“Pseudo-Full-Scale” Evaluation of Occupant Comfort in Tall Buildings
Tracy Kijewski-Correa¹, J. David Pirnia²

¹Associate Professor, Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN, USA, tkijewsk@nd.edu
²Graduate Student, Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN, USA, jpirnia@nd.edu

ABSTRACT
While it can be challenging to “engineer” tall buildings to satisfy habitability limit states, the situation is further compounded by a lack of clear metric and criteria for quantifying accelerations that negatively impact occupants. In part this is due to the fact that human perception of motion is influenced by a number of factors including motion frequency, amplitude, duration, and waveform (peak factors), and only recently were these wide ranging factors investigated on human subjects using faithful motion simulators. Despite the improvement in recent simulator studies, many other environmental factors are not accurately recreated (visual and audio cues) leaving full-scale observations (tenant interviews correlated with recorded full-scale accelerations) as the only truly definitive means to establish occupant perception criteria. Sadly, the lack of accessibility to tall buildings and other practical barriers (bad press, liability) prohibit such efforts. The present study offers a compromise to the reality facing in-situ validation of occupant comfort. In this effort, full-scale acceleration data collected from a case study tall building is compared to the waveforms determined from extensive motion simulator tests to be most disruptive to occupants. The investigation considers waveform, energy level and the frequency of oscillation in classifying wind events observed in full-scale and then estimates the frequency with which occupant comfort may be potentially impacted in actual tall buildings to offer a “pseudo-full-scale” occupant comfort investigation. While this cannot capture the ideal products of a tenant interviewing process, it does provide some indication of how common potentially disruptive motions are in modern tall buildings.

INTRODUCTION
Habitability limit states often govern the design of tall structures, as wind-induced accelerations increase and become more perceptible to occupants. Drift criteria alone are inadequate to ensure habitability of a tall building, where prolonged accelerations at top floors may cause occupants extreme discomfort during a high wind event [1]. Thus a subject of considerable attention in the tall buildings community is this issue of occupant comfort and how best to quantify acceptable levels to avoid remedial actions that can be costly and damaging to a building’s reputation. Ideally, acceleration levels causing perception or other undesirable sensations should be quantified through a tenant interviewing process in realistic building environments where accelerations are recorded and correlated through occupant feedback using a standardized assessment form [2]. Unfortunately, there are many practical barriers to studying the effects of building motion on human comfort in-situ, largely due to a lack of accessibility and owner fears over bad press or even liability.

As a result, perception limits instead have been traditionally determined based on the response of individuals to tests using uniaxial motion simulators [3-5], though more recently bi-directional simulators have been utilized [6]. In most cases, such experiments relied on sinusoidal excitations (peak factor of ~1.4); however, there are discrepancies between these idealized testing environments and the actual motions of a tall building [7]. Since the motion of
tall buildings is a narrowband random response including bi-axial and torsional components, the use of uniaxial sinusoidal motions is not entirely faithful. In addition, the absence of visual and audio cues in the test environment neglects critical stimuli, particularly for torsional motions, which are known for triggering visual stimulus [8]. In addition, the extent to which each contributing factor triggers perception or other undesirable response (fear, nausea, task disruption) varies from person to person, and the means to best quantify these accelerations (peak vs. RMS and perception vs. tolerance) is still contested [9].

Recent perception investigations have attempted to address the criticisms of earlier work by investigating the effects of frequency, amplitude, duration of motion, and waveform (peak factors) on human comfort using bi-directional, narrowband motions [10-11]. The findings from these studies have particularly underscored the influence of waveform (sinusoidal, Gaussian, burst) or peak factor and duration on habitability limit states. As this study has been perhaps the most comprehensive, it becomes an excellent basis for what the authors now propose as a “pseudo-full-scale” evaluation of occupant comfort in the absence of an actual tenant interviewing process.

Figure 1: Example of peak factor calculation for a given sample response window
APPROACH

In the present study, the motion simulator conditions that were identified in [10] as being disruptive or causing nausea are used as search parameters in the full-scale data from a building affiliated with the Chicago Full-Scale Monitoring Program. This will provide a rational basis for evaluating the building’s acceleration responses and determining the frequency of “nauseating” or “task disruptive” waveforms, to offer a “pseudo-full-scale” evaluation of occupant comfort in tall buildings. These response features that will be searched over moving windows of two durations within the data are waveform (using peak factors), response level (using standard deviation or RMS), and dominant frequency of oscillation (spectral estimate of fundamental frequency in sway).

**Peak Factor Estimation:** A methodology was developed to obtain peak factors based on a constant probability of up-crossing regardless of the window over which the statistic is extracted. First, a bandpass filter isolates the dominant frequency of oscillation over the analysis window, thereby isolating lateral responses only. The response envelope (peak values) are then extracted and then moving windows (lengths of 12 or 50 minutes, corresponding to the durations of motion simulator tests in [10]) are passed over the record, translating by a ten second increment. The peak factors themselves are based on a probability of up-crossing equal to approximately 1/1000 to provide an equal baseline across different duration analysis windows. A linear regression of the up-crossing analysis was used to interpolate/extrapolate to the appropriate level, as shown in Figure 1, so as to retain consistency with the peak factors defined in [10]. Finally, uncorrelated segments meeting the selected peak factor criteria are identified for both long and short duration events and these are retained for further analysis. An illustration of this process is provided in Figure 1 for a sample response window.

![Figure 1: Illustration of the peak factor estimation process](image)

**Figure 2:** Full-Scale peak accelerations in fundamental sway modes by month for the case study tall building in 2007

EVALUATION USING TRADITIONAL HABITABILITY CRITERIA

Because of the sensitivity of the subject, the details of the building used as the case study in this paper must be withheld, but certain details relevant to the habitability discussion and particularly to the concept of peak factors are now offered: the building is residential with an in-situ
fundamental period of approximately 5 s in both lateral directions. A summary of the peak accelerations observed for this building over a one-year period is provided in Figure 2 and are well below 10 milli-g. In terms of evaluating the acceptability of these motions, many different criteria exist for evaluation of occupant comfort, however this study will utilize the criteria compiled and presented on the website of ASCE’s Tall Buildings Committee: www.nd.edu/~tallbldg (Fig. 3). As evidenced by Figure 3a, the acceleration levels observed in 2007 for the case study buildings should not result in disruption to tasks or nausea [2,7]. Furthermore, as shown Figure 3b, as an annual event, these peak accelerations are within the limits specified by Council on Tall Buildings and Urban Habitat (CTBUH) for residences.

(a)

![Figure 3a: Level of disruption as a function of peak acceleration.](image)

(b)

![Figure 3b: Habitability criteria for peak accelerations.](image)

Figure 3: (a) Level of disruption as a function of peak acceleration and (b) habitability criteria for peak accelerations as a function of annual recurrence rate, as compiled by ASCE Tall Buildings Committee (www.nd.edu/~tallbldg).
EVALUATION OF THE ROLE OF PEAK FACTOR

Of the three waveforms investigated in [10], sinusoidal, Gaussian, and burst with peak factors of 1.7, 3.3, and 4.8, respectively, a Gaussian response was found to be the most likely to induce nausea in occupants. It is hypothesized that this is the case because of the randomness of the motion, keeping the occupant effectively “off guard.” This effect becomes more pronounced in longer duration events (50 minutes vs. 12 minutes). According to [10], for short duration events (12 minutes), nausea almost never occurred, while task disruption rates decreased slightly from those under the longer duration test. Thus this study will attempt to identify occurrences of task disruption in full-scale using 12-minute duration events and occurrences of nausea using 50-minute duration events.

The analysis of the full-scale data for this case study building will begin by identifying the events with varying peak factors classified as uncorrelated, short duration events (using 12 minute moving windows). The peak factors identified are sorted into three waveform categories: sinusoidal (<2.5), Gaussian (2.5-4.05), and burst (>4.05). Examples of each of these waveforms are provided in Figure 4 and the occurrences of these waveforms over a one year period in the case study building are provided in Figure 5. Gaussian and sinusoidal waveforms contribute approximately equally to the types of triggered responses of the case study building, while burst...
waveforms typically compose 10% or less of the triggered response, though tend to be observed more in the y-axis response.

Figure 5: Full-scale response characterization by waveform type (12 minute blocks) for case study building in 2007, x-sway in top graph and y-sway in bottom graph

This analysis is now extended to consider the role of amplitude for the full-scale waveforms classified as Gaussian over the two window durations (12 and 50 minutes). As such, disruptive responses identified by in the full-scale records can be correlated to the rates of nausea and task disruption observed in motion simulator tests for Gaussian excitations at comparable amplitudes and 0.2 Hz oscillation frequency. Figure 6 provides the number of occurrences of a events of a given duration, with a Gaussian peak factor, within a specified amplitude range (RMS or standard deviation), over a particular time period (in this case June 2007). For example, in June 2007, the maximum short duration event (12 minute) identified in the full-scale data has an RMS acceleration of 0.75 milli-g and according to [10] would cause task disruption to 7.5% of occupants, while the maximum long duration (50 minute) event identified in the full-scale data has an RMS acceleration of 0.45 milli-g and would be projected by [10] to induce nausea in 2% of occupants.

Monthly results of the full-scale analyses are tabularized in Tables 1-2 for RMS amplitude levels and corresponding percentages of occupants likely to experience task disruption (Table 1) and nausea (Table 2) according to the trends observed in [10]. Note that these results are not mutually exclusive across analyses, meaning an event inciting a particular amplitude level in the x-direction may also be counted as an event for the y-direction. Task disruptive (short duration) events exceeding 1.5 milli-g RMS occurred at least 4 times during 2007, corresponding to task disruption for a projected 14% of occupants (Table 1). Similarly, long duration events exceeding 1.0 milli-g RMS occurred at least 5 times during 2007, leading to potential nausea in 5% of occupants. The higher occurrence rates observed for in the x-direction are associated with the generally larger accelerations on that axis (see Fig. 2). It is also worth
noting that these evaluations do not consider the role of torsional responses, which were purposefully filtered here to correlate observations with bi-directional motion simulator studies. As these motions are observed to be particularly disruptive, they should receive specific attention, though this is beyond the scope of the present conference paper.

![Graphical representation of data](image)

Figure 6: Gaussian long (50 minutes) and short (12 minutes) duration events observed in full-scale for x (top) and y (bottom) sway responses for case study tall building in June 2007

**CLOSING DISCUSSION**

In this study, a “pseudo-full-scale” evaluation of occupant comfort is attempted by correlating full-scale accelerations from an instrumented tall building with motion simulator studies that evaluated the influence of frequency, amplitude, duration and waveform on a group of human subjects. Though not the ideal scenario, as one would desire the ability to survey tenants of instrumented buildings directly, this study represents an attempt to practically assess occupant responses to annual wind events given the barriers prohibiting the ideal investigations. This of course assumes that the susceptibility of occupants in the case study building are comparable to the test subjects in the motion simulator studies and also does not account for the potentially significant role of torsional response. With that being said, this study cataloged the number of
full-scale occurrences of short duration events that proved to be task disruptive and long duration events that proved to be nauseating in motion simulator studies and projected the number of occurrences annually and the percentage of occupants likely affected. In terms of using this analysis to determine if performance of a tall building is “acceptable,” one must first acknowledge that there is considerable debate surrounding what an owner or designer may view as the “permissible” or “tolerable” percentage of occupants affected in a given way by a given motion. While perception is a measure of tolerance (zero tolerance), other tolerance criteria based on disruption of task or onset of nausea, as used in this study, would permit some motion beyond that which is perceptible, while excluding responses that may better be addressed by education of occupants. A similar sentiment is shared by [2]:

### Table 1: Task disruption (12 minute window) summary for Gaussian-type events in 2007

<table>
<thead>
<tr>
<th>Minimum STD Nausea [milli-g]</th>
<th>Task Disruption Rate1 [%]</th>
<th>Quantity of Events Exceeding Minimum STD</th>
<th>Yearly Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>F</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>0.5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1 From [10]
2 Quantity of Exceedance / (Minutes in a Year / Window Length)

### Table 2: Onset of nausea (50 minute window) summary for Gaussian-type events in 2007

<table>
<thead>
<tr>
<th>Minimum STD Nausea [milli-g]</th>
<th>Nausea Rate1 [%]</th>
<th>Quantity of Events Exceeding Minimum STD</th>
<th>Yearly Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>F</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>0.5</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1 From [10]
2 Quantity of Exceedance / (Minutes in a Year / Window Length)
the paramount issue to the building designer is the level of motion tolerance which building occupants will accept. In this context it is important to distinguish between “threshold of perception” and “level of tolerance”.

This then indicates that the current analysis should be married with a risk-based assessment metric [12] to provide the client with a decision matrix for determining the level of motion they are willing to tolerate (risk they are willing to absorb) on behalf of their tenants.

ACKNOWLEDGEMENT

The authors wish to acknowledge the financial support of the National Science Foundation, Grant CMMI 06-01143 and their wider collaborations with the Chicago Full-Scale Monitoring Program (established under PI: Dr. Ahsan Kareem of the University of Notre Dame; NSF Grant CMS-00-85109). The authors are grateful to the building owners, engineers and managers for their continued support of these efforts.

REFERENCES

References should be numbered sequentially in order of appearance, using the Journal of Wind Engineering and Industrial Aerodynamics referencing format. The following instructions and examples


