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Occupant comfort in wind-excited tall buildings: Motion sickness, compensatory behaviours and complaint [☆]

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ABSTRACT

1014 central business district workers in Wellington, New Zealand, were surveyed about their experiences of wind-induced building motion, susceptibility to motion sickness, reported compensatory behaviours, and complaints about building motion. Overall, 41.7% of the respondents reported that they had felt wind-induced building motion, and 41.6% of those respondents reported perceptible motion at least once a month. Difficulty in concentrating was the most frequently reported effect of building motion, reported by 41.9% of the respondents who had felt building motion. This suggests that early onset motion sickness develops in many building occupants. Despite a strong preference to avoid working in tall buildings, highly susceptible individuals were equally likely to work on high floors as low floors, increasing their potential exposure to building motion. These highly susceptible individuals were more likely to report symptoms of motion sickness due to building motion. Despite the reported adverse effects of motion sickness, building occupants in general almost never make formal complaints about building motion, contradicting the widely held assumption that complaint is an effective index of building performance. Some building occupants then actively compensate for the effects of building motion by taking more breaks and in some cases taking motion sickness tablets. Implications for occupant comfort, motion sickness, the rate of occupant complaint and compensatory behaviours are discussed.

1. Introduction

New high strength materials, advanced construction techniques and sophisticated computer modelling have allowed building designers to create super-tall structures that are inherently light and slender, with low damping, which are significantly more wind-sensitive than relatively older buildings (Kwok et al., 2009). Wind excitation causes low frequency, low acceleration building vibration, mostly between 0.08 and 1 Hz. These wind-induced building motions can be perceptible to building occupants (Burton, 2006; Goto, 1983; Hansen et al., 1973; Lee, 1983), may cause fear and alarm (Burton, 2006; Hansen et al., 1973), and induce symptoms of motion sickness (Goto, 1983; Hansen et al., 1973). The effect of building motion on occupant work performance and occupant comfort are not well understood. Consequently, there are currently no internationally agreed guidelines to quantify an ‘acceptable’ level of building motion (Kwok, et al., 2009).

1.1. Previous survey-based research

Few studies have examined the occupant response to actual tall building motion because of the difficulty of recruiting participants, the unpredictability of when building motion will occur, the reluctance of building owners to allow researchers to measure building accelerations, and the general unwillingness of organisations in tall buildings to commit staff time to external research. Given these difficulties, most studies have used simulators in an attempt to replicate building motion.

Hansen et al. (1973) conducted the first building occupant survey, finding that 36% of the respondents in one building, and 47% in another, experienced motion sickness during a windstorm. Goto (1983) observed that following a typhoon, causing a peak acceleration of 14 mG (1 mG is equal to 1/1000th of gravity or

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0.0098 m/s^2) in one tall building, over 95% of the occupants above the 13th floor reported perceptible building motion. Seventy-two per cent of the occupants reported physiological or psychological symptoms, including motion sickness, headaches and 'uneasiness and strain', the likelihood of which increased with the floor they occupied. Denoon et al. (2000) examined the occupants of three wind-sensitive control towers, finding no correlation between 'acceptability' of motion and formal complaint. Occupants of these structures reported some level of habituation to building motion. Denoon et al. (2000) found no relationship between building motion and cognitive performance, concluding that natural variations in work performance were larger than any measureable effect of building motion. However, limitations in the sensitivity of the tests used and analysis methods may have contributed to the inability to detect potential degradation in work performance. Burton (2006) found that only 5.8% of Hong Kong residents, from a sample of over 5000, reported that they had ever felt building motion. Of that small percentage, only 2.3% issued a formal complaint to their employer or the building owner. While minimising perceptible building motion remains an important design criteria, Kwok et al. (2009) states that future research should focus on understanding the effects of motion on building occupants' comfort and general well-being.

1.2. Motion simulator studies

Motion simulator studies attempt to determine the threshold of perception for motion in the frequency and acceleration range of tall buildings and examine the potentially disruptive effects of vibration on task performance. Khan and Parmelee (1971), in one of the earliest motion simulator studies, observed that motion became perceptible at accelerations of 4 mG (r.m.s.). Chen and Robertson (1972) showed that the perception of motion is frequency dependent, where acceleration-based thresholds of perception decrease as the frequency of motion increase. The expectation of motion and standing (relative to sitting) increased participants' sensitivity to motion. Irwin and Goto (1984) observed that frequencies below 1 Hz were more nausea inducing, but frequencies above 1 Hz had a larger effect on manual task performance (e.g. line tracing, needle threading); though it is generally accepted that sickness only occurs below 0.4 Hz (Guignard and McCauley, 1990). Tamura et al. (2006) observed significant inter-individual variation in thresholds in perception, and also observed that mean thresholds decreased as frequency increased up to 1 Hz, i.e., individuals become more sensitive to motion as it approaches 1 Hz.

Most simulator studies have used sinusoidal motion to simulate building motion, however, building motion is characterised by narrow-band random motion (Isyumov and Kilpatrick, 1996). Burton et al. (2004) is one of the few simulator studies to examine the effects of random motion, finding that reported disruption to task performance and difficulty concentrating increased with acceleration, and were most variable at 0.5 Hz. In a follow-up study, Burton et al. (2005) found that random motion produced nausea in 40% of participants at low frequencies, but sinusoidal motion did not produce nausea. Longer durations of exposure to motion at higher accelerations were the most likely to induce motion sickness. The authors state that participants subjected to sinusoidal motion have a "greater control of the vibration characteristics" (p. 7) and were therefore able to anticipate motion more easily than during random motion. Other studies have attempted a composite approach, comparing full-scale building accelerations with data from simulator studies to estimate the likely disruption to occupants (Kijewski-Correa and Pirnia, 2009).

1.3. Motion sickness

Motion sickness is characterised by nausea, vomiting, cold-sweating and pallor (Reason and Brand, 1975). Early onset or prodromal symptoms usually precede the classic symptoms of motion sickness. Graybiel and Knepton (1976) term these initial symptoms 'sopite syndrome', which includes drowsiness, difficulty concentrating and depressed mood. Walton et al. (2011) suggest that a dose-response model might be applicable to tall building motion where low frequency, low acceleration motion may induce low severity symptoms such as sopite syndrome rather than high severity symptoms such as vomiting. The authors argue that low-dose motion might produce observable changes in an individuals' behaviour, referred to as compensatory behaviours, as occupants attempt to manage the adverse effects of motion, e.g. taking breaks outside the office building. For over 100 years motion sickness was believed to be caused by some form of conflicting sensory information, a theory which has received significant criticism (Stoffregen and Riccio, 1991). A relatively more recent theory proposed by Riccio and Stoffregen (1991) argues that motion sickness is caused by the inability to maintain control of posture in environments of real or implied motion. Walton et al. (2011) consider implications postural instability theory might have for the occupant response to tall building motion, as exposure to motion alone might be sufficient to interfere with posture and induce motion sickness rather visual cues alone or a visual/vestibular conflict.

1.4. Serviceability criteria

Several standards have been proposed to provide guidelines for 'acceptable' levels of building motion, mostly based on the level of perceptible motion within a probabilistic framework, (Bashor and Kareem, 2007). ISO-6897 (International Organisation for Standardisation, 1984) suggests a frequency dependent level of acceleration for the worst 10-min of an event with a 5-yr return period, for example limiting motion at 0.2 Hz to 5 mG (r.m.s.). Isyumov (1993) suggests a range of 9–12 mG (peak acceleration) for office building, with no adjustment made for the natural frequency of the building. The Architectural Institute of Japan (2004) provide several curves estimating the proportion of occupants that will perceive motion given an event with a one-year return period; the most sensitive being the H-90 curve where 90% of the occupants will perceive motion at 8 mG (peak) at 0.3 Hz. However, the AIJ guidelines only indicate a level of motion that is perceptible, not a level that will be comfortable for occupants. ISO/FDIS 10137: 2007(E) (International Organisation for Standardisation, 2007) propose a curve similar to the AIJ H-90 curve; again, not specifying a comfortable level of motion. Burton et al. (2007) proposes event-duration-dependent guidelines based on "fear and alarm" at acceleration levels similar to ISO-6897 (International Organisation for Standardisation, 1984) and based on survey-based reports of complaint. Further research is necessary to determine what level of motion is comfortable for occupants and to ascertain the level of motion that may lead to performance degradation in building occupants. Comprehensive descriptions and discussion of current serviceability criteria can be found in Kwok et al. (2009).

1.5. Wellington, New Zealand

Wellington, the capital of New Zealand (NZ), has the reputation of being one of the windiest cities in the world. Cook Strait separates the two main islands of NZ, which is 20 km wide at the narrowest point. Mountain ranges on both sides of the Cook Strait funnel the predominantly westerly winds of the "Roaring