10th Australasian Wind Engineering Society Workshop
February 2003, Sydney

Wind Effects in Urban Environment - with Particular Reference to the Design of Tall Buildings and Structures

K C S Kwok

CLP Power Wind/Wave Tunnel Facility
The Hong Kong University of Science and Technology

1. BACKGROUND

In Hong Kong where easily build on land is in short supply due to its complex hilly terrain and there is a population of 7 millions and growing, the vast majority of its population by necessity live and work in high-rise buildings. Hong Kong is also situated in an active typhoon region where the wind load associated with a conservative design wind speed governs the design of all buildings and other civil infrastructures in terms of safety and strength. The current wind loading code, Code of Practice on Wind Effects Hong Kong – 1983, is in the process of a major revision to bring it more inline with current best practice in wind resistant design, based on recent advances in structural dynamics and wind engineering.

Wind tunnel model testing has been an invaluable tool in the design of many tall buildings and structures, ranging from super tall signature buildings to large-scale housing projects. The predicted design wind loads (including shear forces and base moments) and wind-induced responses (including deflections and accelerations) are very dependent on the predicted natural frequencies of vibration and particularly damping values. Despite significant advances in numerical modelling of structures using finite element methods, uncertainties remain in the prediction of the natural frequencies of vibration and particularly the damping values. These uncertainties can be critical in the prediction of the design wind loads and building performance in terms of motion perception and occupant comfort assessment. As a precaution, some of the new generation of tall and super buildings are designed with expensive and large damping devices to minimise perceptible motion and satisfy occupant comfort requirements. Considerable research efforts are needed to achieve a better understanding of the mechanisms that affect the dynamic behaviour of tall buildings, and in particular the structural damping value. Furthermore, much more research efforts in the long-term monitoring of tall building performance (deflections and accelerations) under wind actions are needed to collect reliable full-scale data of actual building deflection and acceleration responses to verify predictions based on wind tunnel model tests.

Hong Kong, with its modern infrastructures and large number of tall buildings and structures, and its vulnerability to strong winds associated with typhoons, is an ideal place to study the wind effects on buildings and structures. A number of research groups in different universities in Hong Kong are actively involved in wind engineering research with relatively generous government funding and well-equipped test facilities including wind tunnels. This paper describes some of the wind engineering research currently underway at the Hong Kong University of Science and Technology (HKUST), with particular reference to the design of tall buildings and structures.

2. WIND TUNNEL MODEL STUDIES

The tremendous growth in research and testing activities in the field of wind engineering during the past thirty years have resulted in significant advances in the understanding of wind effects on buildings and structures. Many of these research findings have been incorporated in wind loading design codes, including the Hong Kong wind code currently being revised. However, due to the complexity of wind/structure interaction, evolution of design concepts, introduction of new material and the significance of meteorological input, wind tunnel model tests will continue to play an important role in the design of modern buildings and structures. Hong Kong, with its many tall buildings, complex topography, typhoon dominated wind climate and a growing expectation of superior building performance, has increasingly relied on wind tunnel model testing technology for the wind resistant design of tall buildings, including both signature tall buildings and large-scale housing projects. Many wind tunnel laboratories from all the over the world, including those from Australia, Canada, China, UK and USA, have contributed to meet this increase in demand for wind tunnel testing services.

A state-of-the-art boundary layer wind/wave tunnel, the CLP Power Wind/Wave Tunnel Facility (WWTF) as shown in Fig. 1, has been in operation at HKUST since mid-2000 (Kwok and Hitchcock, 2001). The Facility was built to address the need, both locally and regionally, for an advanced testing laboratory to conduct wind related teaching and research, and to serve the engineering and construction industry. It is equipped for studying building aerodynamic response, cladding and structural pressures, pedestrian level wind environment, dispersion of pollutant gases, and other wind-related problems. Further details on the test capability can be obtained from the Facility's website: http://www.ust.hk/~webwwtf. On-going research projects for the wind tunnel include:

- Interference excitation of tall buildings with complex geometry and mode shape
- Aerodynamic treatment of tall buildings
- Effects of complex topography on Hong Kong wind climate
- Aerodynamics of long-span bridges
- Vibration control of wind-excited tall buildings

Other related research projects include:

- Evaluation of motion perception and occupant comfort based on motion simulator experiments
- Measurements of dynamic properties of tall buildings
- Long-term monitoring of wind-induced response of tall buildings

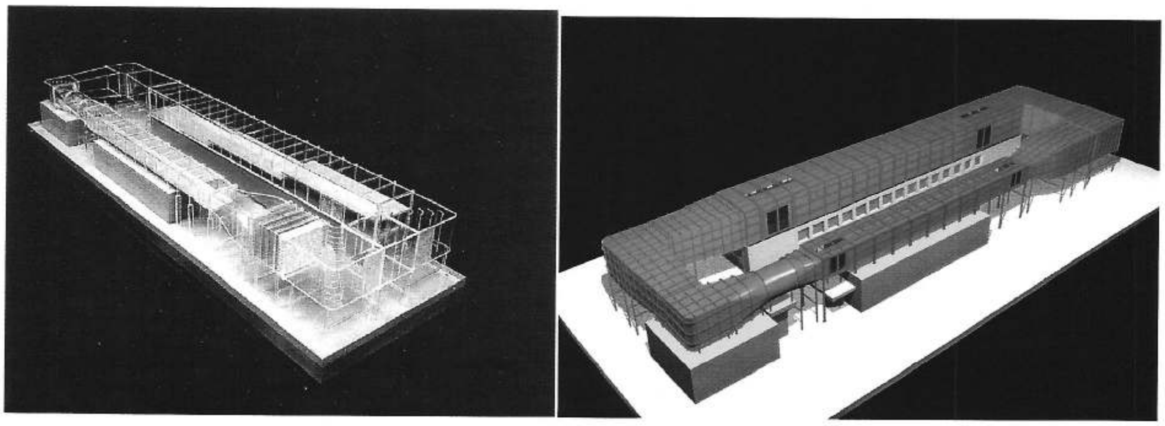

Fig. 1 Layout of the CLP Power Wind/Wave Tunnel Facility

In addition to the wind tunnel facility at HKUST, the University of Hong Kong operates a boundary layer wind tunnel for many years and the City University of Hong Kong has commissioned the design of a boundary layer wind tunnel in late 2002, apparently with a blockage tolerant test section. The Hong Kong Polytechnic University also has a research group actively involved in wind engineering research, notably in bridge and cable aerodynamics.

3. DESIGN FOR TYPHOONS IN HONG KONG

The Code of Practice on Wind Effects Hong Kong – 1983, currently governs the wind resistant design of all buildings and structures in Hong Kong. The wind code is published by the Building Department (previously the Building Authority), which is also the approving body for almost all buildings and structures. The format of the code, the calculation procedure and the various coefficients and constants are mostly adopted from the British Standard BS CP 3: Chapter V: Part 2: 1972. The Building Department also published a Practice Note for Authorized Persons and Registered Structural Engineers, PNAP 150 - 1994, to provide guidance to wind tunnel model testing of buildings, which have increasingly been employed for the design of tall buildings and structures in Hong Kong.

The most contentious specification of the Hong Kong wind code and PNAP 150 is a mean hourly design wind speed of 64 m/s at the gradient height, which is assumed to be at 250 m above ground for a general terrain and at 300 m for a built-up terrain. There have been considerable debates in the past twenty years over the validity of such a high design wind speed at these heights, with quite a number of publications devoted specifically to this topic, for examples Davenport et al. (1984), and Melbourne (1984). More recently a comprehensive study of the Hong Kong wind climate and the effects of topography has been undertaken based on a 1:400 scale model study of the flow field around Waglan Island and a 1:2000 scale topographic model of Hong Kong (Hitchcock et al., 2001, and Kwok and Hitchcock, 2001). Typhoon wind record collected at Waglan Island up to 1999 was also analysed using a peak over threshold approach (Holmes et al., 2001). The results of these recent studies reinforce the early findings of Davenport et al. (1984) and Melbourne (1984) that the 50-year return period mean wind speed is much less than the value suggested in PNAP 150 for heights of 200m~300m. Recent results of a typhoon wind study for Hong Kong based on computer simulation using the wind field model and the radius to maximum winds model proposed by Vickery et al. (2000a, 2000b) also suggested significantly lower upper level (500m) design wind speeds.

An ad hoc committee was formed in early 1990s by the Building Department to revise the Hong Kong wind code, in consultation with local practising engineering consultants and government departments. A Draft Revision was compiled in 1996, which incorporated many modifications based on advances in the past decades in the understanding of wind characteristics and dynamic effects of wind on structures, but this was never released publicly. The latest Draft Revision 2002 is currently undergoing a public review process. More recent inputs were considered in producing the latest Draft Revision, particularly in the following areas:

- Wind velocity and turbulence profiles for typhoons.
- Design wind speed.
- Dynamic effects, both alongwind and crosswind, for wind sensitive structures.
- Topographical effects.
- Guidelines on wind tunnel model studies.

The latest Draft Revision is definitely a step in the right direction in modernising the Hong Kong wind code to bring it more inline with current best practise in wind resistant design of tall buildings and structures.

4. FIELD MEASUREMENTS ON TALL BUILDINGS AND STRUCTURES

Virtually all the studies conducted so far on the behaviour of actual buildings under wind actions have been for landmark "one-off" buildings and structures. These works are invaluable to those specific buildings and also provide general information regarding wind excitation and response of tall buildings and structures.

In order to meet the high demands for housing from the 7 million populations in Hong Kong, hundreds of high-rise residential buildings are being built each year. These buildings range from luxuriously appointed apartment buildings exceeding 250m in height, to more affordable mass housing designed by the Hong Kong Housing Authority. These new generations of residential high-rise buildings are the subjects of a research project, which aims to:

1. Measure the dynamic characteristics of the buildings, including natural frequencies of vibration, mode shapes, and damping values.
2. Study the performance of the buildings under strong wind action.
3. Survey occupant perception of motion and comfort in the buildings under strong wind conditions.
4. Examine the adequacy of the current wind resistant design approaches of codes of practice in Hong Kong for tall buildings.

The results from these studies are expected to produce a useful database of dynamic properties of tall buildings to validate numerical modelling techniques and generalised predictive processes. The results will also provide a better understanding of the performance of tall buildings under strong wind conditions. This knowledge will facilitate optimisation of tall building design, in terms of safety, strength and occupant comfort, and may deliver significant cost savings in the construction of tall buildings, particularly those mass housing projects in Hong Kong.

4.1 Measurements of dynamic properties of tall buildings and structures

Various techniques have been successfully employed to excite different types of structures from which the resultant vibrations are analysed to identify their dynamic characteristics. For substantial structures such as tall buildings, a relatively large force is generally needed to excite the structure to vibrate at a level detectable by conventional instrumentation. The tower crane commonly used during the construction of tall buildings is a convenient mechanical shaker to excite a building to facilitate dynamic measurements. While the natural frequencies of vibration can be readily determined from very small but detectable vibration, the small load capacity of a construction crane, compared with the mass of a large tall building, often makes it difficult to transfer a sufficiently large and sustained force onto the test building to attain a large enough deflection amplitude to measure the damping decay accurately. In Hong Kong and many other countries where there are stringent safety requirements, the use of crane excitation for measurement purposes has yet to be attempted.

A variable-speed (frequency) mechanical shaker, such as an eccentric mass shaker, can concentrate input energy at a range of fixed frequencies and hence is an ideal tool to excite a building to vibrate at the fundamental mode and any higher modes of interest. This is also a reliable method to determine the damping values, and any amplitude effect on damping, by analysing the free vibration decay for desired amplitude of vibration and a desired frequency. The design and fabrication cost of a mechanical shaker is not prohibitively expensive and is readily justified by the quality of the measured data. A uni-directional mechanical shaker, based on a high precision, computer-controlled, servomotor driven ball-screw mechanism and a payload of up to 1 tonne, is being fabricated at HKUST. The load capacity and range of excitation frequencies of the shaker are designed to excite the vast majority of buildings and structures to detectable amplitude of vibration.

Forces of nature such as minor tremors, earthquakes and winds are convenient sources of large magnitude ambient excitations to which all buildings and structures respond. However, tremors and earthquakes are prevalent in only clusters of earthquake prone regions, and their occurrences are unpredictable and have short duration only. In contrast, winds of any strength are regular occurrences and are reliable sources of excitation, particularly for Hong Kong.

With an experienced team, synchronised human excitation is a simple and quick method to excite a building to facilitate the measurement of the dynamic characteristics. This technique has been successfully employed for measurements on light-weight structures such as light towers and lattice structures (e.g. Glanville et al., 1996), more substantial structures such as airport control towers (e.g. Kwok et al., 2000), and buildings up to 32 storey high (Denoon et al., 1998; Rooney, 2002). For more massive structures such as tall buildings, typically up to twelve people are assembled for the shakedown tests. The team of "shakers" is lined up along a long wall, such as an external wall or a lift foyer wall, on the level at which the sensors are located. Each individual performs synchronised "push-ups" against the wall, prompted by using a metronome set close to the natural frequency of the building along the direction of force application. The building vibration builds up progressively as each push-up is applied, until the vibration reaches a level (usually after 15 to 20 cycles of push-ups) clearly measurable by the sensors, which is usually displayed continuously by a chart-recorder and/or an oscilloscope. Upon a simultaneous cessation of the push-ups, the building vibration is allowed to decay naturally, from which the frequency of vibration and damping value can be accurately determined.

Preliminary measurements have been taken on a group of residential tall buildings approximately 110 m in height (38 storeys) and with a crucifix cross-section, which is a standard building design adopted by many property developers including the Hong Kong Housing Authority. The natural frequencies of vibration and damping values were determined using both the wind excitation and synchronised human excitation approaches. Figure 2 shows a typical acceleration record and the corresponding acceleration spectrum for the test building under wind excitation. Figure 3 shows a typical building vibration build-up and decay curve obtained by using the synchronised human excitation method with a team of six "shakers". Generally, the translational natural frequencies, at between 0.7 Hz to 0.8 Hz, were higher than expected, suggesting the buildings are structurally very stiff. This is largely due to the current stringent requirements in Hong Kong for the wind resistant design of tall buildings to withstand a 50 year return period gradient height design mean wind speed of 64 m/s, and partly because of the design requirement to restrict maximum lateral deflection to not exceeding 1/500 of the building height (CPSUC-1987). The damping value is of the order of 0.8 % of critical damping, which is within the range expected for tall buildings undergoing low amplitude vibration. Measurements taken at the corner of the building revealed a torsional natural frequency of approximately 0.64 Hz, which is lower than the translational natural frequencies, largely due to the structural system adopted to link the four building wings to the central core.

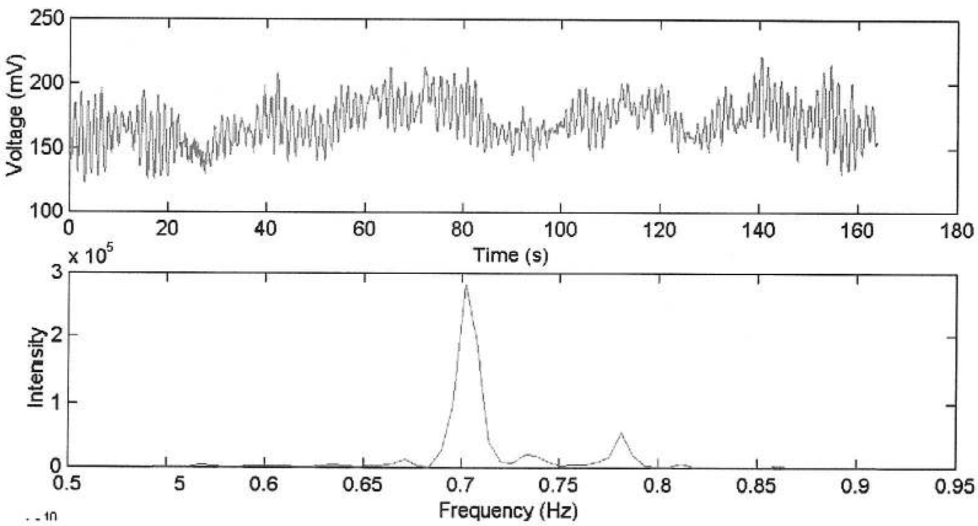

Figure 2. Building acceleration trace and spectrum under wind excitation

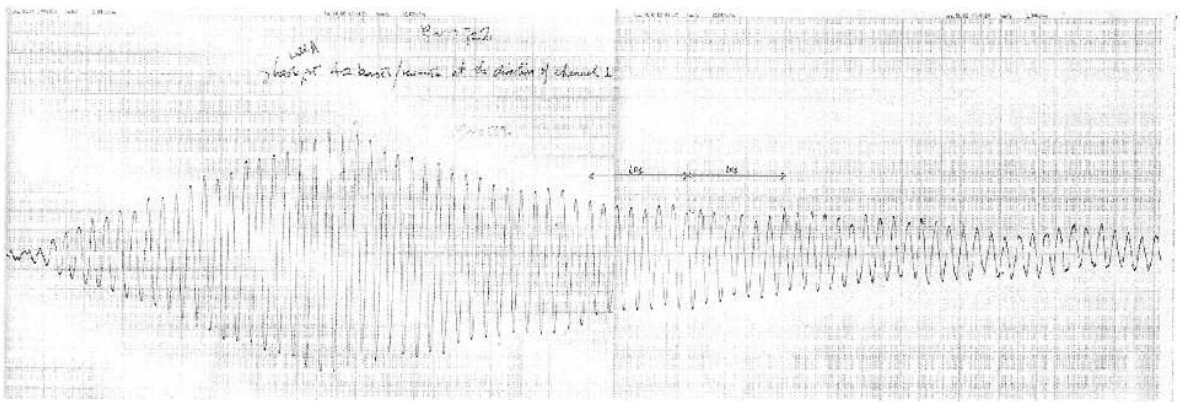

Figure 3. Building vibration build-up and decay curve obtained by synchronised human excitation

4.2 Long-term monitoring of tall building vibrations under strong winds

A number of landmark tall buildings and structures have been the subject of long-term monitoring after their completion to assess their behaviour under wind actions, and where possible to compare with wind tunnel model test results. Significant improvements in instrumentation, data collection and processing techniques have facilitated a better in-depth investigation of the behaviour of actual tall buildings under wind actions. However, more studies are needed to verify predictions based on wind tunnel model tests.

An extensive program of measurements on some well-known landmark tall buildings has been conducted in Hong Kong during 1990's (Li et al., 1998). These measurements included the wind climate of Hong Kong and the dynamic characteristics of the tall buildings. More recently reported are results of full-scale measurements on the 384m tall Di Wang Tower in Shenzhen, China, during Typhoon Sam which made landfall near Hong Kong and Shenzhen in September 1999 (Xu et al., 2000).

Advances in GPS technology in the last decade have made available a powerful instrument for precision positioning of, and deflection measurement on, structures. Recent measurements by Tamura et al. (2001) and Breuer et al. (2002), based on extensive dynamic calibrations and monitoring of the wind-induced response of steel towers and an industrial chimney under light winds, showed that GPS can be used to measure wind-induced building displacements reliably in real-time and with an accuracy within approximately ±10mm. Chen et al. (2001) also employed GPS technology to monitor the vibration of the 384 m tall Di Wang Building in Shenzhen, China. Despite the attractiveness and effectiveness of GPS, care needs to be taken in the siting of the equipment, data processing and analysis to minimise and correct for errors caused by clock errors, satellite orbital errors, atmospheric effects and most importantly multi-path effect caused by adjacent reflective surfaces.

Agreement has been reached to initiate a long-term monitoring program for a major high-rise residential development in Kowloon, which comprises of five buildings ranging in height from 200m to 250m. Both conventional accelerometers and GPS will be utilised in the measurement program. Negotiations are in progress for other long-term monitoring programs involving the newer non-standard residential high-rise buildings designed by the Hong Kong Housing Authority, most of which underwent wind tunnel model studies, and the Macau Tower studied by Holmes (2000).

5. ACKNOWLEDGEMENTS

The authors are indebted to the many building owners and managers for their kind permissions for access to the buildings tested, and for the provision of space and facilities, without which this work would not have been possible. Special thanks go to past and present students and colleagues at the Department of Civil Engineering, University of Sydney, and at the CLP Power Wind/Wave Wind Tunnel Facility, Hong Kong University of Science and Technology who have assisted in many ways, in particular Drs Roy Denoon, Matthew Glanville, Peter Hitchcock and Graeme Wood. The research project currently underway in Hong Kong is funded by the Research Grants Council of Hong Kong (Project HKUST6222/01E).

6. REFERENCES

Breuer, P., Chimielewski, T., Gorski, P. and Konopka, E., (2002), "Application of GPS technology to measurements of displacement of high-rise structures due to weak winds", Journal of Wind Engineering and Industrial aerodynamics, 90, 223-230.

British Standard BS CP 3: Chapter V: Part 2: 1972.

Chen, Y.Q., Huang, D.F., Ding, X.L., Xu, Y.L. and Ko, J.M. (2001), "Measurement of vibrations of tall buildings with GPS: A case study", Proceedings of International Symposium on NDE for Health Monitoring and Diagnostics, Newport Beach, California, USA, 477-483.

Code of Practice for the Structural Use of Concrete-1987, Building Authority, Hong Kong.

Code of Practice on Wind Effects Hong Kong-1983, Building Authority, Hong Kong.

Davenport, A.G., Georgiou, P.N., Mikitiuk, M., Surry, D. and Kythe, G. (1984), "The wind climate of Hong Kong", Proceedings of 3rd International Conference on Tall Buildings, Hong Kong and Guangzhou, pp. 454-460.

Denoon, R.O., Wood, G.S., Hitchcock, P.A. and Kwok, K.C.S. (1998), "Full-scale measurement of dynamic characteristics of an apartment block during construction", Proceedings of Australasian Structural Engineering Conference, Auckland, 501-505.

Glanville, M.J., Kwok, K.C.S. and Denoon, R.O. (1996), "Full-scale damping measurements of structures in Australia", Journal of Wind Engineering and Industrial Aerodynamics, 59, 349-364.

Hitchcock, P.A., Chim, K-S, Kwok, K.C.S. and Yu, C.W. (2001), "Non-typhoon wind conditions at Hong Kong Waglan Island", Proceedings of Australasian Wind Engineering Society 9th Workshop on Wind Engineering, Townsville, Australia July.

Holmes, J.D., (2002), "Wind loads on the Macau Tower – Application of the Effective Static Load Approach", Proceedings of 1st International Symposium on Wind and Structures, Cheju, Korea, January, pp. 81-89.

Holmes, J.D., Hitchcock, P., Kwok, K.C.S. and Chim, J. (2001), "Re-analysis of Hong Kong typhoon wind speeds using the 'peaks over threshold' approach", Proceedings of 5th Asia-Pacific Conference on Wind Engineering, Kyoto, Journal of Wind Engineering, No. 89, October, pp. 165-168.

Kwok, K.C.S. and Hitchcock, P.A. (2001), "Wind tunnel model testing at the CLP Power Wind/Wave Tunnel Facility (WWTF)", Proceedings of International Conference on Construction, Hong Kong, June, Vol. 2, pp. 74-82.

Kwok, K.C.S. and Hitchcock, P.A. (2001), "Designing for typhoons in Hong Kong", Proceedings of 5th Asia Pacific Conference in Wind Engineering, Kyoto, Journal of Wind Engineering, No. 89, October, pp. 689-692.

Kwok, K.C.S., Denoon, R.O. and Letchford, C.W. (2000), "Towards a better understanding of the wind-induced response of towers: Field measurements", Proceedings of 1st International Symposium on Wind and Structures for the 21st Century, Cheju, Korea, 99-114.

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

Melbourne, W.H. (1984), "Design wind data for Hong Kong and surrounding coastline, Proceedings of 3rd International Conference on Tall Buildings, Hong Kong and Guangzhou, pp. 461-467.

Practice Note for Authorised Persons and Registered Structural Engineers PNAP 150 – 1994, Building Authority, Hong Kong.

Rooney, D. (2002), "Imperfect models", Civil Engineers Australia, March, pp. 39-40.

Suda, K., Satake, N., Ono, J., and Sasaki, A. (1996), "Damping properties of buildings in Japan", Journal of Wind Engineering and Industrial Aerodynamics, 59, pp. 383-392.

Tamura, Y., Suda, K. and Sasaki, A. (2000), "Damping in buildings for wind resistant design", Proceedings of 1st International Symposium on Wind and Structures for the 21st Century, Cheju, Korea, 115-131.

Vickery, P.J, Skerlj, P.F., Steckley, A.C. and Twisdale, L.A., (2000a), "Hurricane wind field model for use in hurricane simulation", ASCE Journal of Structural Engineering, Vol. 126, No. 10, pp. 1203-1221.

Vickery, P.J, Skerlj, P.F. and Twisdale, L.A., (2000b), "Simulation of hurricane risk in the U.S. using Empirical track model", ASCE Journal of Structural Engineering, Vol. 126, No. 10, pp. 1222-1237.

Xu, Y.L., Zhan, S. and Ko, J.M. (2000) "Effects of Typhoon Sam on Di Wang Tower: Field measurement", HKIE Transactions, 7(2), 41-48.