Full-Scale Monitoring

Three Lessons Learned from a Chicago Program

By Tracy Kijewski-Correa, Ph.D.

Trends and attitudes toward full-scale monitoring of buildings in the United States have varied regionally. In seismic zones, human and property losses have generally led to municipal incentives and even federal sponsorship of massive instrumentation efforts. This has resulted in an overall positive public perception surrounding monitoring and even open disclosure of building details and datasets, with many lessons learned. In contrast, monitoring under wind had previously only been undertaken in situations where a building's performance was suspect. Thus the studies were often confidential and public perception was not generally unfavorable, even though there is as much to learn and benefit from full-scale monitoring of buildings under wind as there is under earthquakes. Clearly, with respect to embracing full-scale monitoring nationwide, we are behind the curve. This has resulted in a lack of systematic validation of tall buildings, even though these projects are valued in the hundreds of millions of dollars and impact the safety and comfort of millions of Americans each day.

Recognizing this deficiency, the author and her colleagues established the Chicago Full-Scale Monitoring Program in 2001, with support from the National Science Foundation. The main goal of the project is to evaluate the performance of high-rise buildings under wind by comparing their measured and predicted responses, generated through the use of commercially available finite element models and wind tunnel testing. By pooling the expertise of researchers at the University of Notre Dame, consultants at the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario, and designers at Skidmore Owings and Merrill (SOM), this program was able to instrument three tall buildings in Chicago with a collection of global positioning systems (GPS), accelerometers and meteorological stations/anemometers (*Figure 1*) to observe their responses under a variety of wind events. Due to owner confidentiality, the identities of the buildings cannot be disclosed; their general designations are as follows:

Building #1 is a steel, stiffened tubular structure

Building #2 is a reinforced concrete shear wall/outrigger system

Building #3 is a steel tubular system

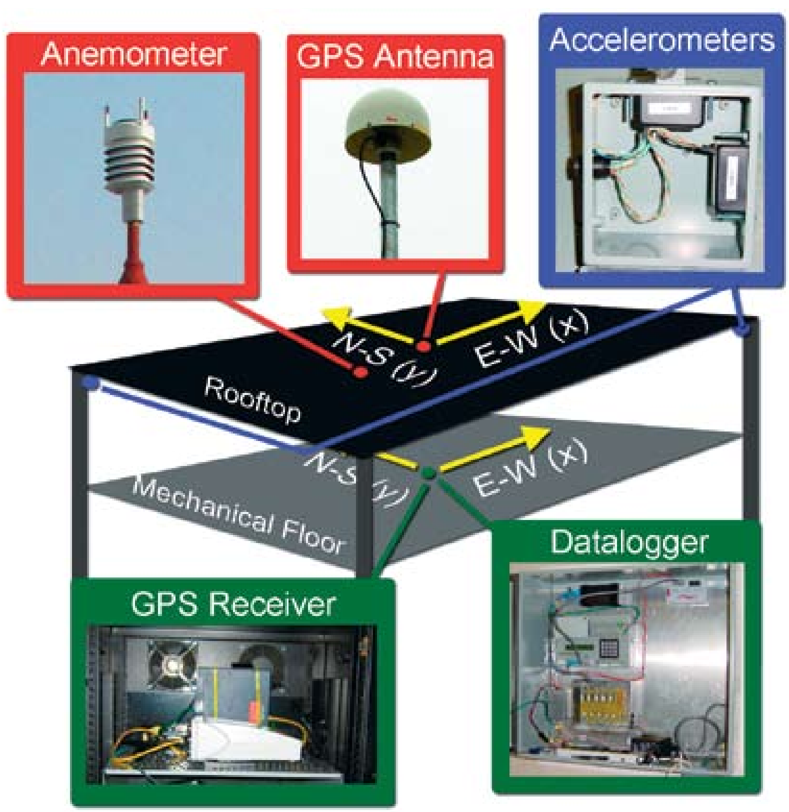

Figure 1: Schematic of sensors distributed on generic floor plan; dashed lines indicate rooftop installations.

A fourth building in Seoul, Korea was added in 2005, comprised of a reinforced concrete core and belt wall system; a fifth composite building in Toronto, also employing a core and outrigger, was added in 2007. The data from these buildings continues to stream into the program and has been supplemented by other full-scale data sets for a more comprehensive assessment of dynamic properties in common lateral systems. These include a full-scale database of 67 buildings in South Korea, including 25 steel-framed structures ranging from 30 to 66 stories in height, 22 reinforced concrete apartment buildings ranging from five to 30 stories, and 20 low-rise reinforced concrete structures in the range of five to 10 stories, from collaborations with Seoul National University of Technology. The following outlines three lessons learned from the analysis of these rare full-scale data sets under wind.

LESSON 1

Accelerometers Alone are Insufficient to Monitor Wind-Induced Motions

The displacement response of any structure under wind can be characterized by three components: a *mean component* (Δ) that does not vary over a specified time interval, a *background component* (δ_B) that does vary over this time interval, but at a slow rate, and a *resonant component* (δ_R) that also varies over this time interval but at fast rate, oscillating at the natural frequencies of the structure (*Figure 2*). While many monitoring applications attempt to recover displacements by double integrating recorded accelerations, two constants of integration are neglected, implying that the mean and background components of the displacement response cannot be fully recovered. Studies have shown that the background response contributions can be as high as 20-80% for some structures in certain wind events, implying that a large portion of the overall response picture may be lost when using accelerometers alone. The only way to recover these components is by directly measuring full-scale building displacements. Unfortunately, until recently, there were no reliable means to do so, though the rapid advancement of GPS now makes this possible. The GPS necessary for high fidelity structural monitoring, on the order of 5 millimeters in accuracy, is ten times more expensive that traditional sensors like accelerometers and requires a local stationary reference point. 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 on a tall building, and has proven that GPS can be as accurate in full-scale as established technologies like accelerometers (*Figure 3a*). Having established confidence in GPS data, these efforts then allowed the documentation of the background responses of tall buildings for the first time in full-scale (*Figure 3b*). However, it should be noted that GPS is not an off-the-shelf technology. In fact, the continuous variation in satellite visibility and orientation, as well as the potential for multipath distortions, requires considerable signal processing and compensation to achieve consistently reliable measurements.

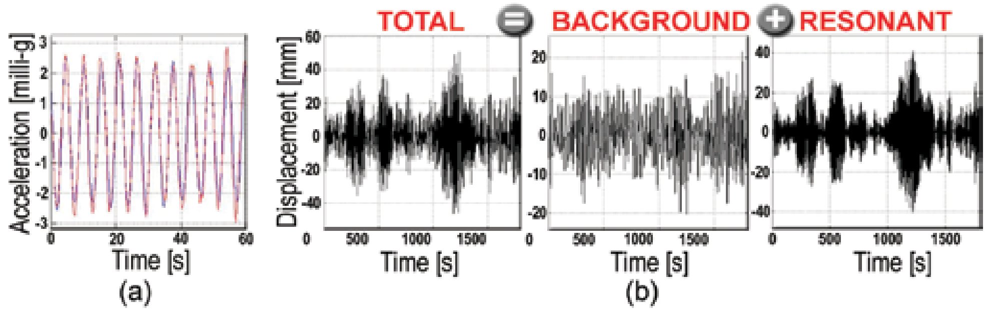

Figure 3: (a) Comparison of full-scale accelerations measured by accelerometer (blue) and by GPS (red) on Building 1 of the Chicago Full-Scale Monitoring Program; (b) decomposition of full-scale displacements of Building 1 into its background and resonant components.

LESSON 2

Dynamic Properties Can Show Amplitude Dependence, Even Under Wind

Though the linear equation of motion is often invoked to simplify analysis, it is not reasonable to suggest that these structures are truly linear. In fact, nonlinearities in connections and the interaction of non-structural elements have produced variations in both frequency and damping with amplitude. As a result, when considering different limit states in design (10 year vs. 50 year wind events), it is entirely conceivable that the structure's dynamic properties will differ for each of these limit states. The general hypothesis is that buildings soften with increasing amplitude, leading to a reduction in frequency or elongation of period, generally accompanied by an increase in energy dissipation (damping). These behaviors are expected to plateau as cracks or interfaces between components widen and eventually lose contact.

Indeed a softening of frequency with amplitude, with a strongly linear trend, has been observed for both the fundamental sway modes of the three high rises in Chicago. By normalizing the slope of the linear fit to this trend by its y-intercept (initial frequency), provided in *Table 1*, the degree of amplitude dependence can be verified. Thus, Building 1 shows an amplitude dependence of only 1-2% of the initial frequency – indicating it is fairly insensitive to this phenomenon, quite similar to Building 3, which also shows modest amplitude dependence (2.5% in both axes). It should be reiterated that both of these buildings are steel tubes, which engage columns in axial shortening/elongation in a so-called cantilever behavior. This is in contrast to Building 2, whose y-axis shows significantly more amplitude dependence than its x-axis (11% vs. 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, it should be noted that Building 4, which is also concrete, shows only 1.1-1.3% amplitude dependence in its two fundamental sway modes. This observation underscores the author's hypothesis that the *structural system, and*

Table 1: Best-fit line to amplitude-dependent natural frequencies in fundamental sway modes of Buildings 1-4 of the Chicago Full-Scale Monitoring Program.

	X-Sway (Hz)	*Y-Sway (Hz)*
Building #1	-0.0034x + 0.2078	-0.0019x + 0.1438
Building #2	-0.0062x + 0.1827	-0.0204x + 0.1854
Building #3	-0.0030x + 0.1200	-0.0029x + 0.1200
Building #4	-0.0027x + 0.1992	-0.0023x + 0.2076

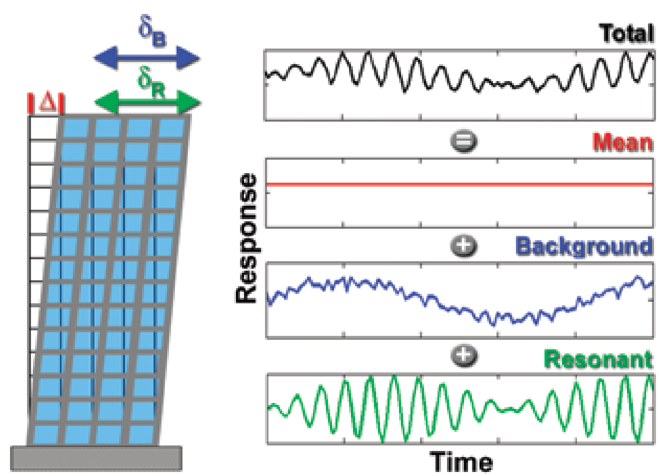

Figure 2: Schematic demonstrating the mean, quasi-static (background) and resonant response components.

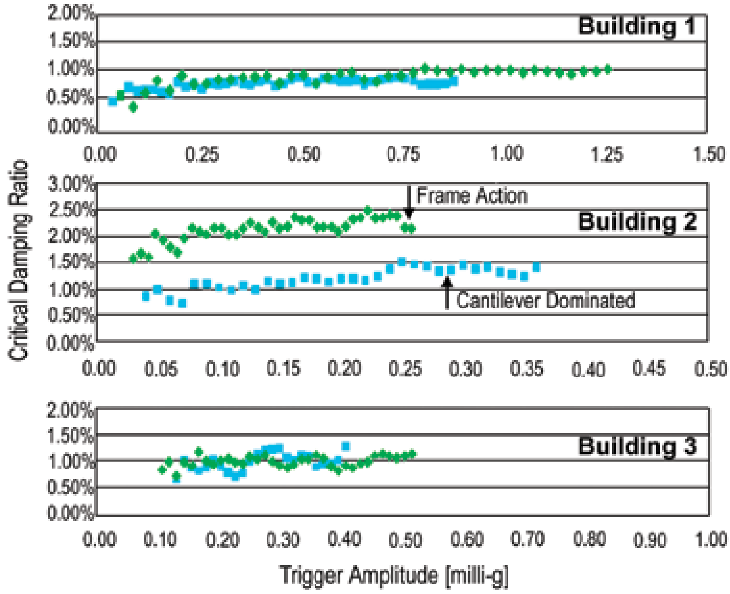

Figure 4: Amplitude-dependent critical damping ratios in fundamental sway modes of Buildings 1-3 of the Chicago Full-Scale Monitoring Program.

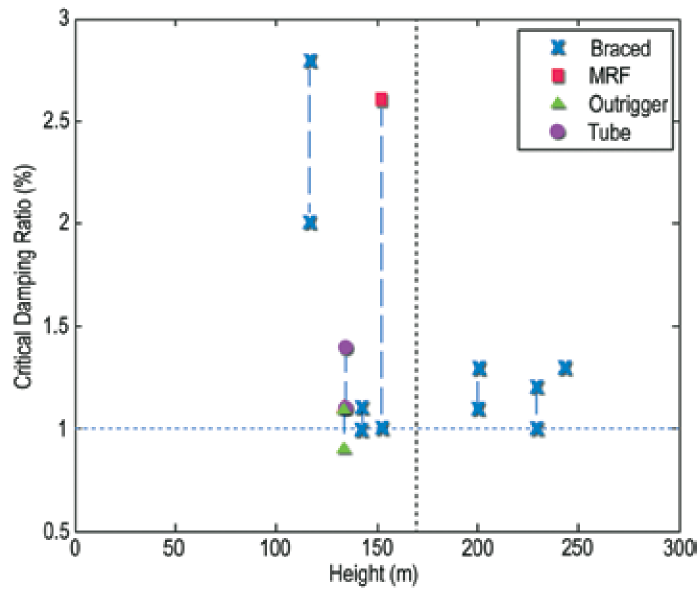

Figure 5: Critical damping ratio as a function of height for common steel structural systems in Korean Full-Scale Database.

specifically its primary deformation mechanism, is the key predictor of these behaviors. Building 2's x-axis is dominated by axial shortening associated with its slender shear walls and outriggers, much like the core and belt walls (virtual outriggers) of Building 4. The fact that comparable levels of amplitude dependence are observed in these and other cantilever-dominated systems like tubes would at least suggest that this *amplitude dependence in frequency is more pronounced in systems dominated by shearing (frame action)*, such as Building 2's y-axis, which relies on the weak axis of the shear walls in conjunction with the slab action of the floor system for its lateral resistance.

It is now interesting to explore whether analogous behaviors are observed in the critical damping ratios. *Figure 4* shows the result of the amplitude dependent damping analysis on the three buildings in Chicago. The trends here are clearly not linear, but do demonstrate a very subtle increase in damping with amplitude. Perhaps more interesting to note is that the two steel tube buildings (Buildings 1 and 3) both show comparable damping ratios on their respective fundamental sway axes, while Building 2 again shows distinctly different behaviors on its two axes. In fact, the y-sway axis, again previously noted to be dominated by more frame action, shows markedly higher damping than the x-axis of the building known to be dominated by its tall, slender shear walls behaving as vertical cantilevers. This is particularly an interesting finding considering that damping values are traditionally assigned to a project based on the construction material, or perhaps gauged from damping databases where damping ratios are parameterized by generic quantities like building height. Instead, the results for Building 2 suggest that damping is more closely tied to the structural system and its deformation mechanism, which can vary even within a given building. Further, even for the two tube systems in Buildings 1 and 3, although both being of steel, Building 1 has lower damping and is known to have a greater proportion of cantilever action in its structural system. This motivates the third and perhaps most important lesson…

LESSON 3

Damping is Lower in Systems with Greater Cantilever Action

The findings surrounding the damping values in *Figure 4*, as well as the trends surrounding amplitude dependence of frequency, suggest that structural system type can be correlated with trends in the in-situ dynamic characteristics. This hypothesis was explored in greater detail using the database of 67 buildings from South Korea, which includes 22 reinforced concrete buildings employing the same structural system, foundation type and occupancy with heights of 9- to 25-stories. The structural system employed by this subset of buildings is fundamentally a modular shear wall system tied to a reinforced concrete slab and perimeter frames, in many cases characterized by elongated floor plates. For these buildings, damping in the short direction, whose lateral resistance was primarily derived from shear walls, manifested values that *decreased with height*, as the cantilever contribution to the shear wall deformation increased. Meanwhile, in the long direction there was little correlation between damping and height, and instead damping *increased with floor plate aspect ratio*. In the long direction of these modular buildings, slab action is the primary means to engage the various shear wall cores, thus generating more frame action. Since the area of slab present in the building increases with the floor plate aspect ratio, it was only logical that the energy dissipation would also increase in direct proportion. This demonstrates that damping should be parameterized differently depending on the primary deformation mechanism of the structural system it is associated with, and not generically by parameters like material or height.

Investigations involving the steel building subset of this South Korean database further supported the observations in Lesson 2. The eight steel buildings considered had heights from 31-60 stories and include braced/moment resisting frames (MRF), outriggers, and tube systems, as visualized in *Figure 5* where the vertical lines connect damping values for a given building in its two orthogonal directions. It is immediately obvious that damping is not tied solely to structural height, as only one building exhibits the same damping value on both its axes. The black vertical line highlights the fact that only braced frames are used for the taller buildings in this subset. This conscious choice is required to eliminate excessive frame action in tall MRFs and invoke the axial stiffness of the braces and tied columns in vertical cantilever action. Thus, it is not surprising to note that the damping values on the right side of the graph do not exceed 1.5%, consistent with the hypothesis that the *increasing role of axial deformations results in less energy dissipation*. The limited data herein appear to suggest that, beyond a height of 125 meters, the damping falls off considerably, potentially due to the transition to a more cantilever-dominated braced structural system. This may be further supported by the case of the outrigger and tube buildings in *Figure 5*, which are of comparable height and aspect ratio and again made of the same material, yet the outrigger structure has considerably less damping. As an outrigger engages the perimeter columns to resist overturning moments, it increases the degree of cantilever action. On the other hand, a tube structure, though intended to behave as a vertical cantilever, can suffer from a significant amount of shear lag unless diagonal bracing is provided or exceptionally small column spacing is employed. Thus, it is plausible that shear lag (frame action) has contributed to the increased energy dissipation in this particular tube. The traditional MRF makes one appearance in this subset of buildings, as the system used in the long direction of one of the buildings, offering a shear-racking mechanism again dissipating more energy than the slender, braced frame on the opposing axis.

Conclusions

The three lessons presented here are but a small cross section of the insights that can be gained from the full-scale data made available by projects like the Chicago Full-Scale Monitoring Program, ultimately allowing the development of more faithful predictive tools for dynamic properties and critical validations of underlying models and design methodologies. These lessons demonstrate the importance of integrating advanced sensing technologies to fully characterize mean and background response components, the need to account for amplitude-dependence in dynamic properties, particularly for systems dominated by frame action, and the apparent trend of diminished energy dissipation in increasingly efficient structural systems dominated by cantilever action. However, it becomes clear that these lessons learned and the hypotheses they pose must be vetted by more full-scale observations over a wide range of structural systems in varying wind conditions. This will only happen if the community continues to embrace and promote the concept of full-scale monitoring as an important final validation step in the design process. After all, the current practice in seismic zones has already proven that public support and owner incentive for these measures can be established; there is no reason that America's other "windy cities" shouldn't follow suit.▪

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