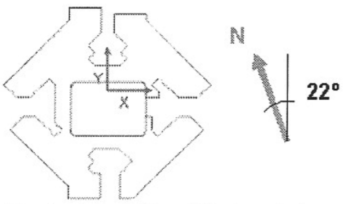

Figure 1: Typical Building Plan and Accelerometer Orientation

These buildings belong to a group of five buildings that are arranged in the configuration given in Figure 2.

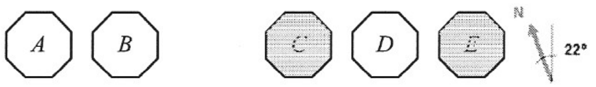

Figure 2: Tower Grouping Configuration

2.0 DATA COLLECTION

Dynamic building accelerations were measured using two orthogonally-mounted accelerometers. These devices were placed at the roof level above the highest occupied floor of each building inside the core of the structure. The input axes of the accelerometers denoted X and Y, were aligned with the core walls, as seen in Figure 1, and are approximately 112° and 22° clockwise from North, respectively.

Accompanying each accelerometer is a signal conditioning unit providing amplification and filtering of the output voltage signal. Records of the acceleration response of each building are stored on a dedicated PC equipped with a 16-bit A/D converter. The accelerometer signal output was sampled at 20 Hz and the sample length was 10 minutes.

3.0 WIND CHARACTERISTICS OF TYPHOONS IMBUDO & DUJUAN

Onsite restrictions prevented the installation of an anemometer on either building to measure the winds associated with Typhoon Imbudo and Typhoon Dujuan. Wind records were obtained from an anemometer located on Stonecutters Island, located to the west of the Kowloon peninsula approximately 3 km from the subject buildings, which generally reflects the overall wind characteristics affecting Buildings *C* and *E*. The propeller anemometer is supported on a mast 50m above ground with near-field topography consisting mostly of water to the southwest, stacked shipping containers to the north, and a 65m tall hill about 0.5 km to the east.

Typhoon Imbudo affected the weather of Hong Kong most severely from July 22 to July 24, 2003. During its passage, its lowest instantaneous mean sea-level pressure was recorded as 997.5 hPa, and caused the Hong Kong Observatory (HKO) to issue typhoon signals #8NE and #8SE [4]. Wind speed and direction were measured during Typhoon Imbudo and their time-histories can be seen in Figures 3 and 4. The maximum 10-minute mean wind speed was 17.0 m/s and the maximum 3-second gust wind speed was 27.3 m/s.

Typhoon Dujuan affected Hong Kong from September 1 to September 2, 2003 causing the HKO to raise typhoon signal #9. The lowest instantaneous mean sea-level pressure was 972.1 hPa [5]. Wind speed and direction were also measured during Typhoon Dujuan and their time-histories can be seen in Figures 5 and 6. The maximum 10-minute mean wind speed measured was 25.9 m/s and the maximum 3-second gust wind speed was 32.5 m/s.

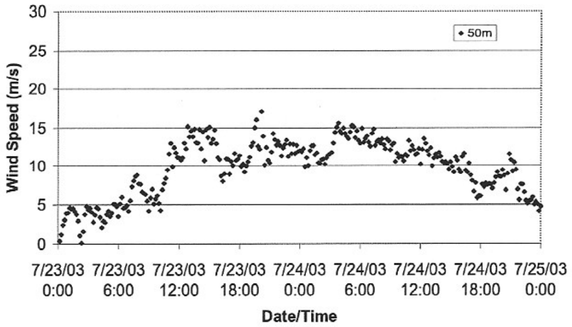

Figure 3: 10-minute Wind Speeds measured at Stonecutters Island during Typhoon Imbudo

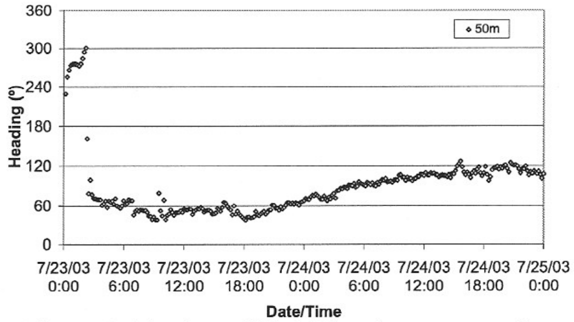

Figure 4: 10-minute Wind Directions measured at Stonecutters Island during Typhoon Imbudo

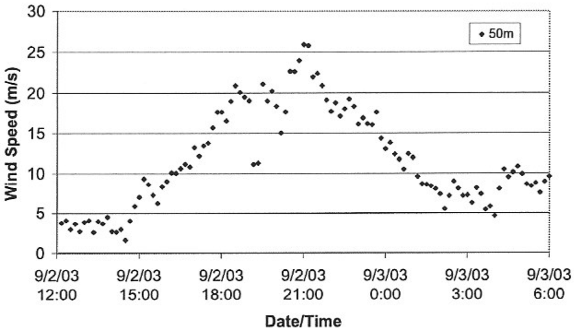

Figure 5: 10-minute Wind Speeds measured at Stonecutters Island during Typhoon Dujuan

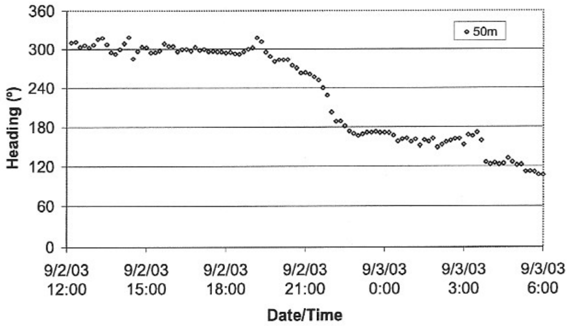

Figure 6: 10-minute Wind Directions measured at Stonecutters Island during Typhoon Dujuan

Because Typhoon Imbudo passed on the southerly side of Hong Kong, it generally caused northeasterly to southeasterly winds. Typhoon Dujuan, however, passed on the northerly side of Hong Kong and generally caused northwesterly to southwesterly winds.

4.0 WIND-INDUCED DYNAMIC BEHAVIOUR OF BUILDINGS *C* AND *E*

Although the stiffness (core) axes for both buildings are aligned approximately 45° to the geometric axes of the building structure, the wind-induced acceleration responses were found to be predominantly in the fundamental modes of vibration, which are aligned closely with the stiffness axes. It was also found that there was higher correlation between wind speed and acceleration response when the dominant wind direction was aligned close to the stiffness, rather than geometric, axes of the building.

When the 10-minute mean wind direction measured from Stonecutters Island coincided with the stiffness axes over the sectors 22° ± 30°, 112° ± 30°, 202° ± 30° and 292° ± 30°, acceleration data was plotted against the 10-minute mean wind speed. Acceleration data was resolved into components parallel to and orthogonal to these directions, which corresponded to responses in the alongwind and crosswind directions. It was necessary to assume that the measurements taken at Stonecutters Island generally reflect the wind conditions experienced at the site of the subject buildings. Peak resultant acceleration responses plotted against the 10-minute mean wind speeds of Typhoons Imbudo and Dujuan are given in Figures 7 and 8. Standard deviation (S.D.) acceleration responses in the alongwind and crosswind directions of Buildings *C* and *E* plotted against the 10-minute mean wind speeds from Typhoons Imbudo and Dujuan are presented in Figures 9 through 12.

It is seen that the acceleration responses of both Buildings *C* and *E* increased as the wind speed increased from the elevated winds caused by Typhoon Imbudo and Typhoon Dujuan. Shielding effects can be seen when comparing acceleration values in the 292° sector in Figures 7 and 8. Building *C* is more exposed resulting in higher peak resultant acceleration values than Building *E*, which is less exposed.

In general, the S.D. acceleration values in the alongwind and crosswind directions increase with increasing wind speed, seen in Figures 9 through 12. The alongwind and crosswind response of Building *C* is seen to be much larger than the responses of Building *E* for wind speeds in the 292° sector. This is attributed to Building *C* being more exposed to winds from this sector.

Overall, the behaviour of the buildings during Typhoon Imbudo and Typhoon Dujuan is complicated by the close proximity of adjacent buildings, which will be analyzed more systematically in a proposed wind tunnel study. Regardless, the inclusion of more data collected over the winter monsoon period will further characterize the responses of both buildings with regards to wind speed.

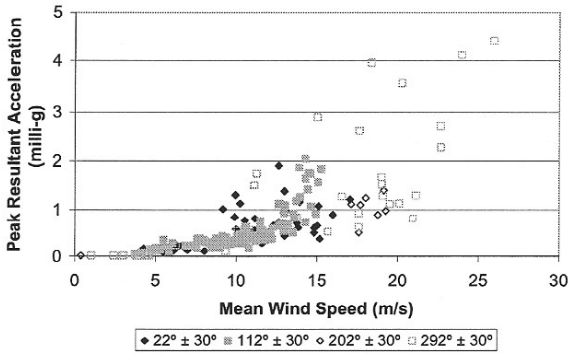

Figure 7: Building *C* Peak Resultant Accelerations

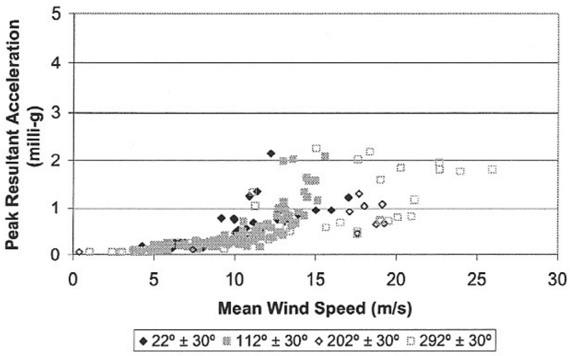

Figure 8: Building *E* Peak Resultant Accelerations

5.0 PEAK FACTORS OF WIND-INDUCED RESPONSE

The average peak wind-induced response ($\hat{x}$) of a building over a duration T may be conveyed as a function of the mean ($\bar{x}$), peak factor (g_f) and the standard deviation (σ_x) of the process (x), as shown in Equation (1) [6].

$$\hat{x} = \bar{x} + g_f \cdot \sigma_x \qquad (1)$$

From the statistical derivation of the peak acceleration, the peak factor may be approximated deterministically in the form given by Equation (2) under the assumption that the process is Gaussian. In this equation ν is the mean value crossing rate and T is the length of time over which the motion is recorded.

$$g_f = \sqrt{2\log_e \nu T} + \frac{0.5772}{\sqrt{2\log_e \nu T}} \qquad (2)$$

In practice, deviations from a Gaussian distribution can occur and their effect can help determine if there are changes in the excitation mechanism. Use of an upcrossing analysis [7] is appropriate for a narrow band response which, in this case, arises in majority from the fundamental mode of vibration.

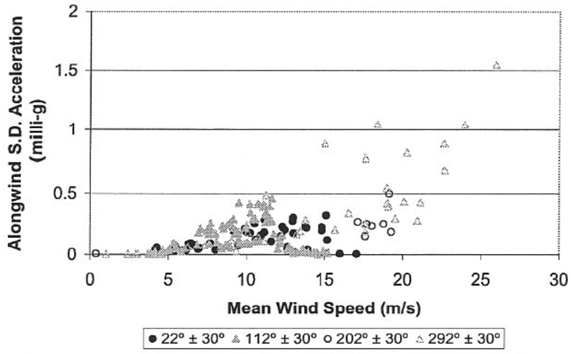

Figure 9: Building *C* Alongwind S.D. Accelerations

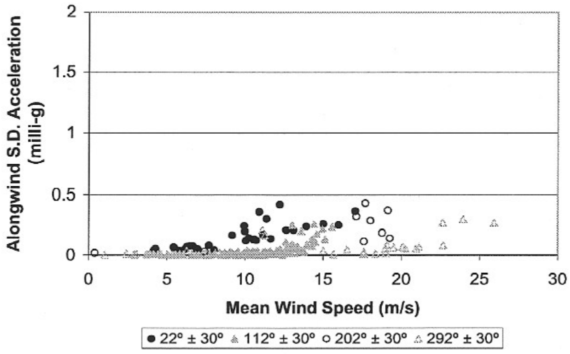

Figure 10: Building *E* Alongwind S.D. Accelerations

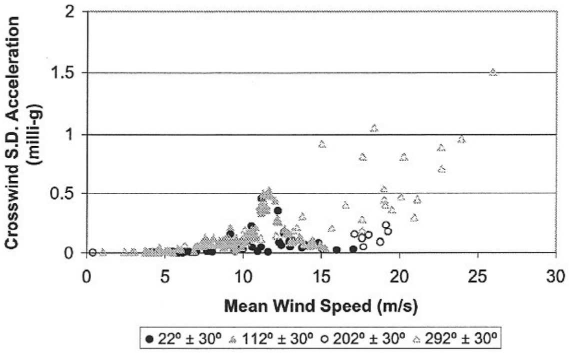

Figure 11: Building *C* Crosswind S.D. Accelerations

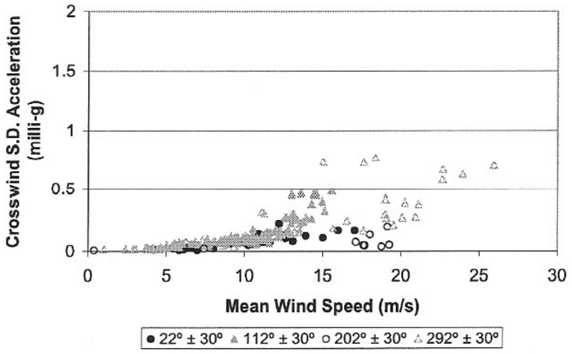

Figure 12: Building *E* Crosswind S.D. Accelerations

For a lightly damped dynamic system, such as that of a structure oscillating about its fundamental frequency, it may be more convenient to express probabilities of exceedence in terms of frequency, or upcrossings, than on a time basis. An upcrossing frequency of 1/200 defines the point at which the probability of a single maximum value exceeds a limiting value of once in 200 cycles on average, or approximately 10 minutes, based on the translational natural frequencies for Buildings *C* and *E*.

Analysis of peak factors during Typhoon Imbudo and Typhoon Dujuan show that the average values for both Building *C* and *E* are in agreement with the value predicted by Equation 2, as seen in Table 1. This suggests that turbulence buffeting is the dominant source of observed excitation [8]. The upcrossing analysis results in Table 1 demonstrate that the peak factors for Buildings *C* and *E* during both Typhoon Imbudo and Typhoon Dujuan are similar to that for a Gaussian process.

		Typhoon				
		Imbudo		Dujuan		Predicted: Equation 2
		X	Y	X	Y	
Building *C*	Mean	**3.5**	**3.3**	**3.5**	**3.4**	**3.4**
	S.D.	0.6	0.6	0.6	0.7	
Building *E*	Mean	**3.5**	**3.5**	**3.5**	**3.4**	
	S.D.	0.6	0.6	0.5	0.6	

Table 1: Calculated Peak Factors during Typhoon Imbudo and Typhoon Dujuan

6.0 CONCLUSIONS

The wind-induced behaviour of two high-rise residential buildings subject to Typhoon Imbudo and Typhoon Dujuan have been analyzed and presented. Wind records were recorded from the Stonecutters Island anemometer, approximately 3 km away from the subject buildings. Typhoon Imbudo had a maximum 10-minute mean wind speed of 17.0 m/s and a maximum 3-second gust wind speed of 27.3 m/s. Typhoon Dujuan had a maximum 10-minute mean wind speed of 25.9 m/s and a maximum 3-second gust wind speed of 32.5 m/s.

The acceleration responses were seen to correlate best with wind speed when aligned with the stiffness (core) axes of the building and generally increased with increasing wind speeds. A general trend of increasing response with increasing wind speed is observed. Some effects of shielding are observed for higher wind speeds. Peak factors, determined through an upcrossing analysis for those responses during Typhoon Imbudo and Typhoon Dujuan, suggest that the wind-induced dynamic behaviour of Buildings *C* and *E* followed a Gaussian process.

Suggested further work includes assimilating data recorded over the winter monsoon season to expand the data used in relating dynamic building acceleration to wind speeds. As well, an aeroelastic wind tunnel study will be performed to assess responses in a more-controlled environment. Furthermore, a topographical study correlating the measurements taken from Stonecutters Island to those experienced by the buildings would be informative.

7.0 ACKNOWLEDGMENTS

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