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Performance of Tall Buildings in Urban Zones: Lessons Learned from a Decade of Full-Scale Monitoring

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Abstract

The lack of systematic validation for the design process supporting tall buildings motivated the authors' research groups and their collaborators to found the Chicago Full-Scale Monitoring Program over a decade ago. This project has allowed the sustained *in-situ* observation of a collection of tall buildings now spanning worldwide. This paper overviews this program and the lessons learned in the process, ranging from appropriate technologies for response measurements to the factors influencing accurate prediction of dynamic properties all the way to how these properties then influence the prediction of response using wind tunnel testing and whether this response does indeed correlate with *in-situ* observations. Through this paper, these wide ranging subjects are addressed in a manner that demonstrates the importance of continued promotion and expansion of full-scale monitoring efforts and the ways in which these programs can provide true value-added to building owners and managers.

Keywords: Tall buildings, Full-scale monitoring, Damping, Frequency, Wind tunnel prediction, Finite element models

1. Introduction

The use of state-of-the-art sensing and diagnostics has been invaluable in a number of industries such as aerospace and automotive. The manufactured systems developed in these fields are heavily instrumented to provide essential feedback both for quality assurance and design improvements, but also for maintenance and operations in-service. While these fields have embraced technology as an essential partner in their design and manufacturing process, the same sadly cannot be said in structural engineering, despite the fact that such systems arguably have even more to gain from *in-situ* validation given their uniqueness, scale, complexity and cost. Consider, for example, modern tall buildings: these major investments, now attracting price tags in the hundreds of millions of dollars, are responsible for providing safe and comfortable home and work environments for their occupants, yet rely solely upon scaled model testing and an assortment of analytical models and design guidelines that have received little systematic validation in full-scale. Perhaps the stark difference in attitudes towards monitoring in these fields stems from history itself: the earliest uses of monitoring for assessment of tall building performance in the US were associated with "suspect" buildings, e.g., the John Hancock Tower in Boston (Durgin et al., 1990). This resulted in a pervasive attitude in non-seismic regions of the United States that a monitored building must be a troubled building. As a result, years later, designers continue to push the envelope with increasingly tall and complex structural forms whose designs remain underpinned by the same collection of un-validated tools and approaches.

A compounding challenge for tall buildings is the fact that their designs are generally governed by serviceability and habitability limit states under wind that are especially sensitive to the structure's dynamic properties. These properties, at least the natural frequencies and mode shapes, result from numerous assumptions made by designers to simplify highly complex and uncertain structures into manageable finite element (FE) models, without ever truly knowing the implications of these choices. They are then forced to make even less guided choices when specifying the anticipated level of damping, having no reliable predictive tool to consult in the design stage. While their choice may be informed by published full-scale damping values, these are generally tied to comparatively shorter structures, whose underlying structural systems differ fundamentally from modern tall buildings, e.g., a large portion of the buildings in the well-known Japanese database (Satake et al., 2003) and the buildings involved

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in the full-scale measurement projects conducted by UK Building Research Establishment (Ellis, 1996; Littler and Murphy, 1994). Moreover, in the case of habitability assessment, the determination of acceptable performance requires understanding the complex interaction between human occupants and the structure, which in and of itself has stirred considerable debate. Unfortunately, only limited studies have attempted to resolve these debates through full-scale investigations (Denoon et al., 1999; Ohkuma, 1996; Ohkuma et al., 1991) and even fewer have been tied to actual validation of the design process (Li et al., 2004; Littler, 1991).

Thus this clear unmet need for *in-situ* validation of tall building design practice inspired the authors' groups in partnership with the design firm of Skidmore Owings and Merrill LLP in Chicago and wind tunnel consultants at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario to initiate the Chicago Full-Scale Monitoring Program (CFSMP) (Bashor et al., 2012; Kijewski-Correa et al., 2006b), which began in 2002 with the instrumentation of three tall buildings in Chicago and later expanded to include a residential tall building in South Korea in 2005 and then Burj Khalifa in 2008. While this project has been accompanied by a collection of much welcomed companion efforts in China, e.g., Central Plaza Tower, Di Wang Tower, and the Bank of China (Li et al., 2005; Li et al., 2003, 2004; Xu et al., 2003), the longevity of the CFSMP and its approach to the systematic validation of the design practice under a wide range of wind conditions remains distinctive. In over a decade of observing these buildings, numerous insights have been gained and will be overviewed in this paper. In some cases, these insights were unexpected, which further demonstrates the value-added by full-scale monitoring. But before discussing these expected and unexpected insights, the buildings that have served as the "living laboratory" enabling these discoveries are first introduced.

2. Overview of the Chicago Full-Scale Monitoring Program Buildings

The insights discussed in this paper are largely drawn from the CFSMP, which initiated in 2002 in downtown Chicago with three tall buildings representative of structural systems common to high-rise construction (Kijewski-Correa et al., 2006b). As this program globalized, a composite high-rise residential building in Seoul, South Korea was added in 2005 (Abdelrazaq et al., 2005). Recently this globalization continued with the addition of the world's tallest building Burj Khalifa, monitored by a unique "Smart Sync" system since 2008 (Kijewski-Correa et al., 2013). To guarantee continued access to the buildings for the life of the program, the majority of the buildings' identities must remain anonymous as required by the owners. Thus the three Chicago buildings will be generically referred to as Buildings 1-3, the Korean site as Building 4, and Burj Khalifa as Building 5. The installed monitoring systems, summarized in Table 1, include accelerometers with approximate resolution of 0.001 milli-g, ultrasonic anemometers with resolutions of 0.1 m/s in wind speed and 1° in wind direction, and global positioning systems (GPS) with sub-centimeter resolution (Kijewski-Correa et al., 2006b; Kijewski-Correa et al., 2013). Noteworthy features of the buildings' lateral systems, which do closely relate to *in-situ* behaviors, are now briefly discussed, with additional details available in a collection of past publications (Abdelrazaq et al., 2005; Baker et al., 2007; Kijewski-Correa et al., 2006b).

Building 1: The primary lateral load-resisting system features a steel tube comprised of exterior columns, spandrel ties, and addition stiffening elements to achieve a near uniform distribution of axial loads on columns across the flange face, with very little shear lag. As such, the building is dominated by cantilever action under lateral loads.

Building 2: This reinforced concrete building relies upon a lateral system comprised of shear walls located near the core. At two levels, the core is tied to the perimeter columns via reinforced concrete outrigger walls in the x-axis to control the wind-induced drift and reduce overturning moment in the core shear walls.

Building 3: Lateral loads are resisted by a steel moment-connected framed tube system comprised of closely spaced, wide columns and deep spandrel beams along multiple frame lines. Overall deformation of the structure is due to a combination of axial shortening, beam shearing/flexure, and connection panel zone distortions.

Building 4: The primary lateral load-resisting system of this building is an indirect outrigger belt wall system

Table 1. Structural system and instrumentation array in each monitored building

No.	Location	Primary Material	Lateral System	Accelerometer		Anemometer		GPS	
				No.	Model	No.	Model	No.	Model
1	Chicago	Steel	Stiffened tube	4	Columbia SA-107 LN	0	N/A	1	Leica MC500
2	Chicago	Concrete	Core + outrigger	4	Columbia SA-107 LN	0	N/A	0	N/A
3	Chicago	Concrete	Tube	4	Columbia SA-107 LN	2	Vaisala WAS425 & FT702	0	N/A
4	Seoul	Concrete	Core + belt walls	6	Wilcoxon 731A/P31	1	FT702	0	N/A
5	Dubai	Concrete	Core + buttressed wall + outrigger	15	Columbia SA-107 LN	1	Vaisala WXT520	1	Leica AT504 GG

located at two mechanical levels. The composite perimeter columns are linked to the reinforced concrete core through a reinforced concrete belt wall and very stiff composite floor slabs to reduce lateral drift. The deformation of the structure is due to both cantilever and frame action.

Building 5: For this building, lateral resistance is supplied by a reinforced concrete hexagonal core, buttressed by high performance concrete walls along three wings. Columns are engaged in lateral load resistance through outriggers at the mechanical levels to achieve nearly ideal cantilever behavior. All vertical elements carry both gravity and lateral loads.

3. Major Findings of the CFSMP

The CFSMP has specifically focused its instrumentation and targeted assessments on particular aspects of the tall building design process, including the predicted dynamic properties and total wind-induced response derived from wind tunnel testing. The following sections overview the insights that have been gained when exploring each of these aspects.

3.1. The value of *in-situ* measurements of displacements

The traditional approach to full-scale monitoring relies solely on accelerometers to capture structural responses, and as a result, displacements are generally recovered by double integration. While this process does pose a range of numerical challenges, and even when these are overcome, the resulting displacements are still incomplete, at least in the case of wind-induced response. This is due to the fact that the displacement response of any structure under wind visually depicted in Fig. 1, can be characterized by three components: a mean component (Δ), a slower-varying background component (δB), and faster-varying a resonant component (δR), oscillating at the natural frequencies of the structure. While much emphasis is placed on the resonant response, studies have shown that non-resonant response can contribute as much as 80% of the total response for some structures in certain wind events (Williams and Kareem, 2003). Thus the inability to recover the total displacements, due to the inability to solve for constants of integration when double integrating accelerations, implies that a potentially large portion of the overall response picture may be lost, necessitating an alternative technology for the direct measurement of full-scale displacements. Unfortunately, until recently, there were no reliable means to do so, though the rapid advancement of GPS now makes this possible. In fact the deployment and operation of the GPS on Building 1 of the Chicago Full-Scale Monitoring Program since 2002 is arguably one of the longest sustained deployments of GPS on a tall building and has verified that high-precision GPS, with accuracies on the order of 5 mm, can yield full-scale data of quality commensurate with accelerometers (Kijewski-Correa et al., 2006a).

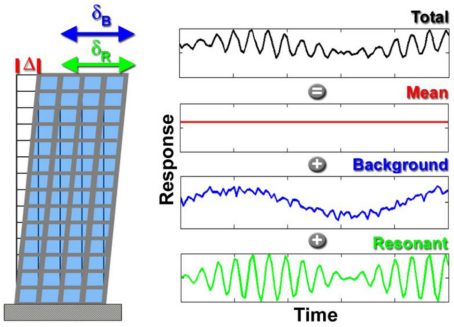


Figure 1. Components of total wind-induced response.

It should be noted that the GPS necessary for high fidelity structural monitoring is up to ten times more expensive than traditional sensors like accelerometers and requires a local stationary reference point. Moreover, because of its sophistication and the uniqueness of its sensing approach, careful understanding of the effects of the continuous variation in satellite visibility and orientation, as well as the potential for multipath distortions, is required to achieve consistently reliable measurements (Kijewski-Correa and Kochly, 2007). Therefore its implementation in every project may not be feasible or successful; however, these devices have proven invaluable in over a decade of monitoring by allowing rare glimpses of mean and background responses previously unobserved in full-scale (Kijewski-Correa and Kochly, 2007).

3.2. Correlation of system behaviors to accuracy and amplitude dependence of frequencies

One of the first validations sought in full-scale monitoring often centers on the analytical models used in the design of the structure, generally created in commercial FE packages. In order to validate the standard assumptions invoked by designers in this process, all the models used in the CFSMP were developed in house by project collaborators at Skidmore Owings and Merrill LLP in Chicago. The fundamental frequencies predicted by these models were then compared with those extracted from the monitored structures during various wind events. Over the last decade, these comparisons have been published in a number of studies (Abdelrazaq et al., 2005; Bashor et al., 2011; Bentz and Kijewski-Correa, 2012; Bentz et al., 2010; Kijewski-Correa et al., 2006b; Kijewski-Correa et al., 2005a; Kijewski-Correa and Pirnia, 2007; Kijewski-Correa et al., 2007; Kijewski-Correa et al., 2005b; Kilpatrick et al., 2003; Pirnia et al., 2007). Bashor et al. (2012) recently presented the frequencies estimated by both standard frequency domain (spectral half power bandwidth) and time domain (random decrement) approaches for hundreds of triggered records from Buildings 1-3 as a function of amplitude, an example of which is presented in Fig. 2.

As this excerpt demonstrates, although a linear elastic assumption is often invoked to simplify analysis, the vari-

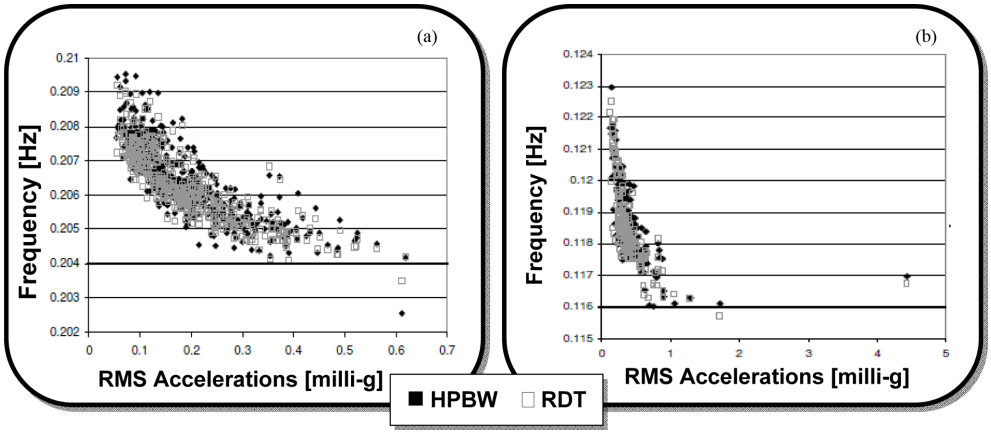


Figure 2. Variation of fundamental frequency with amplitude for (a) Building 1 (x-sway) and (b) Building 3 (y-sway) (adapted from Bashor et al. (2011)).

ations in frequency over a range of events suggest that these structures do not behave as such. These *in-situ* observations confirm that the inherent nonlinearity in materials and connection details, as well as the interaction of non-structural elements, manifest as variations in both frequency and damping with the amplitude of the response. The trends in Fig. 2 suggest that frequencies do soften with increasing amplitude, as commonly hypothesized, until reaching a more stable plateau at high enough amplitudes. This plateau effect can be observed for Building 1 in Fig. 2(a), though the range of amplitudes observed was not sufficient to do so for Building 3 (see Fig. 2(b)).

Because of the degree of scatter that can be observed when visualizing a large number of events, and the difficulty in determining the cause of the observed frequency variations due to the inability to control for many possible causes, a multiple-trigger random decrement technique has been implemented to investigate the amplitude dependence within a single event (Kijewski-Correa and Pirnia, 2007). These frequency-amplitude curves can then be fit to identify the rate of softening with amplitude (negative slope term) and the initial frequency of the system (y-intercept). An example of such analysis is presented in Table 2 for Buildings 1-4. Note that Building 1 shows amplitude dependence on the order of 1~2% of the initial frequency, indicating its frequencies are fairly insensitive to amplitude changes, quite similar to Building 3, which also shows modest amplitude dependence. Note that both of these buildings are steel tubes, which engage columns in axial shortening/elongation in a so-called cantilever behavior, though Building 1 has proven far more efficient in doing so. Interestingly, the phenomena observed for Buildings 1 and 3 are in contrast to that of Building 2, whose y-axis shows significantly more amplitude dependence than its x-axis (11% vs. 1.3%). While it may be contended that this is merely a result of the material in question, cracked concrete showing a greater tendency toward amplitude-dependence than steel, the large difference in the degree of amplitude-dependence between the two sway axes within this concrete building suggests another factor is at play. Building 2's x-axis is dominated by axial shortening associated with its slender shear walls and outriggers, while its y-axis relies on frame action of the slabs engaging the distributed columns for its lateral resistance. This is further confirmed by considering Building 4, who similarly shows comparable levels of amplitude dependence on both its axes (approximately 5~6%) and is known to have a continuous structural system achieving comparable degrees of cantilever action along both primary axes. Thus the fact that a comparably lower level of amplitude dependence is observed in cantilever-dominated systems (both concrete and steel) and a considerably higher level of amplitude dependence is exhibited in systems that behave otherwise would at least suggest that this amplitude dependence in frequency is more pronounced in systems dominated by frame action.

Interestingly, these system behaviors were also found to be effective predictors of the accuracy of finite element models. Bentz (2012) conducted a comprehensive study to identify the root of inaccuracies in the FE predictions

Table 2. Primary deformation mechanism and amplitude-dependent fundamental frequency relationship

Building	Dominant Mechanism	Predicted Frequencies (Hz)		*In-Situ* Frequencies (Hz)	
		X-Sway	Y-Sway	X-Sway	Y-Sway
1	Cantilever	0.204	0.143	-0.006x+0.208	-0.002x+0.144
2	Cantilever (X), Frame (Y)	0.149	0.156	-0.002x+0.182	-0.022x+0.186
3	Combination	0.132	0.130	-0.001x+0.220	-0.004x+0.122
4	Combination	0.147	0.152	-0.001x+0.198	-0.001x+0.207

of tall buildings by comparing predicted frequencies to observed frequencies for a range of tall buildings including those outside of the current monitoring effort. In doing so she found that structural system behavior (defined by its degree of cantilever action) is an important indicator of prediction accuracy and that increasingly cantilever systems yielded more accurate predictions of frequencies. This helped to explain why frequencies of Building 1 were more accurately predicted in comparison to Building 3, even though they were both steel buildings, noting that Building 3 has acknowledged greater reliance on force transfer through beam bending and the shearing of connection panel zones. Still, even acknowledging this, accurate frequency predictions for concrete structures has proven to be more challenging given the reliance on the assumed level of cracking and properties of the concrete *in-situ*; however, Building 5 has recently confirmed that sensitivity to such assumptions is dramatically reduced when the primary deformation mechanisms are axial (Abdelrazaq et al., 2012). While being able to predict the likelihood that a predicted frequency will be accurate is valuable, it is even more important to determine the root causes of discrepancies in these predictions, which has been a subject of additional investigations in the CFSMP (Bentz and Kijewski-Correa, 2012; Bentz et al., 2010; Kijewski-Correa et al., 2005b).

3.3. System behaviors as a predictor of *in-situ* damping

While frequencies can be predicted *a priori*, even with admitted limitations, using commercial FE packages, damping, on the other hand, remains without a rational basis for prediction. Derived from many complex and little understood mechanisms contributed by both the structural and nonstructural elements, its inability to relate to system geometries and materials in a direct manner like other properties, e.g., mass and stiffness, implies that damping is generally assumed based on a somewhat archaic understanding of influencing factors. As such, one of the most critical aspects of the monitoring program has been the extraction of *in-situ* damping values. Bashor et al. (2012) similarly evaluated the critical damping ratios in the fundamental sway modes for Buildings 1-3 from hundreds of triggered responses. Figure 3 provides a sampling of this data for the same two cases shown previously in Fig. 2. It is clear that the estimation of damping is highly challenging, given not only its comparatively small role in shaping the overall response, but also given the fact that the forces driving wind-induced response can never truly be measured to support higher accuracy system identification. Despite the level of scatter, Bashor et al. (2012) documented evidence of amplitude dependence (see Fig. 3(a)), suggesting an increase of damping with amplitude, consistent with the widely held hypothesis. Since that prior study generated that data using bulk processing, it provided high-level perspectives on data trends, but had greater potential for error because of the absence of human quality assurance. Thus more in depth evaluation of isolated records is warranted. Applying the multi-trigger random decrement technique will similarly allow the variation of damping with amplitude, for a given event, to be ascertained (Kijewski-Correa and Pirnia, 2007). The results in Fig. 4 show that the two steel tube buildings (Buildings 1 and 3) both have comparable damping ratios on their respective fundamental sway axes, though Building 3 had a comparatively higher level of energy dissipation. Meanwhile, Building 2 again shows distinctly different behaviors on its two axes. In fact, the damping on the y-axis of Building 2, previously noted to be dominated by more frame action, is markedly higher than the damping on the x-axis known to be dominated by cantilever action due to its tall, slender shear walls. This seems to suggest that damping is more closely tied to typology and system behavior, which can vary even within a given building, than solely the construction material. Further, even for the two steel tube systems (Buildings 1 and 3), Building 1 has lower damping and is known to have a greater proportion of cantilever action in its structural system. This is a particularly interesting finding considering that damping values

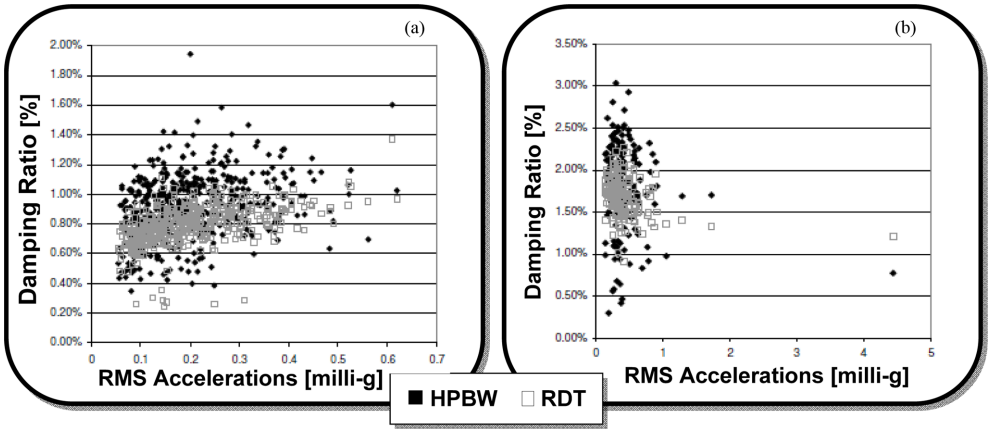


Figure 3. Variation of damping ratio in fundamental modes with amplitude for (a) Building 1 (x-sway) and (b) Building 3 (y-sway) (adapted from Bashor et al. (2011)).

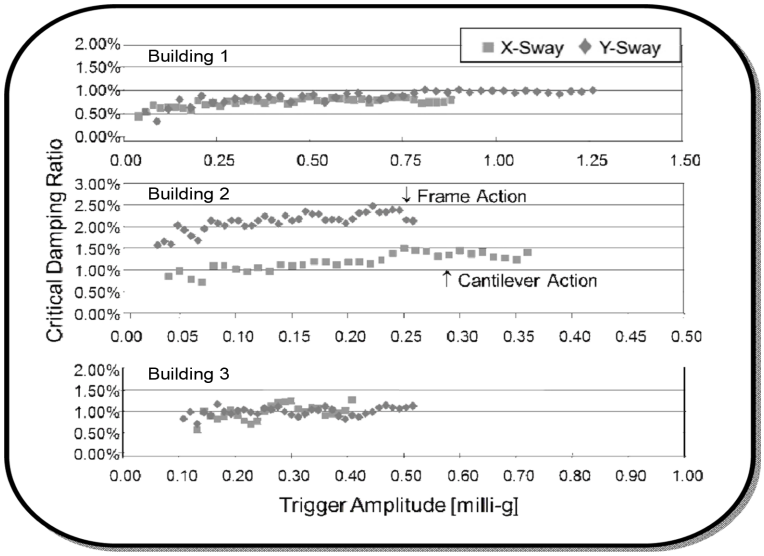


Figure 4. Amplitude dependent damping ratios for fundamental sway modes of Buildings 1-3 (adapted from Kijewski-Correa and Pirnia (2007)).

are traditionally assigned to a building in design practice based on the construction material, or perhaps gauged from damping databases where damping ratios are parameterized by purely geometric quantities like building height and generally correspond to buildings with structural systems rarely found in modern super tall buildings. These observations prompted additional investigations by Williams et al. (2013) that revealed similar trends in other monitored tall buildings. As such, the observation that more cantilever-dominated structures dissipated comparatively less energy motivated the introduction of a new typology-driven damping model (Bentz and Kijewski-Correa, 2013).

3.4. Accurate prediction of wind-induced responses remains challenging

The lack of analytical means to predict the alongwind, acrosswind and torsional responses of tall buildings under the action of wind necessitates reliance on wind tunnel testing for projects of any significance. As the wind-induced responses are especially sensitive to the structural dynamic properties, accurate estimates of these properties in and of themselves are critical to effective prediction, motivating much of the work presented in Sections 3.2 and 3.3. Thus it is important to separate errors in the estimation of dynamic properties from those errors inherent to the prediction of ensuing responses using wind tunnel testing. Moreover, assessment and mitigation of both error sources are vital to improving the economy and efficiency of future tall buildings. While a number of studies have compared wind tunnel predictions to full-scale data (Dalgliesh et al., 1983; Fu et al., 2012; Guo et al., 2012; Lee, 1982; Li et al., 2006; Li et al., 2007), these comparisons have limited relevance to this study as they are (1) often for isolated wind events or based on short-term observations (no more than two years), failing to capture the range of wind conditions that long-term monitoring offers and/or (2) involved buildings that would not be classified as "tall" by today' standards or share the same level of wind sensitivity as the buildings in this study. As such CFSMP's archives of over a decade of full-scale data to facilitate more comprehensive validations are especially valuable. As previous publications have described the methodology used to predict responses from wind tunnel data (Bashor et al., 2012; Kijewski-Correa et al., 2006b), these details will not be repeated herein. Instead this section will focus on discussing general trends in prediction accuracy observed over entire years of full-scale observations. It should first be noted that all of the wind events recorded are well below the design wind speed of 90 mph.

In order to visualize the general trends in response prediction accuracy for the three buildings in Chicago, the rms accelerations observed in full-scale (measured in 2002 for Buildings 1-2 and 2003 for Building 3) are compared to upper and lower bound wind tunnel predictions. The upper and lower bounds were determined by considering the observed *in-situ* properties for best and worst case responses, given the observed uncertainties in damping ratios and wind speeds at the building height. The results are presented in Fig. 5, noting that the measured accelerations are averaged quantities and thus are sensitive to the number of observations used in that average, which are limited at higher wind speeds. Note that the difference between these best case (low) and worst case (high) predictions can be quite significant, underscoring the effect of even minor uncertainties in critical parameters like wind speed and damping ratio.

The wind tunnel predictions for the x-axis of Building 1 are relatively accurate in the sense that the full-scale data fall into the predicted range except for the wind speed subset at 51~66 mph, where the response is over-predicted.

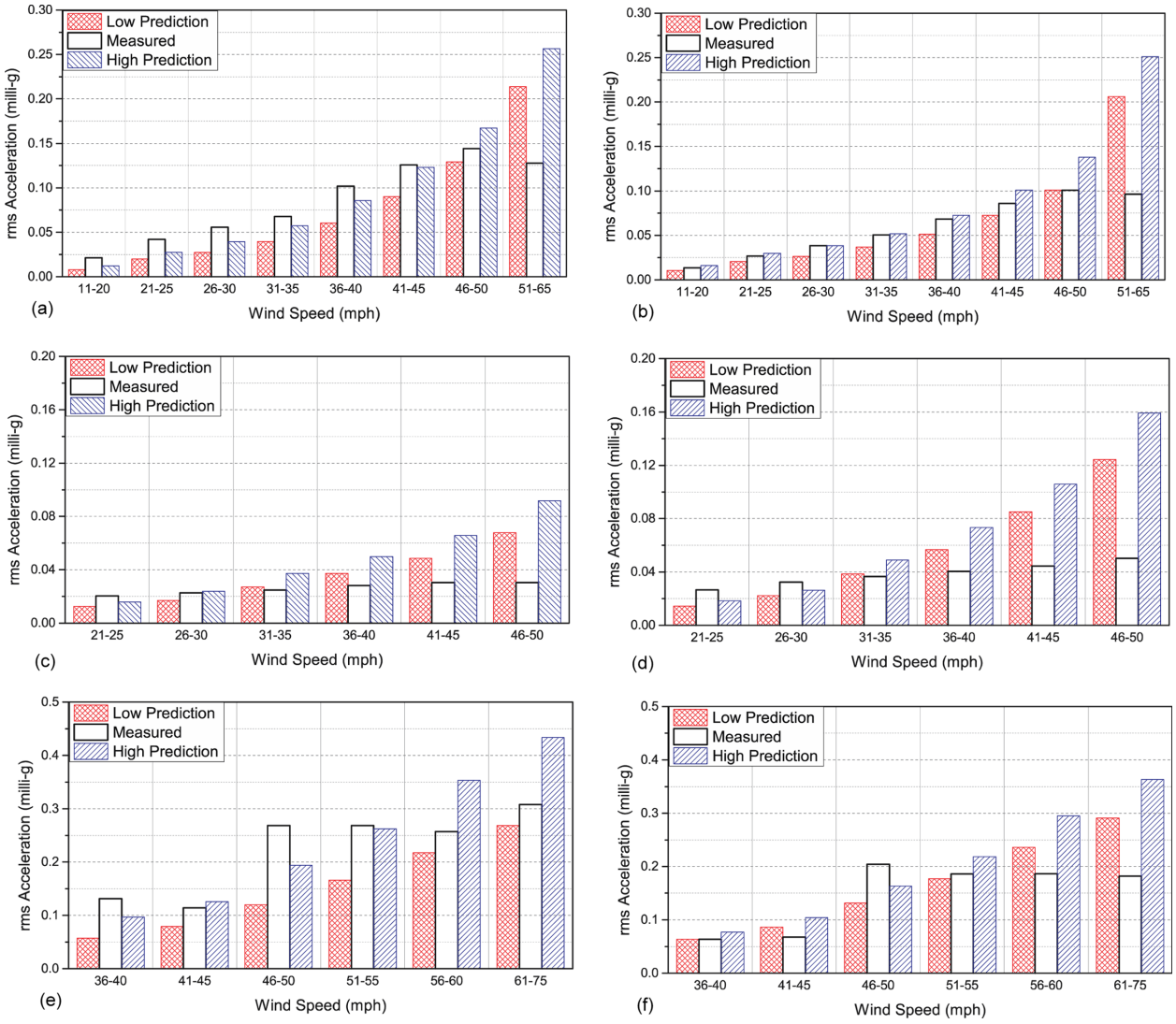


Figure 5. Comparison of average of the measured rms acceleration with wind tunnel predictions for Buildings 1-3, subdivided by wind speed: (a) Building 1, Mode 1 (Y-sway), (b) Building 1, Mode 2 (X-sway), (c) Building 2, Mode 1 (X-sway), (d) Building 2, Mode 2 (Y-sway), (e) Building 3, Mode 1 (X-sway), and (f) Building 3, Mode 2 (Y-sway).

However, for the y-axis, the wind tunnel test tends to under-predict the response for low wind speeds (≤ 45 mph) and over-predict the response for high wind speeds (50 mph). Similar observations are apparent for both the axes of Building 2, where response at lower wind speeds (≤ 25 mph for x-axis, ≤ 30 mph for y-axis) is under-predicted and that for higher wind speeds (30 mph) is over-predicted. For Building 3, such a simple trend does not exist, with predictions both over and under estimating the response. It is hypothesized that the coupling between the fundamental sway modes of this building makes accurate predictions of its response more challenging.

This assessment is expanded to include additional data from 2003 to 2007 for Buildings 1-2 and from 2004 to 2007 for Building 3. For ease of interpretation, the percentage of occurrences when full-scale data fall within the ranges of predictions was tracked, for each sub-set of wind speeds. Figure 6(a) shows the wind speed range over which the full-scale observations most often fell within the wind tunnel predictions and its rate of occurrence. Due to the considerable scatter of the full-scale data, the highest occurrence percentage is only 36.3%, observed for Building 3 in Mode 1. It is hypothesized that the large scatter in the full-scale data may be partially due to the uncertainties introduced in the extrapolations of measured wind speeds in the calculation of the predicted responses. Buildings 1 and 2 actually achieve comparable performance in terms of their best rates of "successful prediction" and the wind speeds over which this occurs. While for Building 3, the best predictions for the two axes occur at different wind speed sub-sets. Given all the factors involved, including differences in the surrounding terrain that could influence one axis more significantly than another, the reasons for such trends are difficult to ascertain. However it

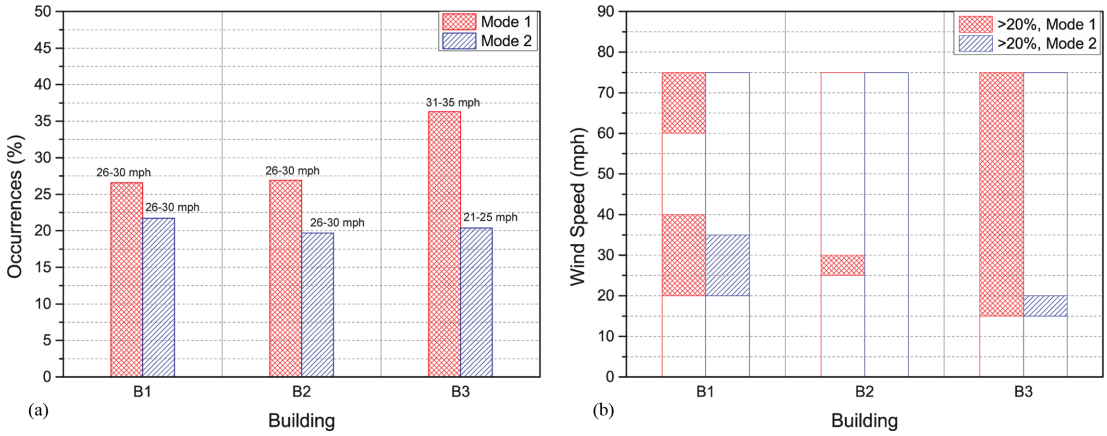


Figure 6. Percentage of occurrences when full-scale data fall within the ranges of predictions: (a) highest percentage of occurrences with its corresponding wind speed ranges for Buildings 1-3, and (b) wind speed ranges where more than 20% of full-scale data fall within the prediction ranges.

is noteworthy that the highest rate of agreement is observed at lower wind speeds (20~35 mph). Additionally, for all three buildings, the predictions for the first mode (fundamental Y-sway mode for Building 1, fundamental X-sway mode for Buildings 2-3) are more accurate than that associated with the second mode (fundamental X-sway mode for Building 1, fundamental Y-sway mode for Buildings 2-3).

To offer a different means to interpret these results, Fig. 6(b) plots the wind speed ranges over which more than 20% of the full-scale data fell within the wind tunnel prediction ranges. This representation reveals that Building 2's responses are most difficult to predict, meeting this minimum threshold of performance only when winds are 25~30 mph. As seen in Fig. 5, the predictions for Building 2 show a greater degree of conservatism, which has also been observed in an earlier study (Bashor et al., 2012). It is also interesting to observe that when wind speed is higher (> 60 mph), the wind tunnel predictions for the first mode (Y-sway) of Building 1 seem to become more accurate, potentially due to the amplitude dependence of damping. Interestingly, the predictions for the first mode of Building 3 are relatively accurate over a much wider wind speed range (15~75 mph), while the second mode prediction is generally less reliable. As Building 3 has some asymmetric features in its mass and stiffness distributions, it would not be surprising to see the two fundamental modes show divergent behaviors *in-situ*.

4. Unexpected Insights

While many of the insights generated from a decade of monitoring could be somewhat expected and were precisely what the project was intended to reveal, the true benefits of full scale monitoring are best demonstrated by those unintended discoveries. One of these discoveries centers on the role of transient events. Current tall building design practice has consciously neglected responses that result from transient wind events, such as thunderstorms and downbursts, due to their short duration. However, full-scale monitoring has evidenced that these events, which occur with frequent regularity in some climates, often result in accelerations that exceed those generated by their stationary synoptic counterparts for a given wind speed, as was observed in the case of Building 4 (Kijewski-Correa and Bentz, 2011). In fact, independent anecdotal reports from occupants of buildings monitored in this program further confirmed that these accelerations may affect human comfort or at least be perceptible on more frequent recurrence intervals. This is consistent with other full-scale studies that documented differences in occupant responses to transient wind events (Denoon, 2004). These observations inspired further research into the *in-situ* characteristics of transient events, the root causes of their comparatively larger accelerations, as well as the potential impacts on human comfort. A suite of analysis tools is now presented to demonstrate how such events can be evaluated.

4.1. Event characterization

Three triggered time histories were collected from Building 5 on April 13-14, 2012, one of which was associated with a sudden increase in wind speed, commensurate with a rapid change of wind direction. This event had many hallmarks of transient events observed in other instrumented buildings in this program (Bentz and Kijewski-Correa, 2009; Kijewski-Correa and Bentz, 2011) and was thus identified for further investigation. To first better describe the characteristics of the resulting three hours of triggered response, the waveform composition within the records is classified. This is accomplished as the first stage of a process discussed in Weigand and Kijewski-Correa (2013) used to assess potential impacts on occupant comfort, the results of which will be presented in Section 4.2. Once each mode is isolated, a short duration moving analysis window (12 minutes) is passed over the record and peak

Table 3. Waveform classification (expressed as a percentage) in Building 5 for April 2012 wind event

Waveform	Mode (sway direction)									
	1 (X)	2 (Y)	4 (X)	5 (Y)	6 (X)	7 (Y)	8 (X)	9 (Y)	11 (X)	12 (Y)
Short Duration Analysis Window										
Sinusoidal	58	48	43	35	31	31	30	40	43	44
Narrowband	29	51	46	48	53	56	60	52	53	53
Burst	13	1	10	17	16	13	10	8	4	2
Long Duration Analysis Window										
Sinusoidal	41	0	15	4	0	14	0	23	0	4
Narrowband	56	100	65	68	76	64	74	58	65	69
Burst	4	0	19	28	24	23	26	19	35	27

factors are estimated by the upcrossing analysis used in the motion simulator studies by Burton et al. (2005). Responses are grouped by peak factor, with those having peak factors less than 2.5 classified as sinusoidal, between 2.5 and 4.05 as being narrowband, and those exceeding 4.05 as being burst-like responses, adopting the convention set in Pirnia and Kijewski-Correa (2009). The process is then repeated for long-duration analysis windows (50 minutes) again for consistency with Burton et al. (2005). While the narrowband Gaussian response with randomly modulated amplitudes is what one would classically expect, *in-situ* observations show patterns where resonant response "locks in" to a specific mode with little amplitude modulation (sinusoids) and instances where large peak factors are observed and responses carry more impulsive features (burst) and often the presence of multiple participating modes. The burst responses are those of particular interest given their tendency to produce high amplitude responses and unique dynamic features (Kijewski-Correa and Bentz, 2011). The classification of waveform, by mode, is presented in Table 3 for several of the modes that have non-negligible participation in the response at one of the building's occupied levels. When applying a similar classification approach to Building 1 in Chicago, Bentz (2012) found the distribution of wave forms to be typically 50% Gaussian, 30~40% sinusoidal and 10~20% burst-like, in this case only within the fundamental mode since higher mode responses were not observed in this building. While the long-duration analysis window shows that Building 5 has comparable features, for the shorter duration window, there is a reduction in the amount of sinusoidal response observed. Modes 5 and 6 show the greatest pre-disposition to burst-like responses in this event, with Modes 1 and 7 similarly showing elevated amounts of burst-like response. It is also interesting to note that while Mode 1 shows this tendency, similar behavior is not observed for its companion fundamental mode on the opposing axis (Mode 2). When considering the wind angles observed in this event, these x-axis responses would be considered acrosswind responses. As the analysis window duration is increased, the fundamental mode in the y-axis, the alongwind axis in this event, can be characterized as completely narrowband response while the higher modes show an increasing percentage of burst like responses. It is not surprising that the only noteworthy presence of sinusoidal response is in the acrosswind axis for the fundamental mode (Mode 1).

The ability of the structure to dissipate energy when impacted with impulsive-type excitations is especially critical. To evaluate the level of energy dissipation available to the building in such instances, a transient system identification approach is applied to the fundamental modal responses in both the x- and y- directions at one of the instrumented levels. The approach, explained in greater detail in Guo and Kareem (2013), uses the wavelet transform (with the Laplace wavelet) in conjunction with transformed singular value decomposition to identify the frequency and damping from the extracted burst-like responses in the three hours of recorded data. The results are shown in Fig. 7 as a function of the maximum amplitude of that burst-like response, while the average values are summarized in Table 4. Both sets of results express the frequency and damping during the burst-like events as a percentage of previously observed *in-situ* dynamic properties for measured narrowbanded responses to stationary wind events, referred to as reference properties. While the burst-like responses oscillate at a frequency identical to these reference properties (those observed in corresponding modes in the stationary narrowband responses), the damping values in the burst-like responses show more scatter and suggest that at the higher amplitudes of the response, less energy may be dissipated than in the case of its stationary counterpart, though at lower amplitudes, the reverse is true. More importantly, these results confirm that this analysis tool can be used to extract reliable estimates of nearly instantaneous dynamic properties from recorded responses, which is a tremendous advantage when considering the number of hours of data normally required to extract reliable damping estimates by traditional stationary analysis approaches.

4.2. Monitoring informing decision support tools

An equally important benefit of full-scale monitoring is the ability to provide real-time decision support for the management and operation of the building. The globalization of this project has made this consideration a growing priority now that owner-driven requirements have sha-

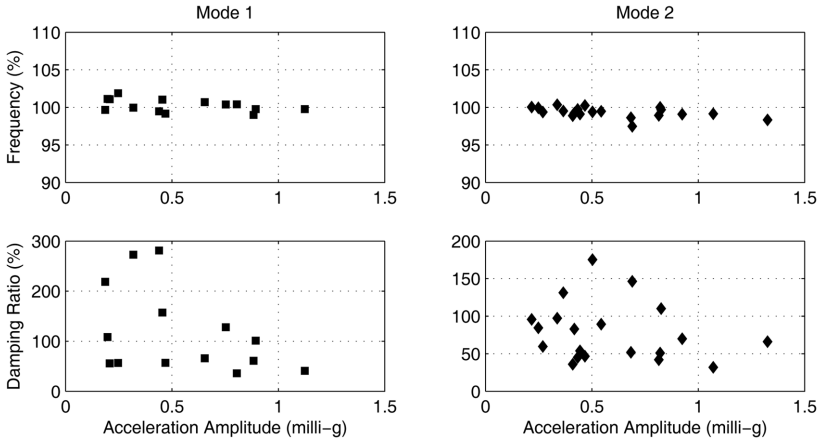


Figure 7. Amplitude dependence in dynamic properties (as percent of reference properties) of Building 5 in transient events.

Table 4. Average frequency and damping values of Building 5 under impulsive motions (as percent of reference properties)

f(%)	ξ(%)	f(%)	ξ(%)
100	117	100	79

ped the monitoring program and the delivery of a "Smart Sync" system to Building 5 (Kijewski-Correa et al., 2012). Particularly for habitability assessment, which involves delicate matters like occupant perception and comfort, the ability to reliably assess performance without attracting unwanted attention from tenants is critical. For this reason, a framework for pseudo-full scale assessment of occupant comfort was first proposed by Kijewski-Correa and Pirnia (2009). In this approach, full-scale accelerations are mapped to human comfort thresholds derived from extensive motion simulator work (Burton et al., 2005). This framework allows the measured accelerations at a given floor of a building to be translated to what an owner desires most: the likely number of tenants that would have been affected, i.e., would experience sensations such as nausea or task disruption. Through this approach, the complex human-structure interaction that dictates whether habitability performance is acceptable can be accounted for in a reliable manner, without directly interviewing or engaging the tenants themselves. Bentz (2012) extended this framework to account for the role of torsional response and to project these occupant comfort assessments over the entire building to assess the total number of potentially affected tenants, accounting for occupancy rates and even the time of day. Later, Weigand and Kijewski-Correa (2013) further extended this framework to assess the role of higher modes of response, a consideration that is especially critical when considering the growing potential for higher mode contributions to wind-induced response in modern supertall buildings with exceptionally low frequencies. Within this framework, measured responses are automatically processed through a calibrated filter bank to isolate each mode of interest and the resulting modal responses are grouped by waveform, using the peak factor approach discussed previously. Burton et al. (2005) found that narrowband processes are more prone to elicit disruptive effects on occupants. Specifically, short duration windows (12 minutes) were found to influence task disruption, while longer duration windows (50 minutes) best correlated with rates of nausea. As such, only the portions of the responses characterized as narrowband by their extracted peak factors were retained and, for the rms acceleration associated with that segment of the response and its frequency of oscillation, the corresponding rates of nausea and task disruption observed in these motion simulator studies are reported. It is worth noting at this point that task disruption is quite different from perception, which could be more sensitive to other wave forms, such as burst responses. In fact anecdotal evidence suggests that this may indeed be the case. Still, what is important to note is that the same framework used here could be applied to evaluate likely rates of perception if similar high-quality motion simulator results were available for other frequency, amplitude and waveform ranges. This assessment framework is now applied to an event from Building 5 to demonstrate the utility of such a tool in rapidly assessing the habitability performance of the building during this case study wind event.

The assessment focusses on measurements at the lowest (L1) and highest (L2) occupied floors that are instrumented by this program. The results reveal that the x-sway response at L2, in one instance, could have invoked nausea in 5% of the occupants, while there was not a single occurrence at L1 that would have done so, providing considerable assurances to the owner that the majority of tenants would not have objected to the building response in this event. As a point of illustration, the analysis is applied to the response of an unoccupied mechanical space at the upper levels of the building (L3) during this event, which are of course considerably larger than that the occupied portions of the building would even experience in its lifetime. This space was most likely designed

from a strength perspective rather than habitability. Based on this hypothetical case, again offered to demonstrate the functions of this occupant comfort assessment tool, the occurrence affecting the largest percentage of the population is identified for each mode and each hour of the three hour event. For each occurrence that could cause task disruption and nausea, the corresponding percentage of the affected population is denoted by a solid dot in Tables 5 and 6, respectively. For any given mode, different occurrences will cause different levels of affected population, depending on the amplitude. For example, referring to Table 5, in Mode 4 there were three segments causing task disruption at acceleration levels that would have affected 25, 60 and 85% of the population, respectively. It is important to note that the motion simulator tests used herein simulated only a limited range of frequencies and only modes 3-9 of Building 5 fall within that range and thus can be evaluated. Modes 4 and 5 provides the highest potential rates of task disruption (85% of the population would have diminished capabilities to execute cognitive tasks under these conditions). In fact, at least half the population would experience task disruption given the responses observed for any one of the modes in Table 5. Similarly, nausea was found to be induced by longer-duration, sustained motions. Table 6 documents the likely percentages of occupants that would feel nausea under the recorded motions at L3. In this case, only Modes 4 and 5 would affect at least half the population. While this again is merely a hypothetical assessment, had such responses been observed at occupied floors in a building, this analysis would provide an owner important information to support the decision as to whether some remedial actions may be required to improve the habitability performance of the structure, based both on the number of affected occupants as well as the recurrence of the motions annually. Once again, it is reiterated that this example is used as merely a point of demonstration, since such actions in this case would not be warranted for such unoccupied spaces well above occupied floors of tall buildings.

5. Concluding Remarks

This paper presented a series of observations garnered from more than a decade of the Chicago Full-Scale Monitoring Program, which was founded to offer a systematic

Table 5. Rates of task disruption among potential occupants at an unoccupied mechanical space of Building 5 (L3)

Amplitude Level	Population Affected (%)	Mode (Dir.)		Population Affected (%)	Mode (Dir.)		Population Affected (%)	Mode (Dir.)	
		4 (X)	5 (Y)		6 (X)	7 (Y)		8 (X)	9 (Y)
0	0	0	0	0	0	0	0	0	0
1	15	0	0	15	0	0	2	0	0
2	20	0	0	25	0	0	35	0	0
3	25	●	●	30	●	0	55	●	●
4	40	0	0	35	0	●	70	0	0
5	45	0	0	40	●	●	75	0	0
6	50	0	●	42	0	0	80	0	0
7	60	●	0	45	0	0	75	0	0
8	75	0	0	60	●	0	70	● ●	●
9	85	●	●	72	0	●	60	0	0
10	100	0	0	80	0	0	55	0	●

Table 6. Rates of nausea among potential occupants at an unoccupied mechanical space of Building 5 (L3)

Amplitude Level	Population Affected (%)	Mode (Dir.)		Population Affected (%)	Mode (Dir.)		Population Affected (%)	Mode (Dir.)	
		4 (X)	5 (Y)		6 (X)	7 (Y)		8 (X)	9 (Y)
0	0	0	0	0	0	●	0	●	0
1	5	0	0	2	0	0	2	0	0
2	10	0	●	2	0	0	20	0	0
3	12	●	0	3	●	●	25	0	●
4	14	0	0	4	●	0	20	0	0
5	30	0	0	6	0	0	5	0	0
6	40	0	0	10	0	0	5	0	0
7	45	●	●	20	●	0	10	●	●
8	50	0	●	30	0	●	20	0	0
9	52	●	0	35	0	0	30	●	●
10	55	0	0	40	0	0	40	0	0

in-situ validation of the design process supporting tall buildings. The examples presented in this paper underscore the importance of direct displacement measurement using new technologies such as GPS, since accelerometers cannot fully recover the mean and background components of displacement response that are critical for tall buildings under wind. The accurate prediction of this response to wind is driven significantly by the dynamic properties of the structure. To this end, this paper explored how structural system features correlate with the level of accuracy in predicted frequencies, as well as the degree of amplitude dependence they manifest. This program, as well as other full-scale monitoring efforts, suggests that more cantilever-dominated structures display less amplitude dependence in their dynamic properties and are less sensitive to uncertainties in the modeling process. Unfortunately, the lack of effective predictive tools for damping preclude any rational basis for their estimation, though it was demonstrated that system behaviors were found to correlate with the observed damping levels, with more efficient cantilever structures having diminished capacity for energy dissipation. In order to account for the observed uncertainties surrounding dynamic properties, as well as uncertainties in the estimated gradient wind speeds, *in-situ* accelerations were compared to a range of wind tunnel predictions. While accelerations were both under and over predicted, the range of wind speeds for which responses fell within the prediction range was identified for each building. These predictions assumed the classical narrowband response one normally expects under stationary winds; however, this monitoring program has observed transient wind events capable of generating acceleration responses greater than their synoptic counterparts. Thus an analysis of one of these events is presented to demonstrate the characteristics of structural response in these events and the corresponding dynamic properties using a transient system identification framework. As these events can at times trigger perception complaints, a decision support tool was presented that allows a rational assessment of habitability performance without intrusion on occupants. This represents an example of how monitoring can deliver not only feedback to the design process but also an important value-added that can assist in the evaluation and operation of the structure in-service. By doing so, monitoring can be further incentivized so that access to a greater cross section of buildings can be achieved. The days of a monitored building being a "troubled" building can finally be over, as the paradigm shifts to monitoring as a sign of an "intelligent" building. While the insights gained over a decade of monitoring are invaluable, it is important to recognize that in order for this paradigm shift to be achieved, the promotion and support of more full-scale monitoring worldwide is required on the part of engineers and architects so that we may further diversify the structural systems and wind climates within the community's full-scale inventories.

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