SERVICEABILITY ACCELERATION CRITERIA FOR TALL BUILDINGS IN HONG KONG

Roy Denoon
Ove Arup & Partners Hong Kong Ltd.

Introduction

Hong Kong has a very high density of tall buildings, both residential and commercial. Many of these tall buildings are very slender due to space limitations. The location of Hong Kong in a tropical cyclone region adds interest to designing for serviceability accelerations. This paper describes current practice in wind engineering in Hong Kong, with specific reference to designing for serviceability accelerations and proposes a rational framework for the assessment of wind-induced motions in Hong Kong buildings.

Current Practice In Hong Kong Wind Engineering

The current Hong Kong wind code dates from 1983 and does not take account of dynamic effects, instead relying on what are seen as conservative design pressures and an assumption of fully correlated gust loading. The code itself recognises its limitations, recommending wind tunnel testing for buildings of 'unusual shape' or potential dynamic sensitivity. However, the wording is very loose, and many tall buildings are designed to this code.

The design of all buildings and structures is subject to government authority checking before building approvals are granted. This is generally conducted by the Buildings Department, who are also responsible for the wind loading code and the document describing requirements for wind tunnel testing, PNAP150. These documents specify a gradient height hourly mean wind speed of 64 ms^{-1} that must be used in all wind tunnel testing for design loads. However, gradient height may be adjusted through topographical wind tunnel modelling, this having a significant effect on wind speeds at normal building heights at many locations in Hong Kong. It is generally accepted that 64 ms^{-1} is a conservative value of gradient height hourly mean wind speed for a 50 year return period.

However, Buildings Department does not generally interest itself in serviceability accelerations and these can be calculated on the basis of best estimate wind speeds and directionality. Although there is a good deal of agreement on the wind speeds at surface level in Hong Kong during typhoons, there is much less agreement on the upper level wind speeds which may be more appropriate to the design of some of the taller buildings in Hong Kong. Clearly, this is the first issue to be resolved in the prediction of wind-induced building motion.

International serviceability acceleration design practice

The three most common codified design approaches used world-wide are the Canadian National Building Code of 1995, the Japanese AIJ Recommendations 1991, and ISO6897-1984. A number of variants on these are also in common use (Isyumov 1995, P.A. Irwin 1998, Melbourne & Palmer 1992).

National Building Code of Canada 1995

The User's Guide to NBCC-1995 contains a very simple approach to assessment of acceptability of wind-induced serviceability accelerations in buildings.

"...a tentative acceleration limit of 1 to 3% of gravity once every 10 years is recommended......the lower value might be considered appropriate for apartment buildings, the higher value for office buildings."

This approach does not take into account frequency dependence of perception or discomfort. The range of frequencies for which wind-sensitive structures are designed varies from below 0.1 Hz to well over 1.0 Hz. Almost all laboratory studies of motion perception in this frequency range have found evidence of frequency dependence (e.g. Irwin 1981, Goto 1975, Kanda et al. 1994).

The range of acceptable peak accelerations from 10 to 30 milli-g is very wide. The difference between 10 and 30 milli-g in terms of human comfort is very large, as anyone who has ever experienced such accelerations will attest. These criteria are intended for use with code estimations of dynamic response, which the text notes tend "to give conservative results" and suggests that the "designer who has more detailed information available can make suitable allowances."

The single 10 year return period acceleration criteria does not allow provision for separate assessment of the magnitude of motion during extreme wind events and the magnitude of motion during regularly occurring wind events. It does not, thus, adequately address the issues of both fear and annoyance.

Architectural Institute of Japan Recommendations (1991)

The AIJ Recommendations (1991) give four frequency dependent curves for perception and acceptability levels for a one year return period. Curves H1 and H4 correspond to the minimum and average perception thresholds respectively. Curves H2 and H3 are serviceability acceleration design curves for residential and office buildings respectively.

From 0.2 to 1.0 Hz, the gradients of the curves are largely based on ISO6897-1984 and Kanda et al. (1988). The acceleration magnitudes are based partially on field experiments and adjusted on the basis of field experiences (Tamura 2000). However, setting the annual return acceleration criteria below the average threshold of perception seems curious, although the average perception thresholds proposed are above the values found at the locations studied in this thesis. Again, buildings are classified into residential and office usages.

The use of a one year return period acceleration criterion is likely to reflect regularly occurring motion events better than the ten year return period used in the Canadian Code. It may not, however, give an assessment of the likely fear and alarm during extreme events with longer return periods. This should be particularly important in Japan, which is located in a tropical cyclone region.

ISO6897-1984 Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures to low-frequency horizontal motion (0.063 to 1 Hz)

The ISO6897-1984 recommendations are the most commonly used criteria in Australasia and Europe. This standard includes suggested magnitudes for 5 year return accelerations for buildings used for general purposes and for off-shore structures. Minimum and average perception thresholds are also presented.

The figures in ISO6897-1984 were derived from different sources. The perception threshold data were largely derived from simulator experiments using sinusoidal motion, while the acceptability curves were derived from field experience (Irwin 1999). All the curves are presented in terms of r.m.s. accelerations, the acceptability curves being for the worst 10 minutes of a once in five year storm. Because the perception curves are largely based on sinusoidal motion, they overestimate the amplitude of motion at which perception occurs in the field because of the much smaller peak factor ($\sqrt{2}$) of sinusoidal motion compared with random motion in the field (≈ 3.5).

ISO6897-1984 does not classify buildings into residential and commercial but does recommend that acceleration levels in sensitive buildings, such as hospitals, should remain below the minimum perception threshold presented. The curve for off-shore structures is based on amplitudes inducing nausea or interfering with activity.

This is the most convincing of the acceptability design approaches, as it is based on a large amount of field data. It is based on avoidance of fear and alarm, but does not account for dissatisfaction resulting from frequent occurrence of perceptible motion.

Summary of strengths and deficiencies of current design approaches

The Canadian Building Code (1995) acceleration limitations have little to recommend them as they fail to address such basic items as frequency dependence and are so open that they give little guidance to the designer as to the acceleration magnitudes likely to cause complaints among building occupants. The AIJ (1991) recommendations are an advance on the Canadian approach as they recognise frequency dependence and the importance of accelerations with a more regular occurrence. The ISO6897-1984 guidelines are potentially the most justifiable as they are based on field experiences of a large number of buildings in which complaints occurred.

The acceleration criteria that are most commonly recognised in Hong Kong are the NBCC guidelines of 10 to 30 milli-g peak acceleration for a 10 year return period. This is, in no small part, due to the influence of the North American wind tunnel laboratories in the region. In addition to this, some laboratories also quote ISO6897, adjusting for 1 and 10 year return periods, and for peak accelerations. However, there is also a tendency on the part of some to apply factors of around 0.7 to the ISO6897 recommendations when they are employed for residential buildings.

Issues in Designing for Wind-induced Motion in Hong Kong

There are a number of issues that must be considered when designing for serviceability accelerations in Hong Kong. These include consideration of Hong Kong's wind climate, the type of buildings found in Hong Kong, and Hong Kong residents' reactions to wind-induced motion.

The Hong Kong Wind Climate

Denoon (2000) identified two causes of dissatisfaction with wind-induced motion among building occupants: fear and alarm generated from large building motions; and annoyance resulting from frequently perceptible motion. With the exception of typhoons, Hong Kong has a mild wind climate, and this indicates that the principal design consideration must be designing for fear and alarm. Occupant fear about wind-induced building motion in at least one building during Typhoon York led to the occupants evacuating their apartments. This has the potential for danger to occupants if they leave the building during severe typhoons. Although this is an extreme example, it does highlight the need for careful serviceability acceleration design. The Typhoon 10 signal, which is the highest warning level, has been hoisted on average once every 3 or 4 years since 1946. This is probably as good an indicator as any of the typical return period accelerations that should be designed for.

Hong Kong Building Types

Hong Kong contains large numbers of high-rise buildings, encompassing both residential and office buildings. During severe typhoons, commercial buildings are evacuated while residential buildings are almost fully occupied. It makes sense to have more lenient criteria for buildings that will be evacuated during windstorms. In this case, the primary design criterion may be ensuring remaining occupant safety by avoiding any interruption to walking.

Hong Kong also contains some very slender, but relatively short, tall buildings that are susceptible to wind-induced motion. Most of these are in the densely built-up areas of Hong Kong Island where space is at a premium. The reclamation work by the waterfront has also opened up possibilities for extremely tall buildings with much larger floorplates. There is, thus, a great range of building natural frequencies to design for. Almost all studies of perception and tolerance to wind-induced building motion have shown frequency dependence, and this should be accounted for in the design criteria adopted. Clearly, if a set of criteria suitable for a building with a natural frequency of 1 Hz are applied to a building with a natural frequency of 0.1 Hz, a very conservative design would result.

Habituation to, and education about, wind-induced building motion

The concept of wind-induced tall building motion during typhoons is well known in Hong Kong. Correspondingly, it could be expected that a lower level of fear and alarm might result from such motions. This is consistent with the findings of Denoon (2000) that showed that fear and alarm diminished with education and habituation to wind-induced building motion. In Hong Kong, there are a number of warning signals during typhoons with actions associated with them. Planned education about building motion during severe typhoon events should be achievable.

Torsional motion

There are a number of high-rise residential projects currently being built in Hong Kong that are relatively long and thin. A large proportion of the motion at the extremities of the upper floors results from torsional motion. However, because the buildings are long and thin, the torsional velocity is quite low. In cases such as these, the torsional component may be added as a component of translational acceleration and compared to translational acceleration guidelines in the usual way. However, this raises the question of at which location in the tower should these be assessed? This depends very much on the nature of the development, and the views of the developer. Translational acceleration guidelines were developed on the premise that acceleration was equal over the top floor of the building, and were based on an assumption of an acceptable complaint rate. On this basis, it would seem reasonable to spatially average the acceleration over the top floor. However, this would not take account of the fact that the most expensive apartments are at the ends of the building. Clearly, some flexibility and judgement is required.

Recommendations

Although the NBCC guidelines are the most commonly used set of criteria in Hong Kong, they do not reflect the aspects of designing in a typhoon wind climate for a wide range of natural frequencies. The ISO6897 recommendations recognise the importance of frequency dependence and are based on the concept of fear and alarm among building occupants. Noting that the Hong Kong engineering community is fairly conservative in its approach to acceleration design criteria, it is recommended that the ISO6897 recommendations are adopted as the standard design criteria for Hong Kong, but adapted to reflect peak accelerations (Melbourne & Cheung 1988). The five year return period of ISO6897 is fairly consistent with the return period of the highest classification of typhoon affecting Hong Kong.

References

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

Buildings Department, Hong Kong 1994, 'Practice Note for Authorized Persons and Registered Structural Engineers – Wind Tunnel Testing of Buildings'.

Denoon, R.O. 2000, 'Designing for serviceability accelerations in tall buildings', PhD thesis, The University of Queensland.

Goto, T. 1975, 'Research on Vibration Criteria from the Viewpoint of People Living in High-Rise Buildings (Part 1) Various Responses of Humans to Motion', *Nippon Kenchiku Gakkai Rombun Hokoku-Shu*, vol. 237, no. 11, pp. 109-118.

Goto, T., Okhuma, T., Tamura, Y. and Nakamura, O. 1992, 'Guidelines for the evaluation of habitability to building vibration. Part II: AIJ recommendations, 1991.', *Structures Congress '92*, Compact Papers, ASCE, San Antonio, USA, 13-15 April 1992, pp. 484-487.

International Organization for Standardization 1984, *Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0,063 to 1 Hz) ISO 6897:1984,* International Organization for Standardization, Geneva, Switzerland.

Irwin, A.W. 1981, 'Perception, Comfort and Performance Criteria for Human Beings Exposed to Whole Body Vibration and Vibration Containing Yaw and Translational Components', *Journal of Sound and Vibration*, vol. 76, no. 4, pp. 481-497.

Irwin, P.A. 1998, 'Motion Criteria', *Rowan Williams Davies and Irwin Inc.*, Technotes 2.

Irwin, A.W. 1999, *Personal communication.*

Isyumov, N. 1995, 'Motion Perception, Tolerance and Mitigation', *5th World Congress of the Council on Tall Buildings and Urban Habitat*, Amsterdam, Netherlands, May 14-19 1995.

Kanda, J., Tamura, Y. and Fujii, K. 1988, 'Probabilistic criteria for human perception of low-frequency horizontal motions', *Symposium/Workshop on Serviceability of Buildings (Movements, Deformations, Vibrations)*, Ottawa, Canada, May 16-18 1988, pp. 260-269.

Kanda, J., Tamura, Y., Fujii, K., Ohtsuki, T., Shioya, K. and Nakata, S. 1994, 'Probabilistic evaluation of human perception threshold of horizontal vibration of buildings (0.125Hz to 6.0Hz)', *Proceedings of Structures Congress '94, ASCE*, Atlanta, U.S.A.

Melbourne W.H. and Cheung J.C.K. 1988, 'Designing for serviceable accelerations in tall buildings', *Proceedings of the Fourth International Conference on Tall Buildings*, Hong Kong and Shanghai, April/May 1988, pp. 148-155.

Melbourne, W.H. and Palmer, T.R. 1992, 'Acceleration and comfort criteria for buildings undergoing complex motions', *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 41, pp. 105-116.

National Research Council of Canada 1995, *User's guide – NBC 1995 Structural Commentaries (Part 4)*, Ottawa, Canada, pp. 31.

Tamura, Y. 2000, *Personal communication.*