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Title:	New CTBUH Monograph on Building Motion, Perception and Mitigation
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Subject:	Structural Engineering
Keyword:	Structure
Publication Date:	2001
Original Publication:	CTBUH 2001 6th World Congress, Melbourne
Paper Type:	<ol style="list-style-type: none">1. Book chapter/Part chapter2. Journal paper3. Conference proceeding4. Unpublished conference paper5. Magazine article6. Unpublished

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DESIGN CRITERIA AND LOADS

New CTBUH Monograph on Building Motion, Perception and Mitigation

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ABSTRACT

This paper provides an overview of the new Monograph which deals with motions experienced by tall buildings and their impact on design. Of various types of building motions wind-induced vibrations are of greatest concern to designers since they can occur relatively frequently and are difficult to control and mitigate. The Monograph also treats floor vibrations caused by pedestrian traffic, in recognition of their importance for the satisfactory performance of buildings. The new Monograph includes recent findings of controlled “moving room” experiments and deals with the response of human to motions in actual buildings. This includes results by researchers from North America, Japan, Australia, Europe and other parts of the world. Methodologies for predicting wind-induced accelerations of tall buildings are presented and criteria used for their evaluation are discussed. Measures for reducing the wind-induced dynamic motions of tall buildings are discussed. These include the effects of altering the dynamic properties of tall buildings, notably their effective damping, as well as possible modifications to their aerodynamic characteristics, in order to reduce the wind-induced dynamic forces.

Finally, while significant progress has been made since the 1980 edition of this Monograph, many questions about how to predict, evaluate and if necessary mitigate wind-induced and other types of building motion still remain. While the need to limit motions of tall buildings is universally recognized there is still incomplete consensus on how to best gauge acceptable performance. As a result, different points of view are presented to express the diversity of practice in different parts of the world.

1.0 OVERVIEW

Motions can become perceptible and potentially unacceptable in situations where the response of buildings and other occupied structures to the action of external loads has a significant dynamic or oscillatory component. Oscillatory

motions or vibrations occur in situations where structures resonate under the action of external loads such as seismic ground accelerations, wind action and various man-induced excitations. The latter include explosions, sonic booms, vehicular, rail and pedestrian traffic, operating machinery, etc. Of these, wind-induced vibrations tend to have the greatest influence on the performance of tall buildings. While there can be substantial oscillatory motions of a tall building during a strong earthquake, such motions are of short duration and the primary concern of occupants is the integrity of the building rather than motion perception and discomfort. Wind-induced motions of tall buildings can persist for hours and can become perceptible and possibly annoying to its occupants without causing structural distress. Some man-induced motions such as floor vibrations due to pedestrian traffic can also occur frequently and be annoying. Generally, the public does not expect buildings nor their components to move and noticeable vibrations which persist are usually judged to be indications of inferior quality.

Wind-induced motions of tall buildings are not new phenomena and reports of the motion of early skyscrapers abound in the literature. The following quotation from Cushman Coyle's writing in the *American Architect* in 1929 is good advice for both past and current designers of tall buildings:

"In the case of high buildings, the frame must be designed to resist wind pressures with sufficient stiffness to keep the vibration caused by wind within limits that inspire the occupants with confidence in the strength of the structure."

Few building codes, past or present, provide designers with the necessary insight for judging exactly what limits should be placed on the magnitude of vibrations occurring with different recurrence rates and for spaces intended for different activities. It is generally accepted that large motion amplitudes may still be acceptable if they occur rarely and/or the activity intended for the area is a casual one. The public may not be surprised if perceivable motions are experienced in the viewing gallery of a tall flexible structure. The same public will have different expectations, however, for office or residential space in tall buildings. Consequently, attention to wind-induced drift and concern for perceptible motions and potential occupant dissatisfaction have become important considerations in the design of tall buildings. These concerns are being pushed to the limit by continuing construction trends towards super-tall and ultra-tall buildings.

The requirements to limit the wind-induced drift and horizontal accelerations constrains the design of most tall buildings, including those in seismic areas. The wind-induced drift of buildings is limited to assure an acceptable performance of the building envelope and interior finishes. Limits on wind-induced accelerations are imposed in order to assure the comfort of occupants and their confidence in the integrity and quality of the building. While there is considerable experience in setting appropriate limits on the total or the inter-storey drift

of a tall building, much less is known about how building motions are perceived by occupants and under what circumstances they can become objectionable.

The human perception and acceptance of tall building motions depends on both psychological and physiological considerations. Both tend to be highly subjective and therefore difficult to quantify, except in statistical terms. The acceptability of wind-induced building motions is most commonly judged by the magnitude and the recurrence rate of horizontal accelerations which determine the body forces experienced by occupants. The emerging feed-back from the performance of actual tall buildings furthermore indicates that the “habitability” or the total occupant comfort is also influenced by other factors. Particularly important are audio and visual cues which can accentuate motion sensation and heighten the irritation of occupants. While the literature is full with information on the effects of shock and vibrations on humans, most attention has been given to frequencies well above those of interest for tall buildings, whose fundamental natural frequencies of vibration are typically in the range of .1 to .3 Hz (typical periods of 3 to 10 seconds). Higher modes of vibration are rarely excited by wind action. One area with a similar frequency range is the experience with the effects of ship motions on passengers. Unfortunately however, that motion is primarily vertical and of a pitching nature rather than horizontal as experienced in buildings. As a result, it is difficult to transfer the experience with ship motions to the evaluation of horizontal motions in tall buildings.

No specific recommendations on acceptable motions of tall buildings were included in the previous 1980 edition of Monograph 13. Also there are no requirements to control building motions in any of the US Codes, including Standard 7 of the American Society of Civil Engineers. Some codes of practice do contain limits for wind-induced motions of tall buildings. The National Building Code of Canada, since its 1975 edition, contains procedures for evaluating peak wind-induced accelerations and recommendations for evaluating the acceptability of motions. It suggests that the peak horizontal acceleration at the top of a building, predicted for a return period of 10 years, should be limited to 30 and 10 milli-g for office and residential occupancies respectively. Guidelines for the evaluation of the response of occupants of buildings and offshore structures in the frequency range of 0.063 to 1 Hz appear in the International Standard ISO 6897, published in 1984. Detailed requirements have been published by the Architectural Institute of Japan in its “Guidelines for the Evaluation of Habitability to Building Vibration”. Nevertheless, a full understanding of the effects of motion on the habitability of tall buildings has yet not fully emerged.

While the physiological effects of horizontal motions are now more clearly understood, largely as a result of systematic “moving room” experiments, their psychological effects and the influence of other factors, such as wind-induced noise and visually apparent motions, require further study. One common trend which has arisen is the realization that many currently recognized “problem” buildings experience wind-induced motions which contain an appreciable torsional component. In addition to increasing the resultant horizontal acceleration and therefore the body forces experienced by occupants, particularly those near the building corners,

torsional motions can be more apparent visually to occupants along the building perimeter with sight lines to other buildings and outside reference points. The readily apparent lateral swinging of the horizon, which appears due to torsional motions, is an important prompt of building motions, which otherwise may have gone unnoticed. As a result, some criteria suggested in the literature and included in this Monograph impose limits on the wind-induced torsional velocity.

Finally, while significant progress has been made since the 1980 edition of this Monograph, many questions remain about how to predict, evaluate and if necessary mitigate wind-induced and other types of building motions. While the need to limit motions of tall buildings is universally recognized, there is still no consensus on the criteria for gauging acceptable performance. This can only be achieved through further research and feed-back from subjective studies carried out in full scale.

2.0 CONTENTS OF NEW MONOGRAPH

A Table of Contents of the current draft of Monograph 13, entitled “Motion Perception, Tolerance and Mitigation” is included in Attachment 1 to this paper. As seen from the Table of Contents, an attempt has been made to reflect the practice followed in different parts of the world. This has not been an easy undertaking and the inclusion of a sufficiently wide cross-section of different approaches has largely contributed to the delays in finalizing this Monograph. Our current expectations are that a final draft of the Monograph will be established on a web-site later this year, to be announced in the CTBUH Times. Printing will follow once it has been viewed and commented on by tall building designers in the technical community.

3.0 RETROSPECTIVE AND FUTURE DIRECTIONS

The ingredients of current practice largely rely on the results of controlled “moving room” experiments, subjective feed-back from building occupants and the judgement of designers and building owners. To insist that wind-induced building motions should be below occupant perception would invariably require special measures and the commitment of additional resources with a corresponding impact on cost. This should not be done lightly and without careful consideration of alternatives. It is important, therefore, for designers to be familiar with both the physiological and psychological consequences of excessive motions and with both good and bad experiences of the past.

Initial information on how to judge the acceptability of building motions, acquired in support of the design of major tall buildings, such as the World Trade Center Towers in New York and the Sears and John Hancock Towers in Chicago, have become corner-stones of acceptable practice in North America and world-wide. Peter Chen and Leslie Robertson through systematic experiments found that the threshold of human perception to horizontal motions was a peak acceleration of about 3 and 4 milli-g respectively for the 2 and 10 percentiles of their subject. Parallel work by Fazlur Khan and Dick Parmalee con-

firmed these perception thresholds and furthermore, suggested that peak accelerations in excess of 20 milli-g would be disturbing. Hansen, Reed and Vanmarcke were the first to provide subjective information on the response of a substantial number of occupants of tall buildings. Based on their findings, they concluded that both the perception of motion and its judged severity were due to the total effect of body forces and various perceived sensory cues. These included wind-induced noise and such visual cues as the movement of fixtures and the “swinging of the horizon” due to torsional motions. Furthermore, their survey of owners and developers suggested that complaints from a relatively small portion of the population of occupants can be sufficient to trigger concerns and to lead to a potential loss of rentability. They recommended that the onset of unacceptable motions should be taken as the acceleration level which would be considered unacceptable to 2% of occupants of the top 1/3 of the building. Their specific recommendation was to limit the predicted 6-year return period rms acceleration at the top of the building to 5 milli-g. This, in turn, corresponds to mean hourly peak acceleration of approximately 18 to 19 milli-g. This is remarkably consistent with earlier recommendations by Khan and Parmalee. Davenport used the perception threshold data of Robertson and Chen and the subjective feed-back from actual building occupants, provided by Hansen, Reed and Vanmarcke to suggest criteria for acceptable peak wind-induced accelerations for office buildings. The accelerations judged acceptable in Davenport’s Criteria were allowed to increase with decreasing recurrence rate. Results of these early studies are reflected in the practices of different parts of the world and are expected to influence targets for acceptable performance in the future.

While “moving room” experiments have been extremely effective in parametrically examining the response of humans to horizontal motions, including the initial perception of motion, the onset of nausea or “sea-sickness” and the effects of motion on balance, task performance and motor functions in general, such experiments unfortunately have not captured the influence of additional psychological factors, present in real buildings. Most occupants do not expect buildings to move, consequently noticeable motions can cause anxiety and raise suspicions about the quality and integrity of the building. These concerns have been recognized since the birth of the skyscraper. These are elusive questions and can only be settled through subjective feed-back from the occupants of actual tall buildings. It is furthermore important that such feed-back be obtained not only from buildings which have proven to be troublesome, but also buildings which perform well and are recognized as quality structures. This we believe should be one of the main targets of the next edition of this Monograph.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to all contributors of the present Monograph as listed in Attachment 1. Thanks are also extended to Professor Takeshi Goto, Vice-Chairman of Committee 36 both for his technical contributions to the Monograph and his membership of the Editorial Group.

ATTACHMENT I**Monograph 13****Motion Perception, Tolerance and Mitigation
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