Wind Tunnel Study of Peak Wind Pressure on Government Towers in Wanchai during Typhoon York 1999

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In this paper, we report some wind tunnel testing results of peak wind pressure on the building façade of the three government towers in Wanchai North. The emphasis is on the distributions of peak external wind pressure. A number of regions of amplified peak wind pressure or suction are found on some building faces. Occurrence of these high pressure regions is explained from the strong interference effect on these towers which are placed in close proximity with one another and with other neighbouring buildings. We attempt to correlate these localised regions of high wind pressure or suction to the locations of curtain wall breakage on the towers during the passage of Typhoon York in 1999. In spite of the imperfect correlation and many uncertainties connected with the prediction of actual cladding loads and behaviours during the typhoon, we show that a significant portion of cladding failure is found in regions of high peak wind pressure caused by building interference. It is thus important to assess interference effect and the resulting regions of amplified wind pressure for a safe design of façade cladding.

Keywords: Wind Pressure, Interference Effect, Wind Tunnel Tests

Introduction

Typhoon York is the latest typhoon necessitating the hoisting of Typhoon Signal No 10 in Hong Kong. The previous Signal No 10 was issued back in 1983 due to Typhoon Ellen. The eye of York was closest to the Hong Kong Observatory Headquarters around 10 am on 16 September 1999 when it passed about 20 km to the south-southwest. A maximum hourly wind speed of 42 m/s and a maximum gust wind speed of 65 m/s were recorded at Waglan Island. This gust speed is the highest recorded at Waglan. One notable wind damage of York is the shattering of many curtain walls on the high-rise commercial buildings in Wanchai North. The three government towers, namely, Revenue Tower, Immigration Tower and Wanchai Tower, suffered most with failure of more than 400 pieces of glass curtain wall cladding.

Post-event studies were carried out by Architectural Services Department, Hong Kong Government to investigate the causes of cladding failure on the three towers. These included the commissioning of a wind tunnel of study to estimate the peak wind pressure on the building façade during the passage of Typhoon York. The wind tunnel study which was carried by Rowan Williams Davies and Irwin Inc (RWDI) in Canada reported a number of findings (Garber et al 2003). The highest gradient mean wind speed during Typhoon York was estimated at 45 to 50 m/s, which is significantly lower than the code of 64 m/s in the Hong Kong Wind Code 1983 (BD 1983, Choi 1983). The peak combined wind pressure on the cladding, assuming an internal pressure at −0.6 kPa to +0.15 kPa for no dominant openings on the façade, were estimated to range between −2.25 kPa and +1.51 kPa. These pressure values were within the Code values which apparently had been used for cladding design of the three towers. This led to the conclusion that wind pressure alone was unlikely to cause initial failure of the cladding. It was suggested in the wind tunnel study report that flying debris was the culprit to cladding failure. The report also proposed that during the time of most curtain wall failure, wind is blowing roughly from the north and wind incident on the three towers had previously passed Grand Hyatt Hotel, Convention Plaza and Renaissance Harbour View Hotel on its path (Fig 1). However, the report admitted that the sources of wind-borne debris remained unknown.

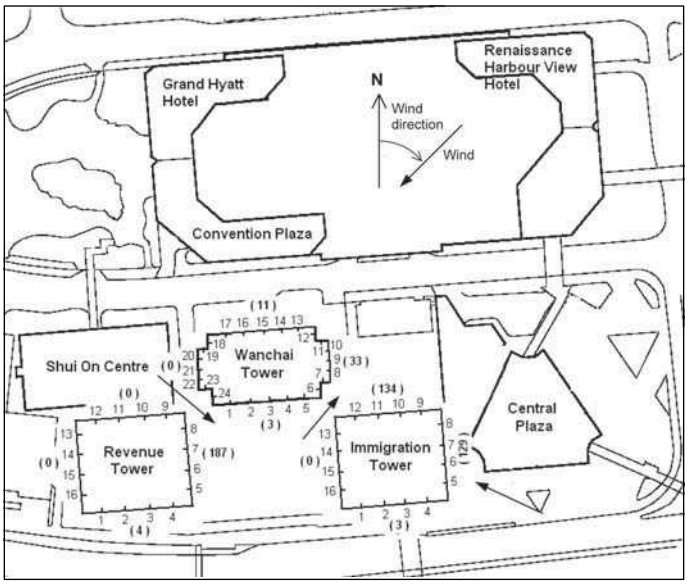


Figure 1 – Pressure Tap Locations on Towers. Number of Curtain Wall Breakage on Each Building Face Indicated inside Brackets. Critical Wind Direction for Each Tower Shown: 115°; 220°; 310°

While it has been accepted by most wind engineers interested in this event that cladding failure on the three towers was most likely caused by wind-borne debris, the authors are in the opinion that the close proximity of the three towers and the surrounding tall buildings is likely to result in strong building interference effects, leading to unusually high wind pressure and wind suction on the building façade (Khanduri et al 1998). To the best of our knowledge, wind tunnel testing was not carried out in the original design of the towers and design wind pressure for the cladding was very likely based on the Hong Kong Wind Code 1983 in which no building interference effects are considered. This paper reports results of another wind tunnel test carried by us on the three towers. Our objective is to investigate the distribution of peak wind pressure on the

façade of the three towers and to correlate the distribution pattern with the actual locations of cladding failure. The emphasis is on the effect of wind pressure alone without the consideration of flying debris. We do not intend to discuss the role of wind-borne debris but rather limit the investigation to the wind pressure distribution and discussion on the significance of building interference effects.

Wind Tunnel Experiment

The experiments were carried out in the boundary layer wind tunnel of the Department of Civil Engineering at the University of Hong Kong. The size of test section was 3.0 m wide and 1.8 m tall. Triangular spires at the entrance of test section and 8 m long fetch of floor roughness elements were used to simulate wind conditions of the general terrain of Hong Kong Wind Code 1983 (BD 1983) at a scale 1:300. Fig 2 shows the simulated and target profiles of mean wind speed and turbulence intensity. Models of all buildings in Wanchai North area bounded by Convention Avenue, Fleming Road, Jaffe Road and Fenwick Street were built at the same scale and included in the wind tunnel tests (Fig 1).

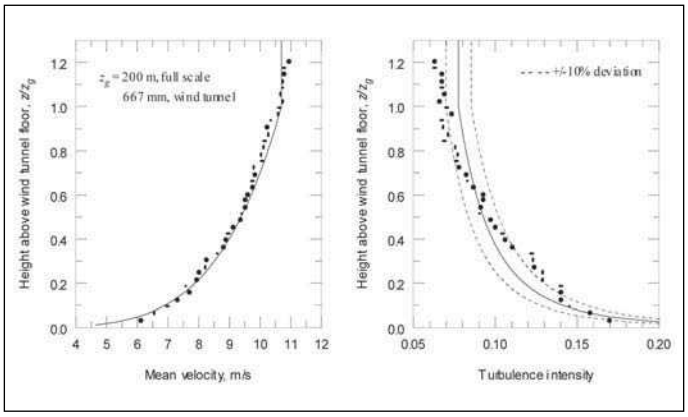


Figure 2 – Wind Characteristics in Wind Tunnel: Mean Wind Speed Profile and Turbulence Intensity Profile. Lines: Hong Kong Code (1983); Symbols: Wind Tunnel Measurement

Pressure taps were installed on models of the three government towers. Fig 1 shows the arrangement and numbering of taps on the plan forms of the buildings. Both Revenue Tower and Immigration Tower were 174 m tall and had plan forms which are almost rectangular. Each of these two pressure models had pressure taps installed on 12 levels along the building height. At each level, there were 16 pressure taps installed, four on each wall of the building. Wanchai Tower had a lower height at 124 m and in plan form, the four corners were recessed. Pressure taps were installed on 8 vertical levels and on each levels there were 24 taps. On the north or south face, there were 5 taps while the east or west face had 7 taps including those inside the recessed corners.

Pressures at the pressure tap locations were measured with pressure transducers through pressure tubing and mechanical scanners. Each wind pressure was measured at a sampling rate of 100 Hz for one minute. Tests were carried out at a wind tunnel speed at about 12 m/s at the upper level. Translating to a full-scale wind speed at about 60 m/s, the pressure measurements corresponded to a full-scale period of one hour and at about 1 second gust resolution. Peak wind pressure was calculated using the peak-value estimation method of Peterka (1983). Compass directions were used to denote the wind incident angles and tests were carried out at 24 wind directions at 15° intervals.

Full-scale Peak Exterior Wind Pressure

Peak wind pressure measured on the wind tunnel models can be converted to prototype values corresponding to an appropriate full-scale wind speed. In Hong Kong Wind Code 1983, the 50-year return wind speeds are adopted as the design wind speed. The mean wind speed is 64 m/s at gradient height and the gust wind speed is 74.9 m/s (Choi 1983). According to records of Hong Kong Observatory, the highest mean hourly wind speed recorded at Waglan Island during the passage of Typhoon York was 42 m/s. The maximum hourly gust wind speed was 65 m/s and this is the highest ever recorded at Waglan. The anemometer at the top of Central Plaza recorded a maximum hourly mean wind speed at 37 m/s and maximum gust at 55 m/s. The wind tunnel study report of RWDI used the mean wind speed data at Central Plaza to deduce that the highest gradient mean wind speed in the Wanchai North area during Typhoon York was about 45 to 50 m/s, with some directional variation (Garber et al 2003). It was also suggested that the wind speeds were well below the value of 64 m/s used in Hong Kong Wind Code 1983.

In this paper, we choose to convert the wind pressure data in the wind tunnel to full-scale value corresponding to the condition of gradient mean wind speed at 64 m/s for the following reasons. The main aim of the study is to investigate the distribution pattern of peak wind pressure and to note those critical areas of building façade exposed to very high wind pressure or wind suction. It is the relative values rather than the exact values of wind pressure that are important. Peak wind pressure is more related to the peak gust wind speed than the hourly mean wind speed. However, it is the commonly accepted method in wind tunnel testing to synthesis peak wind pressure based on a constant hourly mean wind speed. This is based on the assumption of a stationary wind loading process in which a correct simulation of the turbulence intensity or the gust-to-mean wind speed ratio is important in accurate estimation of peak wind pressure. Simulation of wind characteristics in our wind tunnel is targeted at the wind characteristics in Hong Kong Wind Code 1983. For the general terrain in the Code, at a height of 90 m, that is the corrected anemometer height at Waglan Island, the 50-year mean wind speed and gust wind speed are 55.0 and 67.2 m/s respectively (Choi 1983). The gust factor, that is the ratio between gust and mean wind speed is thus 1.22. At heights above 200 m, which is the chosen gradient height, the design mean wind speed and gust wind speed are 64.0 and 74.9 m/s, giving a gust factor at 1.11. On the other hand, the wind records during Typhoon York show a gust ratio factor at 1.55 at Waglan and 1.49 at Central Plaza. This may suggest that the gust factor during the passage of York was higher than the value implied in the Code, and very likely higher than the value simulated in the wind tunnel tests as well. Therefore, synthesis of full-scale wind pressure using a full-scale mean wind speed at 45 to 50 m/s, as in the study by RWDI (Garber et al 2003), may not be able to simulate accurately the peak wind pressure which was due to wind gusts with a gust factor higher than expected. Our choice of 64 m/s as the mean wind speed may produce more realistic peak wind estimation. We are further assured by noting that in the drafting of Hong Kong Wind Code 2004, Typhoon York was considered producing winds at 50-year return (BD 2004). It is also worth noting that the actual peak gust wind speed recorded at Waglan during the passage of Typhoon York was 65 m/s which was close to the Code value.

Assuming the same peak pressure coefficient between prototype and model, full-scale peak exterior wind pressure, $\hat{p}_p$, on building façade of the three towers experienced during Typhoon York is obtained from the peak wind pressure on the wind tunnel model, $\hat{p}_m$, as:

$$\hat{p}_p = \hat{p}_m \times \left(\frac{64 \text{ m/s}}{\overline{V}_m} \right)^2$$

where $\overline{V}_m$ is the upper-level mean wind speed in the wind tunnel. This is only the exterior wind pressure on the building façade and the net wind pressure acting on the curtain wall cladding is the combination of this exterior pressure and the internal pressure. We have not carried out a rigorous study on the internal pressure. The study of RWDI suggested values of internal pressure allowances ranging between −0.6 kPa to +0.15 kPa. This is for the case of no dominant opening on the building envelope corresponding to the time before any breakage of glass curtain wall panels. This internal pressure which is assumed to be due to uniform air leakage through the building envelope depends to a certain extent the pressure distribution on the building envelope.

Results and Discussion

Among the three towers, the building face which suffered the most severe cladding failure was the east face of Revenue Tower. A total of 187 pieces of glass cladding were broken (Fig 1). Fig 3 shows the distribution of the highest peak wind pressure experienced by Revenue Tower at all pressure tap locations over all wind angles. In our analysis, we do not consider any directional variation of wind speeds and one value of full-scale gradient mean wind speed at 64 m/s is used for all wind directions. The highest peak wind pressure data shown in Fig 3 are simply the largest (or lowest) value among the data at the 24 wind angles tested. The design wind pressure values recommended in Hong Kong Wind Code 1983 are also plotted in this and subsequent figures. They are based on 50-year return design gust wind speeds and pressure coefficients at values of +1.0 for windward building faces and −1.0 for leeward and side faces. For suction (negative) wind pressure on the edge zones of the leeward and side faces, the pressure coefficient is increased to −1.4. These three profiles of peak wind pressure are plotted in Fig 3. We are not aware of any wind tunnel test carried out during the initial design of the three towers. We believe that the cladding design had been based on these simple peak wind pressure profiles or the peak pressure values at the roof height.

In spite of all the uncertainties concerning actual wind speeds during Typhoon York and actual pressure values using in the initial design, the simple comparison made in Fig 3 shows some meaningful observations. It is evident that the highest positive peak wind pressure on all locations is below the design curve except at some low-level locations very near to the ground. In the 1983 version of the Code, the design pressure decreases towards the ground in the same way as the wind speed. The 2004 version of the Code provides a lower zone where the wind pressure ceases to decrease at heights below one building breadth (BD 2004). Our results support the improvement made in the 2004 version. As for the peak negative wind pressure (peak suction), Fig 3 shows that the wind tunnel values exceed the Code values at a number of locations on all four faces. This occurs not only at tap locations inside the side edge zones of the building faces (solid symbols in Fig 3) but also in the inner zones of the faces (open symbols). The east face of the tower, in particular, experiences the highest suction pressure. The suction at all the four tap locations, no 5 - 8, is much higher than the Code values, especially at middle and lower levels of the tower. Fig 4 shows a photograph of the cladding damage on the east face of Revenue Tower. Although a majority of the total 187 damaged cladding was clustered on the higher-level northern edge of the east face, scattered damages were found on the entire east face. When we analysis the peak wind



Figure 4 – Breakage of Curtain Walls on East Face of Revenue Tower

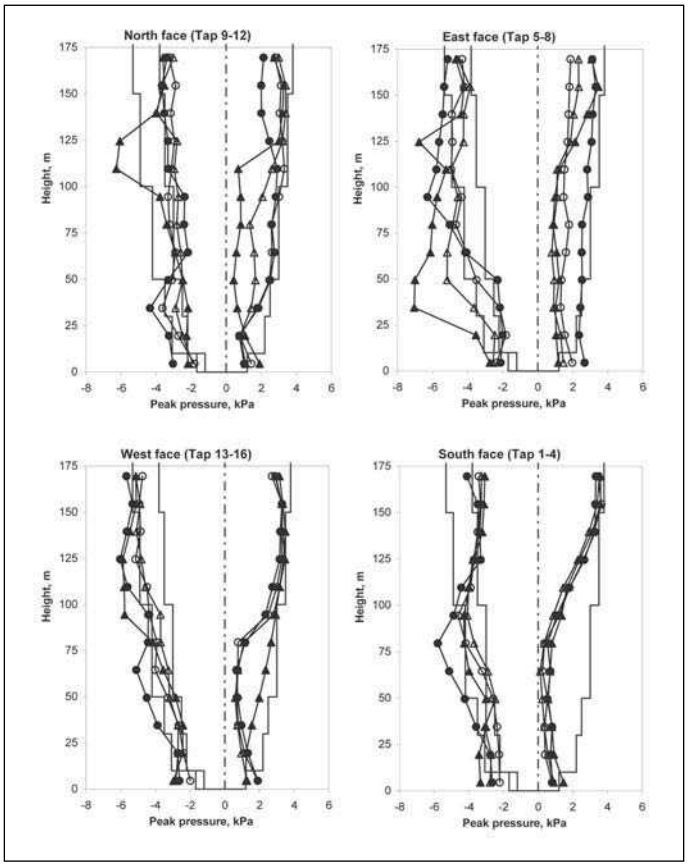


Figure 3 – All-angle Largest Peak Maximum and Minimum Wind Pressure on Four Faces of Revenue Tower. Symbols: {●, ○, △, ▲} for Tap No {1, 2, 3, 4}; {5, 6, 7, 8}, {9, 10, 11, 12} or {13, 14, 15, 16}

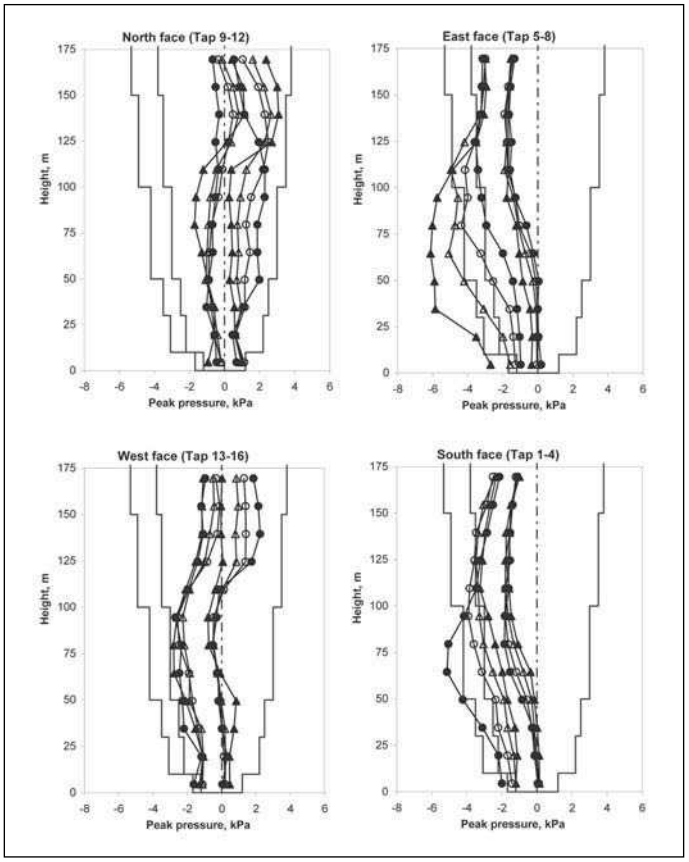


Figure 5 – Distribution of Peak Maximum and Minimum Wind Pressure on Four Faces of Revenue Tower at Wind Direction 310°. Symbols: {●, ○, △, ▲} for Tap No {1, 2, 3, 4}; {5, 6, 7, 8}, {9, 10, 11, 12} or {13, 14, 15, 16}

pressure at different wind incident angles, we find that the largest wind suction on the east face occurs at wind direction around NNW (310°). Fig 5 shows that distribution of peak (maximum and minimum) wind pressure at the wind angle 310°. At this wind direction, wind is channeled to flow through the gap between Revenue Tower and Wanchai Tower at high speeds (Fig 1). This explains the occurrence of the high suction on the east face, especially at tap no 8 which is nearest to the flow separation at the northeast corner. Wanchai Tower has a lower height and the flow channeling effect is limited to the middle and lower levels of Revenue Tower. On the upper levels, high positive pressure is found on the north and west windward faces of the tower. In case of initial breakage of some cladding, adverse internal pressure effect may develop inside the building on the upper levels.

In terms of the total number of breakage, Immigration Tower suffered most. Its north and east face each had over 100 pieces of curtain walls damaged. Distributions of the all-angle largest peak positive and negative wind pressure on four faces of the tower are shown in Fig 6. The photograph in Fig 7a shows the damage on the east face. Many panels were broken near the location of tap no 5 on all levels with slightly more breakage at lower levels. It is observed in Fig 6 that high peak positive pressure is found at tap no 5. The values almost reach the Code values at the upper levels and on the lower levels, they exceed the Code values. The largest peak positive pressure on tap no 5 occurs at wind direction 115° and the wind pressure distributions at this wind angle are shown in Fig 8. It is interesting to note that tap no 5 alone experiences very high positive pressure while all the other three building faces are under negative wind pressure. Even on the east face, the next two tap locations have much lower peak positive wind pressure and tap no 8 on the other end of the east face even has negative pressure all the time. This wind pressure distribution is obviously due to the presence of Central Plaza in the upwind position (Fig 1). We have not measured internal pressure but with the assumption of uniform air leakage through the building façade, the internal pressure inside the tower should have

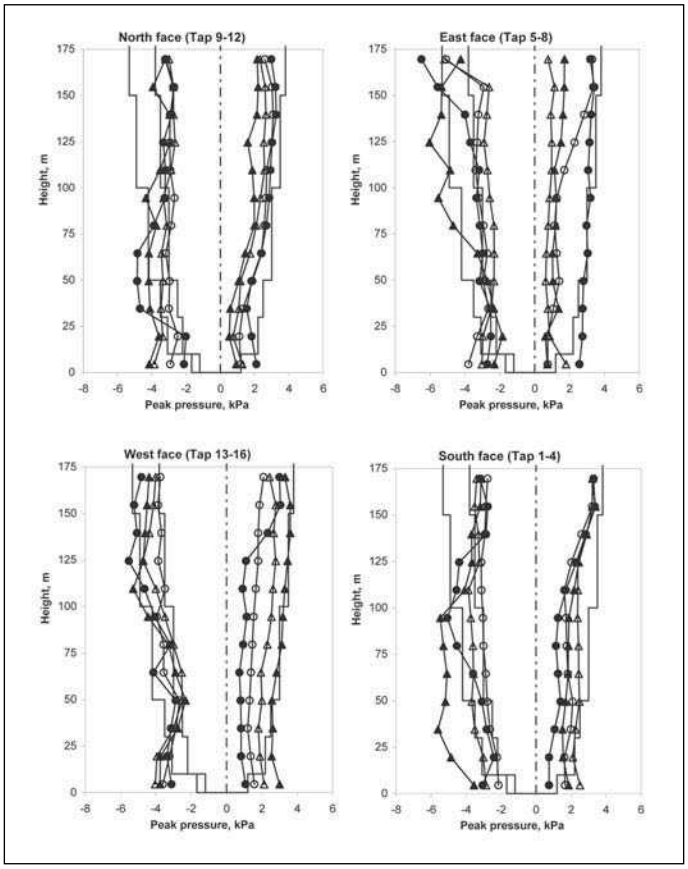


Figure 6 – All-angle Largest Peak Maximum and Minimum Wind Pressure on Four Faces of Immigration Tower. Symbols: {●, ○, △, ▲} for Tap No {1, 2, 3, 4}; {5, 6, 7, 8}, {9, 10, 11, 12} or {13, 14, 15, 16}

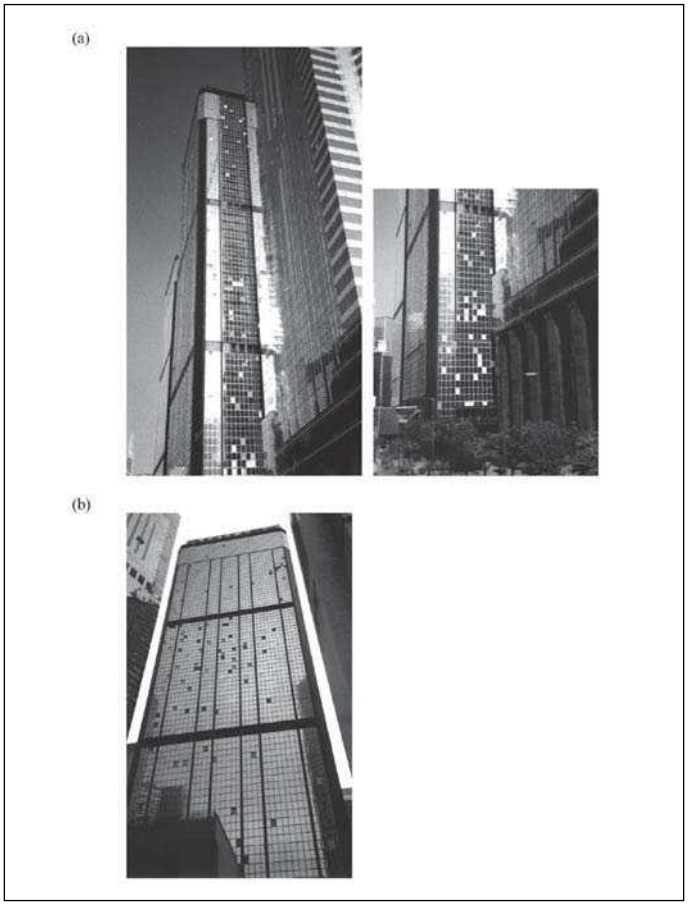


Figure 7 – Breakage of Curtain Walls of Immigration Tower: (a) East Face; (b) North Face

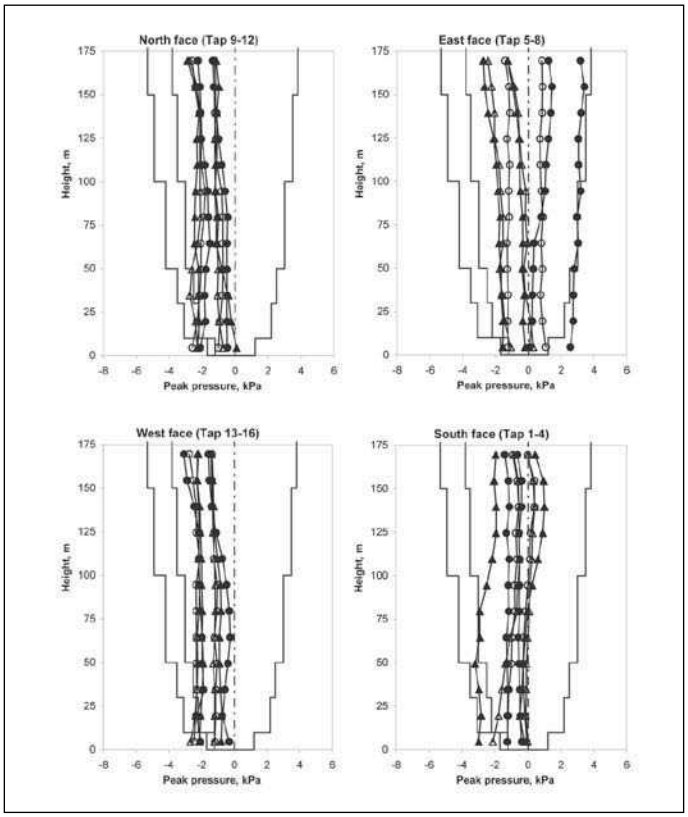


Figure 8 – Distribution of Peak Maximum and Minimum Wind Pressure on Four Faces of Immigration Tower at Wind Direction 115°. Symbols: {●, ○, △, ▲} for Tap No {1, 2, 3, 4}; {5, 6, 7, 8}, {9, 10, 11, 12} or {13, 14, 15, 16}

a value close to the average exterior wind pressure. This means that at wind direction 115°, the internal pressure is likely to have quite high a negative value. The south edge of the east face (tap no 5) is thus under a combined wind pressure significantly higher than the Code values and probably the design values.

On the north face of Immigration Tower, Fig 7(b) shows that cladding failure occurs quite evenly on all parts of the face with slightly more breakage on the eastern half and on the middle levels. The all-angle largest peak wind pressure distribution on Fig 6 shows that tap no 9 experiences the most severe wind suction at lower levels. Actually at middle and lower levels, all the four tap locations have largest peak suction slightly exceeding the Code values. Comparing with the other three faces, taps on this north face additionally experience high peak positive pressure which occurs at other wind angles. Analysis of the pressure data shows that the largest positive wind pressure on the north face of Immigration Tower occurs at wind direction around 0°, that is wind from the north and the largest wind suction occurs due to flow separation when wind blows from the east, that is at wind angle around 90°.

The third tower, Wanchai Tower, experienced a relatively smaller number of breakage, including 11 breakage on its north face and 33 breakage on its east face. Fig 9 shows the distribution of all-angle largest peak wind pressure on its four faces. Unlike the other two towers with flat faces, the east and west faces of Wanchai Tower have recesses at the corners (Fig 1). Tap no 6 and 7 inside the recessed region of the east face experience very high peak negative pressure. This correlates well with the locations of cladding failure as shown in the photograph of Fig 10. These high suction pressure occurs at wind angle 220° and the wind pressure distributions at this wind angle is shown in Fig 11. Wind blowing from the southwest is channeled to flow fast through the narrow gap between Wanchai Tower and Immigration Tower. Intense flow separation occurring at the eastern edge of the south face (between tap no 5 and 6) is believed to cause the high suction pressure at tap no 6 and 7 (Fig 1).

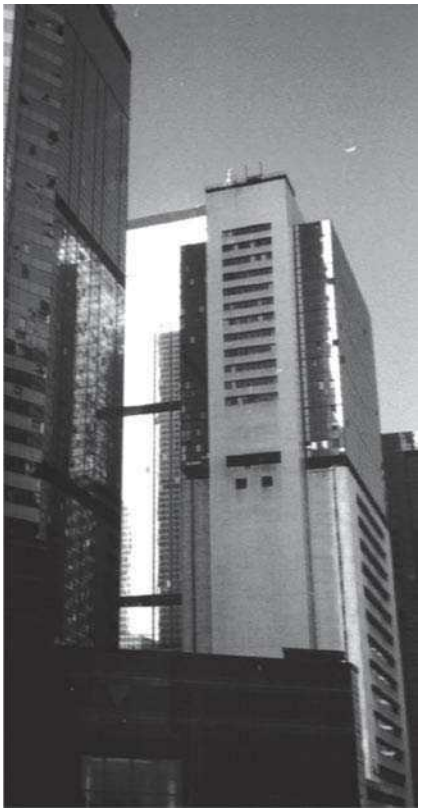


Figure 10 – Breakage of Curtain Walls on East Face of Wanchai Tower

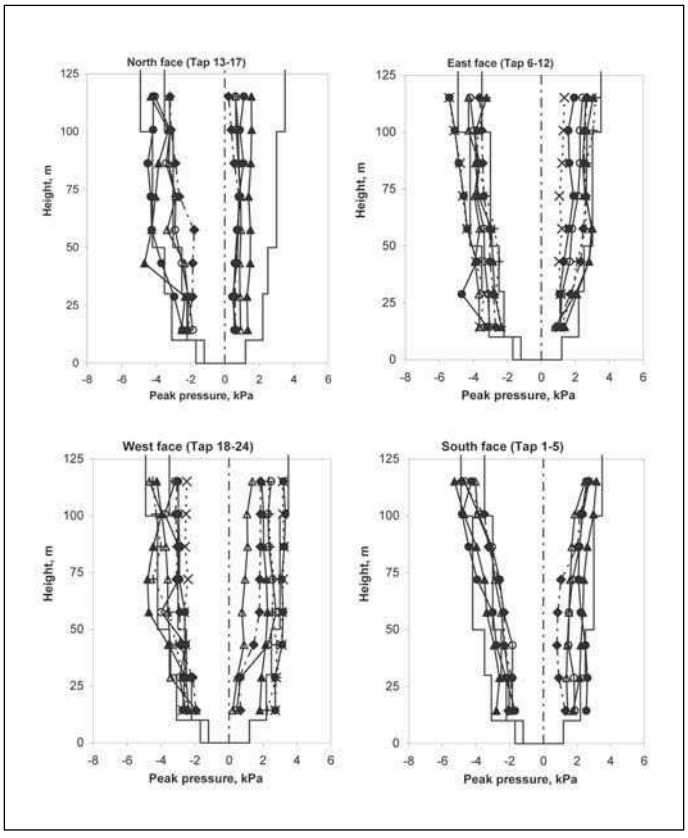


Figure 9 – All-angle Largest Peak Maximum and Minimum Wind Pressure on Four Faces of Wanchai Tower. Symbols: {●, ○, ◆, △, ▲} for Tap No {1, 2, 3, 4, 5} or {13, 14, 15, 16, 17}; {●, ×, ○, ◆, △, +, ▲} for Tap No {6, 7, 8, 9, 10, 11, 12} or {18, 19, 20, 21, 22, 23, 24}

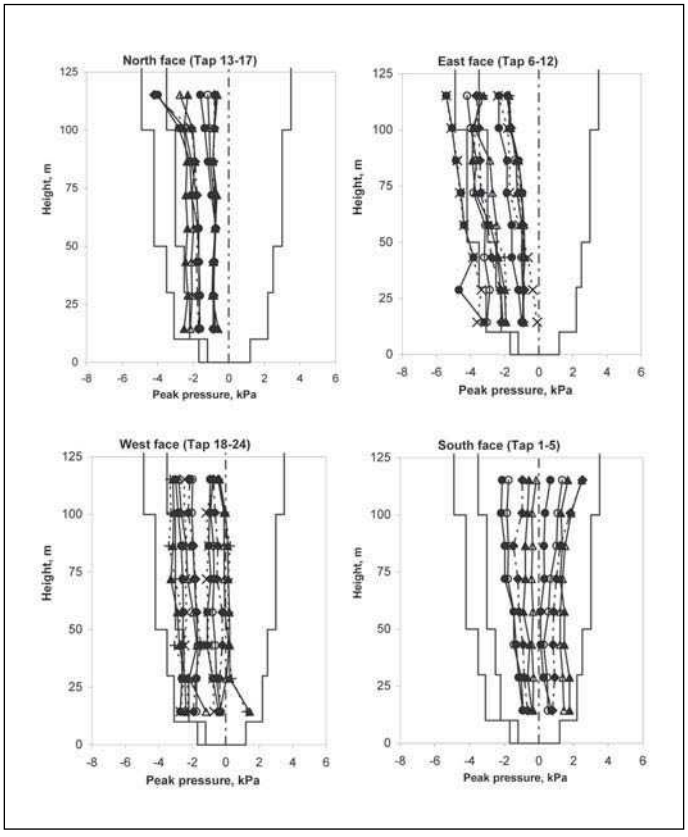


Figure 11 – Distribution of Peak Maximum and Minimum Wind Pressure on Four Faces of Wanchai Tower at Wind Direction 220°. Symbols: {●, ○, ◆, △, ▲} for Tap No {1, 2, 3, 4, 5} or {13, 14, 15, 16, 17}; {●, ×, ○, ◆, △, +, ▲} for Tap No {6, 7, 8, 9, 10, 11, 12} or {18, 19, 20, 21, 22, 23, 24}

Conclusions

In this paper, we study the distribution of peak wind pressure on building faces of the three government towers in Wanchai North using wind tunnel models. The results show that amplified levels of peak positive and negative wind pressure are found on some parts of the building façade as a result of strong interference effect caused by the close proximity of the towers and with the neighbouring buildings. Some degree of correlation is found between the location of these local regions of high wind pressure or suction and the location of curtain wall breakage during the passage of Typhoon York.

There are a number of uncertainties in a more rigorous estimation of the actual wind pressure experienced by the building façade during the typhoon and the cladding failure mechanisms. Actual wind speeds recorded by the anemometer on Central Plaza during the typhoon suggested wind speeds significantly lower than the 50-year design wind speed in the 1983 version of Hong Kong Wind Code and that the mean wind speed changes with wind direction. However, the maximum gust wind recorded at Waglan Island is close to the 50-year return value. The role of internal pressure is important but is difficult to estimate from wind tunnel tests. There is no knowledge on the actual design cladding pressure used in the initial design of the towers. In this paper, we do not intend or attempt to address these and other uncertainties. Instead, we simply assume a full-scale mean wind speed equal to the 50-year return wind speed implied in Hong Kong Wind Code 1983 at all wind angles and convert the wind tunnel peak pressure values to this full-scale condition. We focus on the locations of the highest peak wind pressure or suction and attempt to explain their occurrence from building interference effect.

The study demonstrates the importance of building interference effect on the generation of amplified peak wind pressure and suction on the building façade even for these towers of simple building shapes. For a future building, these localised high pressure or suction regions can be roughly predicted with the knowledge of interference effect but precise locations of the critical regions and the wind pressure levels can only be confidently found from wind tunnel tests. In the global change of increasing stronger typhoons, wind tunnel tests of cladding pressure becomes more important to safeguard buildings with breakable cladding and curtain walls.

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