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# Wind-Induced Motion of Tall Buildings: Designing for Occupant Comfort

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**Abstract**

A team of researchers and practitioners were recently assembled to prepare a monograph on “Wind-Induced Motion of Tall Buildings: Designing for Habitability”. This monograph presents a state-of-the-art report of occupant response to wind-induced building motion and acceptability criteria for wind-excited tall buildings. It provides background information on a range of pertinent subjects, including:

- Physiological, psychological and behavioural traits of occupant response to wind-induced building motion;
- A summary of investigations and findings of human response to real and simulated building motions based on field studies and motion simulator experiments;
- A review of serviceability criteria to assess the acceptability of wind-induced building motion adopted by international and country-based standards organizations;
- General acceptance guidelines of occupant response to wind-induced building motion based on peak acceleration thresholds; and
- Mitigation strategies to reduce wind-induced building motion through structural optimization, aerodynamic treatment and vibration dissipation/absorption.

This monograph is to be published by the American Society of Civil Engineers (ASCE) and equips building owners and tall building design professionals with a better understanding of the complex nature of occupant response to and acceptability of wind-induced building motion. This paper is a brief summary of the works reported in the monograph.

**Keywords:** Tall buildings, Wind-Induced motion, Human perception, Occupant comfort

## 1. Introduction

The past few decades have witnessed a tremendous growth of tall and super-tall buildings all over the world, particularly in east and south Asia, the Pacific Rim and the Middle East. Although advances in engineering materials, structural design and knowledge of wind-structure interaction ensure that these buildings meet strength and safety requirements under wind actions, occupant response to wind-induced building motion of new buildings of ever increasing height and complex shape remains a major challenge for property developers, building owners and tall buildings design professionals.

Up until the 1970’s tall building construction was in its infancy (Robertson, 1973). It was during that decade that the methodologies employed by structural engineers in the design of tall buildings showed a marked increase in complexity, and the design trends of massive unresponsive structures were retired. Individuals were given the opportunities to work and live in these new tall structures, but their expectations (which were translated up from low-rise buildings) were such that they believed the high-rise should be immune to wind-induced vibration.

Tall building structures, like all structures, move due to the action of wind. From a structural standpoint building motion is expected and is not an indication of inferior design. In general, it would be prohibitively expensive to design and construct a building that would not move in a windstorm. Granting that minimal wind-induced vibration must be permitted, the question becomes how to determine levels of motion and corresponding occurrence rates that are acceptable to both building inhabitants and building owners.

## 2. Tall Building Response to Wind

Building motion due to wind consists of two components: a static or sustained action, which is not apparent to occupants but is included in the estimation of the building drift, and oscillatory or resonant vibration, which is due to the dynamic and varying action of wind. It is this resonant motion that becomes perceptible to occupants,

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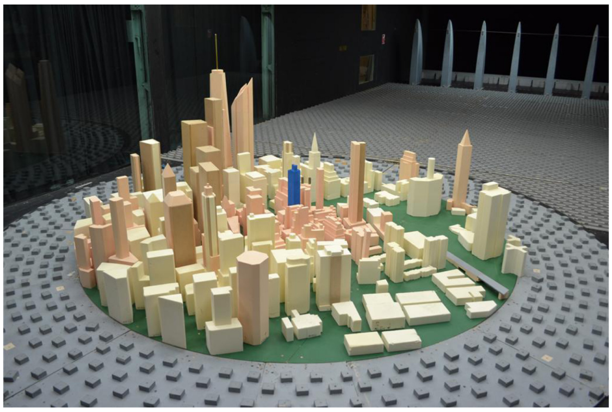

**Figure 1.** Test section of a wind tunnel [BMT Fluid Mechanics].

and if excessive can cause possible "discomfort" or even "fear".

There are numerous approaches suggested in wind codes and standards to predict accelerations from which building motion acceptability is primarily based. More refined estimates can be obtained from aerodynamic databases, either proprietary databases that exist at wind tunnel laboratories or in the public domain such as that described by Zhou et al. (2003) and included in newer editions of ASCE 7. Ultimately, the usual practice is to undertake project-specific wind tunnel tests.

The principal advantages of wind tunnel testing versus a code-based approach are: the effects of the surroundings can be fully accounted for, as can the unique architecture of the building and the directional characteristics of the local wind climate. An example of a tall building in the wind tunnel is shown in Fig. 1.

While the wind tunnel has clear advantages over a code-based approach in predicting the acceleration response, there are still a number of uncertainties in the reliability of the predictions. The key uncertainties result from the wind climate analysis and the assumed structural properties of the building.[1]

## 3. Requirements of Occupant Comfort Criteria

The principal aim behind designing for wind-induced vibration in occupied buildings is to provide an environment in which the inhabitants are comfortable and content, while ensuring task performance is not degraded. Two factors need to be considered in order to maintain an acceptable environment for occupants: the mitigation of fear for safety and the elimination of discomfort. Fear and alarm resulting from an experience with wind-induced vibration is associated with two things: the occurrence of an extreme wind event and/or the belief that a tall building should remain stationary. Discomfort results from sustained or frequently occurring motions.

People will tolerate discomfort felt infrequently and/or for short periods of time, but not as routine occurrences. That is, a larger vibration will be tolerated if there is a longer period between occurrences. It is believed that acceptability of maximum vibrations experienced will increase if the time between events is increased, that is for a longer recurrence interval (Hansen et al. 1973).

In terms of recurrence intervals, occupant comfort assessments on the 5-year and 10-year intervals have been justified in that perceptible motions occurring on average at this rate will not affect the functioning or commercial viability of a structure. Although this longer recurrence interval may adequately mitigate fear for safety resulting from extreme motions (and extreme events), it does not appropriately address the discomfort associated with regularly occurring wind events. A more recent trend has seen the evaluation of vibrations in windstorms with a one-year recurrence interval become more common. This shorter recurrence interval is more relevant to occupants' daily lives.

In some cases, significant building movements (such as those starting to make walking difficult) in buildings affected by rare tropical-cyclone events have been accepted by building owners, rather than incurring the cost of installing dampers. Such buildings were shown to perform well on a day to day basis and occupants were forewarned about the motions that may be noticed when strong winds were occurring.

Most problems in practice have come from movements which are felt much more regularly than the 10-year return period.

## 4. Human Perception and Tolerance of Motion

### 4.1. Human Physiology

How humans perceive and respond to changes in their physical environments is among the most technically challenging and conceptually sophisticated areas of modern psychology. The human body is a closed, integrated network of interacting subsystems: structural, hydraulic, electrical, chemical and thermodynamic. The human brain is the central control unit over all these subsystems, and it is supplemented by optical and acoustic systems. Overall biodynamical response of the human body varies in a random fashion from person to person.

Human responses are complex physiologically and behaviorally and are likely to be masked by the way in which we interpret and report them. There is a wide variation in individual ability to detect motion and this is

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[1] Wind climate data rarely fits the theoretical distribution curves perfectly. The goodness-of-fit of these curves has a considerable effect on the predicted accelerations.

recorded in surveys that reliably record individual sensitivity and susceptibility to motion sickness.

### 4.2. Motion Simulator Investigations

Experiments conducted on human test subjects using shake tables and purpose-built motion simulators is the most commonly adopted research approach to study human response to wind-induced building motion, an indicative motion simulator is shown in Fig. 2. The ability to conduct experiments under carefully controlled test conditions compensates for the potentially biased findings associated with the inability to reproduce a realistic living and working environment and test subjects' motion expectation.

Motion simulator and shake table experiments have been conducted by a number of researchers including: Khan and Parmelee (1971), Chen and Robertson (1972), Goto (1975), Irwin (1981), Kanda et al. (1988), Goto et al. (1990), Shioya et al. (1992), Shioya and Kanda (1993), Noguchi et al. (1993), Denoon et al (2000), Burton et al. (2003, 2005, 2006), Michaels et al. (2013) and others, under carefully controlled experimental conditions. In these motion simulator experiments, uni-directional, bi-directional, and/or yaw (torsion) vibrations have been simulated by varying frequencies, amplitudes and durations, and with human subjects tested in different postures or engaged in different activities to assess their perception of motion, cognitive performance or task performance. Although the vast majority of the earlier experiments were based on sinusoidal vibrations, more recent experiments conducted by Denoon et al. (2000) and Burton et al. (2003, 2004a, b, 2005, 2006) focused on random vibrations and included task distractions to reproduce an environment normally encountered in wind-excited buildings.

There have been very few motion simulator investigations that have focused primarily on the tolerance threshold of motion, as distinct from the perception threshold. It has been previously noted that the environmental conditions in the motion simulator are such that space and fear are not accurately represented (Reed et al., 1973), and since difficulty exists in replicating these environmental factors in the simulator, it is problematic to extract information regarding motion acceptability directly from an individual's tolerance of the simulator's motion.

### 4.3. Field Investigations

The study of occupant response to wind-induced building motion is best studied in real buildings under real wind actions. However, weather unpredictability necessitates a long-term monitoring program and the reluctance of building owners and tenants to participate, due to a combination of commercial, legal, operational and security reasons, has stifled many research efforts to generate meaningful results.

There have been relatively few tall buildings that have been monitored over extended periods of time. Of those that have, only in a few cases have investigators been given access to the building occupants to interview them about their motion experiences. In even fewer cases have the investigators been given permission to publish the results of interviews. As such, much of the information about occupant response to motion in buildings, even monitored buildings, is anecdotal.

The first report of monitoring was the landmark study of Hansen et al. (1973), in which the occupants of two buildings were surveyed post a wind event and asked "how many times a year would a similar experience occur before it became objectionable?" Thus they obtained a

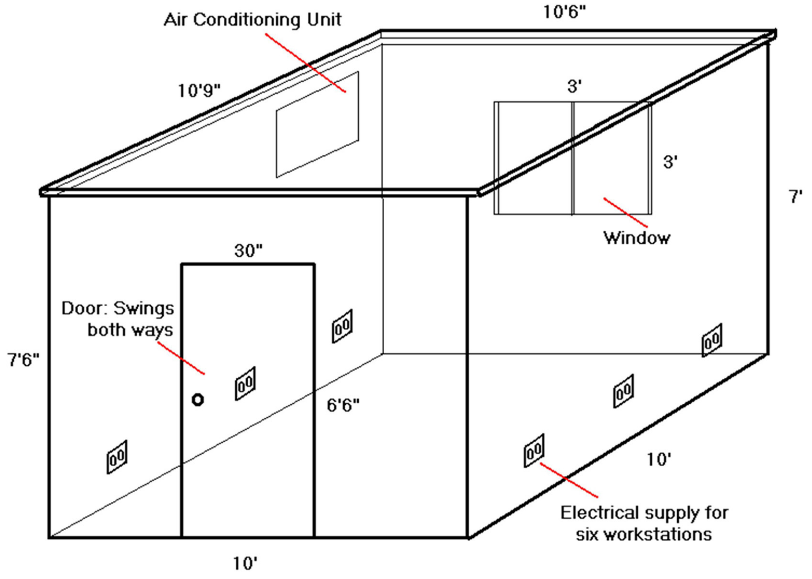

**Figure 2.** Drawing of a motion simulator test room.

relationship between motion intensity (for two different values of rms acceleration at the top of the buildings) and the percentage of people that can be expected to object.

One of the longest on-going and perhaps most monumental studies in the field is the Chicago Full-Scale Monitoring Project (Kijewski-Correa et al., 2006). The project was established in 2001 to facilitate the monitoring of several tall buildings for validation of performance against predicted wind tunnel and analytical models in order to calibrate the current state-of-the-art in design. A step towards establishing levels of acceptability has been discussed qualitatively by Kijewski-Correa and Pirnia (2009), and supports the observations by Burton et al. (2005) that the narrow-band waveform is most disruptive. There is also evidence that objection levels are subject to “habituation,” i.e., the notion that experience, education, or reassurance can be effective in placating initial concerns.

Typically tall buildings are an example of a low-dose environment as they rarely, if ever, induce vomiting. However, under certain conditions there are reports of building occupants taking motion sickness tablets to counteract symptoms of nausea (Melbourne and Cheung, 1988), and of employees asking to be dismissed for the day due to discomfort. There are other examples of hotels, e.g., one in Chicago which offers a motion sickness pill, while the Hyatt in San Francisco alerts its guests of the potential motion of the building under winds through a printed note, assuring their guests that this is the normal behavior of the building.

In a recent study (Lamb et al., 2014) it was reported that long duration exposure to low amplitude accelerations, around or possibly below the threshold of perception, can cause greater occupant discomfort than previously thought. In the study a survey measured a range of potential symptoms of motion sickness, work performance (objective and subjective measures), wellbeing, and reported building motion and showed that motion-induced discomfort developed after sustained exposure to motion. Affected individuals attempted to manage their own discomfort, and indicated a preference to work at different location during motion and took 30-40% longer breaks.

### 4.4. Cues to Motion Perception

While kinaesthetic perception has been the focus of most research into human perception of wind-induced building motion, there are a number of other cues that may trigger perception of motion by building occupants. The most common of these are visual and acoustic cues.

Examples of visual cues include swinging lights, moving blinds/curtains, swaying plants, sloshing liquids, and other hung or loosely suspended fittings and objects (as shown in Fig. 3). These are all internal visual cues. Other internal visual cues can arise from occupants swaying in response to the motion and observing motion as a result of parallax effects. There are also external visual cues that may trigger perception in occupants who are accustomed to motion in a given building and have a degree of expectation of such motion occurring on windy days. Cues could include swaying trees, extended flags, and other indications that there are high wind speeds.

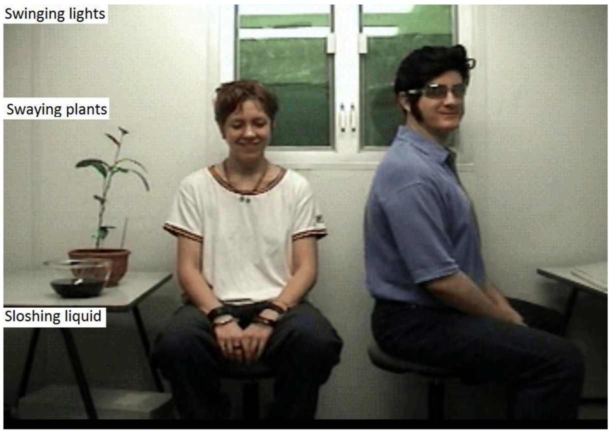

**Figure 3.** Typical visual cues to motion perception.

Like visual cues, there are a number of possible sources of acoustic cues. Some of the audible motion cues may provide information about the frequency of the motion and others may not. The most common acoustic cue that would provide an occupant with information about the natural frequency of the motion, which would supplement and be consistent with kinaesthetic cues, is structural noise, such as creaking resulting from the building sway. Other cues that have been experienced are venetian blinds impacting window frames as they sway back and forth. Wind noise can also be a strong audio cue for building occupants.

Another type of cue, which is not strictly an acoustic cue, is being prompted about building motion by other occupants of the building. This type of cue increases in likelihood when there are large numbers of people congregated.

It has been postulated that torsional motion needs to be considered from a viewpoint of introducing an external visual cue due to the rotation of the building relative to external visual references and hence a translational motion can be visually detected. However, it has equally been postulated that at the amplitudes at which this would occur, there are already internal visual cues, including those caused by parallax as a result of occupants swaying in reaction to the motion. Naturally, where torsion is present it means that translational motions will be different at different locations on the floor-plate of a building. It is common to assess the motion at either an extremity of a

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[2] In order to demonstrate a curve valid for comparison in Figure 4 the ISO6897-1984 guideline has been multiplied by a peak factor of 3.5. This peak factor converts the rms acceleration specification into comparable peak acceleration.

floor, at a radius of gyration (or central point between the center of rotation and the floor extremity), or the center of the floor or a combination of these three.

## 5. Occupant Comfort Design Criteria

Building codes and standards evolved originally to promote safety of buildings and serviceability issues such as building deflections, velocities and accelerations have often been regarded as being related more to the quality of the building than to safety. Therefore codes and standards have tended to steer clear of rigidly defined serviceability criteria since this area could be regarded as something to be negotiated between the owner and the designers, depending on the desired level of quality for the building. As a result, acceleration criteria over the past 30 years have received diverse consideration.

The groundbreaking work of Chen and Robertson (1973) provided information on human perception thresholds for sinusoidal excitation as a function of frequency. The first published full-scale evaluation of occupants' responses to accelerations was introduced by Reed et al. (1973). The results of this full-scale research allowed for the development of the first criteria governing wind-induced vibration in tall buildings. The criteria were expressed in terms of rms acceleration for a return period of 6-years.

The first codified serviceability criteria were introduced in the National Building Code of Canada (1977). It suggested limiting the peak building accelerations occurring once every 10-years to 1-3% of gravity, with the lower range applying to residential buildings and the higher values to commercial buildings.

By synthesizing laboratory motion simulator investigations from Khan and Parmelee (1971) and Chen and Robertson (1973), and full-scale knowledge from Hanson et al. (1973), Irwin (1978) proposed the design recommendations which led to the development of the ISO6897-1984 guideline for evaluating the acceptability of low-frequency horizontal motion of buildings subjected to wind forces. The guidelines were dependent on frequency and used the rms acceleration of the worst consecutive 10 minutes of a windstorm, with a return period of 5-years.[2]

Melbourne and Cheung (1988) altered the curves provided by ISO6897-1984 to specify the limiting acceleration in terms of peak acceleration as opposed to the rms acceleration. This proposed maximum peak acceleration criteria for any return period was reflected in the Australian Wind Engineering Society Commentary (1989).

The Architectural Institute of Japan (AIJ) Recommendations (1991), superseded by AIJ Recommendations (2004), delivered guidelines for evaluating wind-induced building vibration based on previous motion simulator investigations (Goto, 1975, 1983; Kanda et al., 1988) and the ISO6897-1984 guidelines. The basic evaluation curve is specified with peak accelerations of 1-year recurrence at the fundamental natural frequencies of the building; however it introduced the concept of criteria that were graduated according to the target quality of the building. The suggested magnitudes of vibration in residences are defined as two thirds of those acceptable in offices. The resultant curve for residences is close to the 90% level of the perception probability (Tamura, 2003).

Isyumov (1993) suggested criteria of acceptable wind-induced motions of tall buildings, for a return periods of 1-year, that were considered by the American Society of Civil Engineers (ASCE) and the Council of Tall Buildings and Urban Habitat (CTBUH) technical committees as tentative guidelines. These guidelines were later adopted by the National Building Code of Canada (1995). Three ranges of accelerations were suggested, 5-7 milli-g for residential buildings, 7-9 milli-g for hotels and 9-12 milli-g for office buildings, which would be vacated during severe windstorms.

A more current ISO standard, ISO10137 (2007) which supersedes ISO6897, has moved to the 1-year return period and retains the previous dependence on frequency. However it now uses peak acceleration rather than rms. Similarly to the AIJ criteria two curves are presented for residential and office criteria where the former is 2/3 of the latter.

Shown in Fig. 4 is a comparison of current occupant comfort guidelines for the 1-year return period used by tall building designers globally along with key results from various motion simulator and full-scale studies.

## 6. Design Strategies for Mitigating Motion

The dynamic response of a tall building to wind excitation is influenced by many factors; such as the site conditions (which may change over the life of the building), shape and height, and dynamic characteristics (which include vibration periods, mode shapes, mass distribution, lateral stiffness distribution, and damping).

The strategies that can be adopted to reduce wind-induced building motion are either by aerodynamic treatment (such as changing the building shape along the height, tapering the buildings along its height, varying plan shape, introducing porosity, changing the corner shape, and adding spoilers) or by alteration of the dynamic characteristics of the buildings (including mass, stiffness, mode shape and damping), or a combination of both (Kareem et al., 1999). In the early days of wind engineering, the usual approach was to stiffen the building. This approach is attractive since it avoids impacting the exterior architecture but does lead to increased structural cost and may impact the functionality of the interior spaces (e.g., by increasing the sizes of the structural columns).

The feasibility of making simple improvements to the shape depends on the nature of the aerodynamic effect causing the motions. Buffeting forces from other structures are particularly difficult to reduce without major changes to building form, whereas self-induced vortex shed-

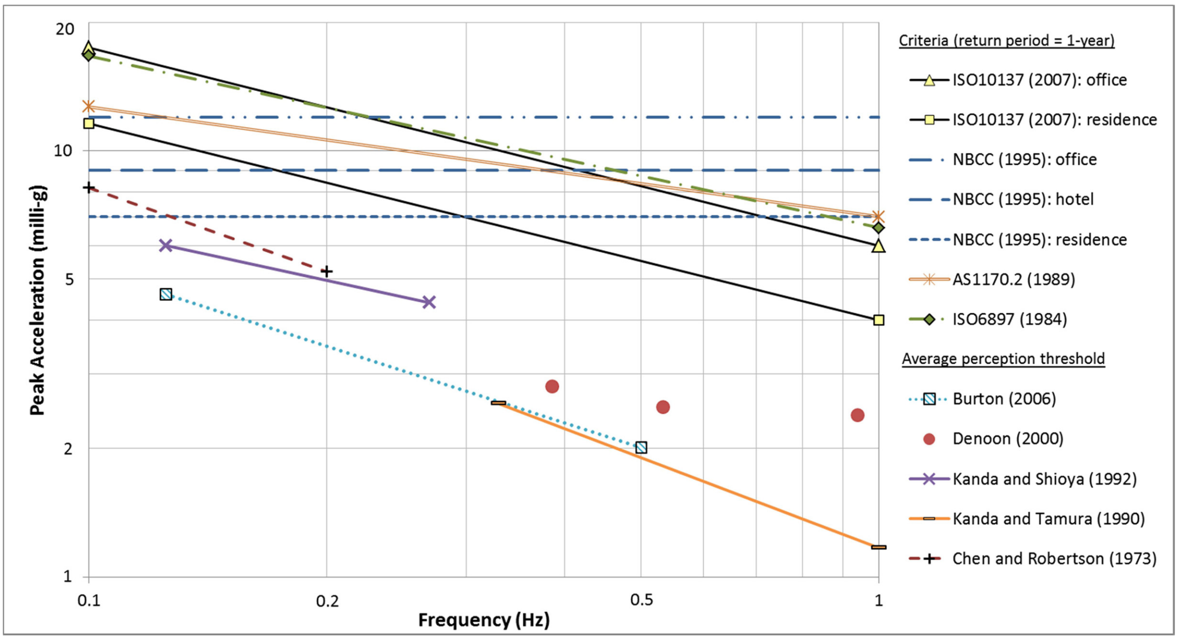

**Figure 4.** Comparison of average perception thresholds, and suggested criteria, for the 1-year return period.

ding forces can sometimes be reduced by relatively small measures, which introduce more three-dimensionality to the building form particularly towards the upper levels. Classic examples to reduce dynamic motions include tapering towards the top, progressive corner cut-outs, and, for more circular plan buildings, spiral forms and even irregular surface roughness arrangements and porosity.

In addition to aerodynamic and structural modifications, implementation of supplementary damping systems has also gained much recognition as a workable and reliable technology. Adding damping can be effective as the accelerations of a building vary roughly in inverse proportion to the square root of the damping ratio. It is quite feasible to double or triple the damping of a building through the addition of supplementary damping devices, thus achieving 30% to 40% reduction in the wind-induced building accelerations.

Auxiliary damping devices can be either passive or active. Passive devices can increase the level of damping within the structure through either direct or indirect energy dissipation mechanisms. Falling within the first category are all those solutions that make use of materials selectively installed within the structural system that are capable to dissipate energy when undergoing cyclic excitations (e.g., viscoelastic dampers). As part of the second category are those auxiliary damping systems that incorporate a secondary mass – a rigid body or a fluid – either directly connected to the main structure via a series of springs and dashpots (e.g., TMDs) or free to move through a perforated media (e.g., TLDs).

Active devices utilise a sophisticated computerised system that is capable of monitoring the structural movement of the tall building and drive actuators operating on a secondary mass to control the motion. Compared to the passive devices, active dampers can be more compact and efficient but far more expensive to deliver, operate and maintain.

## 7. Experiencing Tall Building Motions

As people do not have much occasion to quantify the acceleration levels they are experiencing as they go about their daily lives, they usually do not have a sense of what 5, 10 or 20 milli-g feels like. Therefore when discussions between designers, owners and wind engineering experts take place, it can be helpful to go into a “moving room” or chamber to experience various levels of motion. This can be educational, and while it is not the ideal statistical sampling of the building occupants that one would like, it has been found to be a useful aid to decision making.

By simulating building motion for wind speeds of different recurrence intervals, participants are able to appreciate the relationship between comfort and frequency of occurrence.

## 8. Conclusions

The second half of the 20th century has witnessed a tremendous increase in the construction of tall buildings and structures, particularly in growing economies. Although significant research efforts in the past four decades have provided a better understanding on the subject, understanding occupant response to wind-induced building motion remains a major challenge in the design of tall buildings today.

Despite the variations in experimental setup and test methodology, a number of important observations and conclusions can be drawn from research conducted in this field. Generally, human perception of motion is dependent on frequency. There is little doubt wind-induced building motion at acceleration levels above perception thresholds can cause some degradation in occupant comfort and may elicit fear and alarm. Prolonged exposure to wind-induced building motion will accentuate the above adverse occupant responses, with fatigue playing an equally important role. Despite the self-reporting of a plethora of adverse responses to wind-induced building motion, occupant complaint behaviour is not well-understood due to the complexity of human psychology and behavioural traits that are influenced by societal and cultural factors. Education of occupants has the desirable effect to alleviate fear and alarm and instil acceptance of infrequently occurring, perceptible wind-induced building motions.

A number of international and country-based standards organizations have adopted these research findings to formulate serviceability criteria to assess the acceptability of wind-induced building motion. The proposed acceptable acceleration values are shown to vary even after they have been standardized for comparison purposes. That being said, the following peak acceleration thresholds are recommended by the monograph as general guidelines with which habitability and the need for mitigation can be assessed:

5 milli-g is a threshold which, while perceptible to some occupants, is unlikely to cause significant adverse occupant response or alarm, provided that such building motion does not occur frequently or continuously for an extended period of time.

10 milli-g is a comfort and well-being threshold that is perceptible to the vast majority of occupants. In practice, buildings that frequently exhibit such wind-induced motion and/or for an extended period of time may not be acceptable to some occupants.

35-40 milli-g is a fear and safety threshold sufficiently severe to cause some occupants to lose balance. The upper value would be more acceptable for buildings with lower natural frequencies (~0.1 Hz), whereas the lower value would be more relevant for buildings with higher natural frequencies (~0.4 Hz). Such building motion is unlikely to occur in tall buildings except during extreme wind events. Nevertheless, such building motion should be avoided where possible.

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