Cover page

Title: *Monitoring Serviceability Limit States in Civil Infrastructure: Lessons Learned from the Chicago Full-Scale Monitoring Experience*

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ABSTRACT

In order to facilitate a paradigm-shift in the application and advancement of Structural Health Monitoring (SHM) as a realistic tool for infrastructure assessment and management throughout the United States, it is important to consider the stakeholders involved. This understanding must weigh their needs, risks and constraints, whether they be practical and/or economic. Unfortunately, stakeholder confidence in SHM has not advanced at a rate commensurate with the advances in sensor and information technologies, and without this confidence, SHM may remain largely an academic exercise. This paper overviews the authors' experiences in the Chicago Full-Scale Monitoring Program performing serviceability/habitability assessment, while focusing on three critical aspects necessary for the SHM paradigm shift: (1) the technical feasibility of monitoring large scale structures with high resolution (sensor technology issue); (2) the technical feasibility of extracting key parameters from measured response quantities with high reliability (information technology issue); and (3) the practical feasibility of building relationships with key stakeholders to permit access, long-term monitoring and ultimate acceptance of the SHM concept (stakeholder confidence issue).

INTRODUCTION

Traditionally, research in structural health monitoring (SHM) has largely focused on the development of sensor and information technologies to enable responses to be measured with high fidelity and key parameters (dynamic properties, damage indices, etc.) to be extracted with high reliability, so that technical confidence in SHM is secured. However, in order to facilitate a paradigm-shift in the application and advancement of SHM as a realistic tool for infrastructure assessment and

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management, it is equally important to consider the stakeholders involved. This understanding must consider their needs, risks and constraints, whether they be practical and/or economic. These vary with region, as West Coast stakeholders have a vastly different incentive base (survival) than Midwest or Eastern stakeholders (serviceability/habitability). As a result, there can be no “one size fits all” approach to SHM for Civil Infrastructure, particularly across hazards (earthquakes vs. wind). Unfortunately, stakeholder confidence has not advanced at a rate commensurate with the advances in sensor and information technologies, and without this confidence, SHM may remain largely an academic exercise.

Though not established with the intention of monitoring “structural health,” the authors have gained substantial experience related to practical deployment of monitoring systems in Civil Infrastructure, specifically buildings, through their work in the Chicago Full-Scale Monitoring Program [1]. This process began in 2001 with the prototyping of systems specifically tailored to the needs of the tall buildings community, which is particularly interested in serviceability and habitability evaluations, and has led to one of the longest full-scale monitoring efforts in this country outside of a seismic zone. The program deployed an array of servo-force balance accelerometers, ultrasonic anemometers and even high-precision GPS to continuously monitor and validate in full-scale the responses of three signature buildings in the city [1-3]. Efforts have now recently expanded the program to include buildings overseas [4]. Specifically, since private sector stakeholders were involved, this application was constrained by a number of key liability, security and confidentiality issues.

This paper overviews these experiences, using this case study of building serviceability/habitability assessment, focusing on three critical aspects necessary for the SHM paradigm shift:

(1) *sensor technology issues:* the technical feasibility of monitoring large scale structures with high resolution;

(2) *information technology (IT) issues:* the technical feasibility of extracting key parameters from measured response quantities with high reliability; and

(3) *stakeholder confidence issues:* the practical feasibility of building relationships with key stakeholders to permit access, long-term monitoring and ultimate acceptance of the SHM concept.

ISSUES AND CHALLENGES

Long before the notion of *Performance Based Engineering* was popularized in seismic circles it had been practiced in the design of tall buildings, where survivability, serviceability and even habitability limit states must be simultaneously evaluated. Limiting acceleration perception by building occupants (habitability) is often a controlling structural engineering design parameter for tall buildings, even in moderate wind climates. Significant premium for height in terms of additional structural material may become necessary in order to satisfy current habitability criteria. This premium is beyond that required to meet minimum standards for building strength or lateral drift serviceability criteria related to building partitions or other architectural systems such as cladding and facades.

Since habitability limit states are so critical for this class of structure, effective means to reduce accelerations are equally of interest. Increasing the mass and/or stiffness of a building reduces wind-induced accelerations in many situations; however, there can be exceptions. Additional damping on the other hand, is consistently effective in reducing acceleration responses in habitability limit states, though to date it still cannot be predicted in the design stage. This makes estimates of amplitude-dependent, equivalent viscous damping from full-scale data and the subsequent development of predictive empirical models a vital need for the tall buildings community, in contrast with a seismic community that is generally more interested in hysteretic properties. Thus the full-scale validation of tall buildings under wind has a unique set of constraints and needs that will be now discussed as they relate to *sensor technologies, information technologies,* and *stakeholder confidence*.

Sensor Technologies

There are two practical hardware deterrents to SHM in Civil Infrastructure: availability of high precision sensors for specific building responses like drifts and the cost associated with installation. With respect to the former, responses have been traditionally quantified in full-scale through accelerations, even though most performance metrics reference displacements or drifts. Unfortunately, acceleration measurements are incapable of characterizing the total structural response, which is comprised of static, quasi-static and resonant components, though only the latter can be fully recovered from accelerometers. This implies that accelerometer-based monitoring systems cannot detect permanent offsets due to damage, structural settlement, thermal expansions, and the mean and background components of wind-induced response. In these and other instances, the measurement of total displacements is required. Recent advances in Global Positioning Systems (GPS) have now increased the viability of this technology with sufficient sampling rates (up to 20 Hz) and sub-centimeter accuracy [2]. As such, GPS was added to the Chicago Full-Scale Monitoring Program to allow rare glimpses of the background component of wind-induced response in full-scale [3].

Although GPS can be used to quantify overall roof-level drift, it cannot be used to sense other displacement quantities like interstory drifts that are equally of interest to designers. To date there remains no “off-the-shelf” solution to this problem, though researchers have explored the use of tilt meters and laser-based technologies as potential solutions. Kochly [5] investigated the use of laser-based terrestrial positioning systems (TPS), whose prisms can be strategically placed at various elevations to track elevation-specific lateral displacements in multiple directions. A comparison of the experimental performance of this technology against accelerometers and GPS using controlled motion simulations of buildings under wind is shown in Figure 1a. Note the accelerometer, the foremost trace in the figure, has difficulty accurately capturing the peaks in the response. TPS has better performance in this regard, though GPS performance is better than both. These findings are reiterated in Table I, which lists the RMS displacements of the motion simulator (actual displacements) and the displacements from the various devices. Δ indicates the percent error between each sensor and the motion simulator. The average percent error in peak values between each sensor and the motion simulator is also provided. Over forty tests

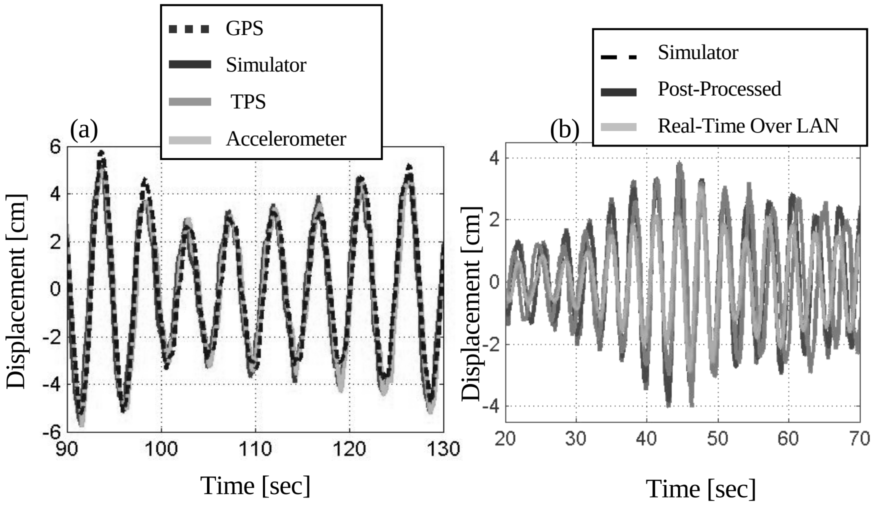

Figure 1. Zoom in of simulated wind-induced response of steel building: (a) traces plotted one atop the other in the following order: GPS, motion simulator, TPS, accelerometer; (b) performance of motion simulator to GPS (post-processed and real-time DAQ over LAN).

were conducted by Kochly [5] to further document performance of each sensing element. This work confirmed that accelerometers were best suited for high-frequency applications (> 1 Hz), while GPS and TPS were better suited for low-frequency applications, though having specific line of sight issues.

The poor performance of the accelerometer is in part associated with the errors inherent to the double integration process, as well as the low-frequency displacement information lost in direct acceleration measurements. Hybrid sensing, which combines complementary technologies like GPS and accelerometers, can remedy issues like multi-path effects in GPS and the loss of static and quasi-static content in accelerometers so that more reliable velocities and displacements can be determined [6]. Still this concept rarely translates into practice and most applications seeking measures of drift, for expedience, directly integrate accelerations [e.g., 7-8], often in real time. Even when the errors in this integration process are minimized, the calculated displacements again represent only resonant response features and are thus incapable of any residual drift detection. Thus, a reliable drift sensor is still needed.

With respect to installation, as will be discussed in a later section, union labor must often be used, leading to installation costs on the order of $1000 for running even a single pair of cables. If instrumentation resides on multiple levels, the costs compound rapidly. As a result, extensive research into wireless sensor networks has evolved, though multi-hop relays, synchronization, packet loss and power constraints have limited their practical utility. The direct use of a building’s existing local area networks (LANs) for data acquisition (DAQ) can offer considerable flexibility without

TABLE I. PERFORMANCE SUMMARY FROM EXPERIMENTAL TESTING

	Motion Simulator (cm)	GPS (cm)	Δ (%)	TPS (cm)	Δ (%)	Acceler-ometer (cm)	Δ (%)
RMS	1.21	1.20	0.5	1.18	2.6	0.85	29.7
Peak Error	--	--	16.8	--	28.4	--	41.9

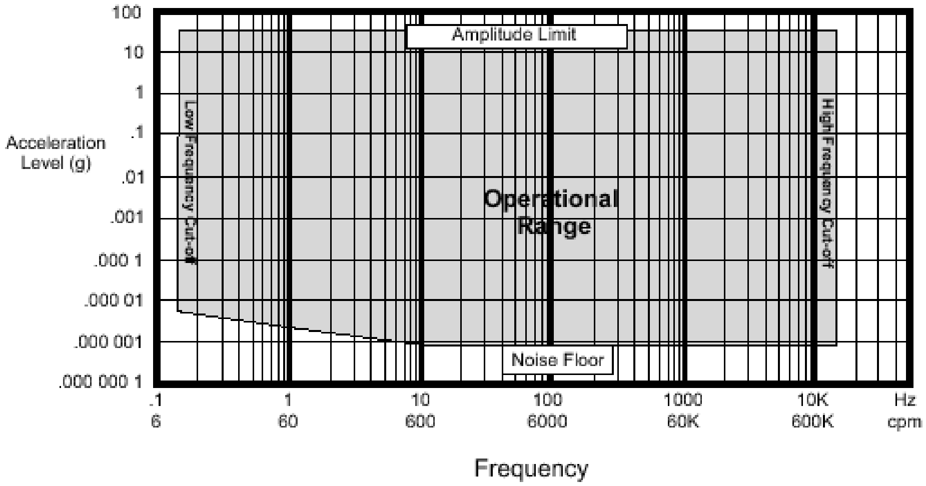

Figure 2. Typical operating range of piezoelectric accelerometers (taken from Wilcoxon Product Catalog).

the synchronization, packet loss and power issues; however, they do require the use of digital sensing elements like GPS. Kochly [5] used the DAQ over LAN approach for real-time kinematic differential GPS and found it to be a highly reliable, though expensive, solution, with performance akin to off-line post-processing, as shown in Figure 1b. Furthermore, the use of digital devices carries with it the added benefit of reduced noise sensitivity and concerns over aliasing. However, high quality digital accelerometers suitable for Civil Engineering applications are not as common. In the Chicago Full-Scale Monitoring Program, there were two specific issues with accelerometer selection. -- the first was related to sensitivity. For serviceability/habitability monitoring, accelerations are on the order of a few milli-g. This requires devices with low noise and high sensitivity (over 1 V/g). The accelerometers used in the authors' work have sensitivities up to 40 V/g, based on the operating range selected. The best digital accelerometer on the market offers sensitivities 1/10th of this level. The second issue is low frequency performance. For low to mid-rise buildings, most every analog accelerometer on the market will have a sufficient frequency range. However, for very tall buildings, traditional piezo-based accelerometers are not viable options due to the roll off of their frequency response or transfer functions in the low frequency range (under 0.2 Hz), particularly at low amplitudes of vibration, as demonstrated by Figure 2. Thus, servo force-balance accelerometers with unit frequency response down to DC are required. These devices tend to be more expensive and more vulnerable to shock due to their high sensitivity. Unfortunately, digital accelerometers to date have been unable to reproduce the low frequency performance of these analog, servo force-balance devices. Thus, there is a definitive need for high fidelity digital response sensors, particularly accelerometers, to enable the use of evolving schemes like DAQ over LAN.

Information Technologies

Real-time data access, processing and visualization, along with intelligent data mining and archiving, are realistic needs for any long term SHM initiative and have been addressed by a number of studies employing commercially available IT software

[9]. However, information processing or specifically system identification needs unique to serviceability/habitability monitoring still require substantial attention. Primary information processing may include the extraction of displacement from acceleration using any number of schemes, including Kalman filtering and smoothing [6]; however, equally if not more important information resides in the dynamic properties themselves. In the case of ambient vibration monitoring, there is no measured system input to be used in the identification process, restricting end users to "output only" schemes. As discussed in Kijewski-Correa and Cycon [10], traditional assumptions of white noise input and the stationarity and ergodicity of the response enable the use of classic schemes associated with Power Spectral Densities and Random Decrement Techniques. However, the primary issue is the significant amount of data required to successfully minimize variance and allow the extraction of critical damping ratios scarcely over 1 or 2%. This prohibits any reliable pseudo-real-time estimates of dynamic properties and makes the identification of dynamic properties at higher-amplitudes quite problematic due to their very isolated occurrences within the time history. The stationary assumption also implies that responses under transient wind events cannot be faithfully analyzed by these techniques. While Maximum Likelihood Estimators have enabled the use of shorter data sets [11], the amount of stationary data required still is on the order of an hour for most applications. Thus, there is a pressing need for more reliable system identification methods for "output only" applications, ideally suitable for cases when limited stationary or even nonstationary data is available [12].

Stakeholder Confidence

Stakeholder confidence in SHM technologies varies greatly, depending on the hazard zone. In California, where recent earthquakes have raised concerns about survivability and rapid reoccupation, monitoring has been widely embraced. This in part is due to code incentives that have motivated and even required developers and owners to incorporate such technologies, e.g., Building Occupation Resumption Program (BORP), as well as high-level, coordinated initiatives such as the California Strong Motion Instrumentation Program (CSMIP). In both cases, there are *fiscal benefits* perceived by ownership that motivate the investment in monitoring. The same attitudes have not spread outside of seismic country into other regions of the United States whose buildings are largely governed by serviceability/habitability limit states. The primary hurdles are *fiscal benefits and liability*.

With respect to fiscal benefits, in regions where serviceability/habitability limit states govern, owners see no fiscal incentive for monitoring, since assessment and reoccupation are non-issues. Thus, unless a building has demonstrated suspect performance, e.g., excessive vibrations disruptive to occupants, owners will not invest in instrumentation. Fortunately, through the support of the National Science Foundation, the authors have been able to instrument a number of buildings at no cost to the owners, thus relieving this first fiscal burden. However, even with the hard cost issue addressed, other fiscal issues remain a major concern. In the authors' experience, owners are often receptive to no-cost monitoring to learn more about the performance of their building and use the real-time data streams for maintenance and operation; however, they have significant concerns about fiscal losses that could result if the building is negatively perceived by the public. In contrast with the attitudes in Asia, an instrumented building in the United States is not an “intelligent” structure but a “suspect” one. Thus there are some issues of public education and perception that must be addressed. In the interim, one must generally guarantee confidentiality of the data and the building’s identify. While this does not prohibit analysis and publication of data and findings in some normalized or anonymous form, it does prohibit dissemination data to the wider engineering community and open disclosure of findings. Furthermore, it restricts the ability of researchers to conduct full-scale assessments of occupant comfort, a critical limit state in serviceability/habitability design that unfortunately requires human feedback for meaningful interpretation of the acceptability of recorded accelerations.

In all cases, legal advisors to the ownership will be involved to protect these investments. In best case scenarios, confidentiality agreements are developed and in some instances legal teams will even require proof of insurance to absorb liabilities associated with rooftop instrumentation that may be dislodged and injure pedestrians, e.g., anemometers. They will also require bonded, union labor for any installation. In worst case scenarios, legal advisors often intercede and completely discourage owner cooperation. They cite the liability of inaction: if some problem should be uncovered and the owners fail to act, then they can be held liable by tenants. Sadly, the legal advisors instead prefer to have owners “in the dark,” as they are not liable for problems they had no knowledge of. This attitude returns to the fiscal benefits issue: monitoring outside of seismic zones is perceived to provide no fiscal benefit and even potential loss and thus should be avoided.

How can these attitudes be changed? Code incentives appear to be the most viable means to make SHM a wide-spread reality. There is precedent for mandated monitoring of “non-seismic” hazards. For example, in the Shinjuku District of Tokyo, populated by a number of tall buildings, pedestrian wind effects have been an issue and thus city ordinance requires developers to install anemometer arrays to verify the safety of the pedestrian environment. Unfortunately, changing municipal codes is a highly political, labor intensive and time consuming process and is often only propelled by public outcry in the wake of a failure or other disaster that could have been arrested by SHM. Still, a code-based incentive will not only bring ownership to the table but it will also help to publicly legitimize monitoring as a pro-active and not re-active measure, which in turn will improve public perception and hopefully their involvement in the full-scale evaluation of perception criteria.

CONCLUSIONS

In order for Structural Health Monitoring to achieve widespread acceptance, research and early deployments must remain sensitive to stakeholder needs, risks and constraints, whether they be practical and/or economic. This paper has specifically focused on the unique needs of serviceability/habitability monitoring under wind as they relate to sensor, IT and stakeholder concerns, emphasizing that there cannot be a “one size fits all” approach to SHM for Civil Infrastructure. Issues such as drift and digital response sensing, reliable system identification using limited response data, and owner incentives in non-seismic zones were discussed, couched in the authors’ experiences with the Chicago Full-Scale Monitoring Program. Most importantly, the authors emphasized the need for wide-spread code incentives to legitimize SHM and achieve its widespread acceptance among the general public and stakeholders.

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REFERENCES

1. Kijewski-Correa, T., J. Kilpatrick, A. Kareem, D.K. Kwon, R. Bashor, M. Kochly, B.S. Young, A. Abdelrazaq, J. Galsworthy, N. Isyumov, D. Morrish, R.C. Sinn, and W.F. Baker. 2006. "Validating the Wind-Induced Response of Tall Buildings: A Synopsis of the Chicago Full-Scale Monitoring Program," *Journal of Structural Engineering*, ASCE, 132(10): 1509-1523.
2. Kijewski-Correa, T., A. Kareem, and M. Kochly. 2006. "Experimental Verification and Full-Scale Deployment of Global Positioning Systems to Monitor the Dynamic Response of Tall Buildings," *Journal of Structural Engineering*, ASCE, 132(8): 1242-1253.
3. Kijewski-Correa, T., and M. Kochly. 2007. "Monitoring the Wind-Induced Response of Tall Buildings: GPS Performance and the Issue of Multipath Effects," *Journal of Wind Engineering and Industrial Aerodynamics*, in press.
4. Abdelrazaq, A., T. Kijewski-Correa, Y.-H. Song, P. Case, N. Isyumov and A. Kareem. 2005. "Design and Full-Scale Monitoring of the Tallest Building in Korea: Tower Palace III," presented at the *6th Asia-Pacific Conference on Wind Engineering*, September 12-14, 2005.
5. Kochly, M. 2006. *Validation of Global Positioning Systems for Monitoring Civil Infrastructure Systems: Performance Assessment and Removal of Multipath Effects.* Masters Thesis, University of Notre Dame, Notre Dame, IN.
6. Smyth, A.W., M. Wu, and M. Kogan. 2006. "Data Fusion of GPS Displacement and Acceleration Response Measurements for Large Scale Bridges," presented at the *4th World Conference on Structural Control and Monitoring*, July 11-13, 2006.
7. Iwan, W.D. 20030. "The Caltech Real-Time Structural Health and Performance Evaluation System (R-SHAPE)," presented at the *2003 Structures Congress and Exposition*, May 29-31, 2003.
8. Celebi, M., A. Sanli, M. Sinclair, S. Gallant, and D. Radulescu. 2004. "Real-Time Seismic Monitoring Needs of a Building Owner – and the Solution: A Cooperative Effort," *Earthquake Spectra*, 20(2): 333-346.
9. Kwon, D.K., T. Kijewski-Correa, and A. Kareem. 2006. "e-Analysis of High-Rise Buildings Subjected to Wind Loads," *Journal of Structural Engineering, ASCE*, in review.
10. Kijewski-Correa, T. and J. Cycon. 2007. "System Identification of Constructed Buildings: Current State-of-the-Art and Future Directions," presented at *3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-3'2007*), November 14-16, 2007.
11. Erwin, S. and T. Kijewski-Correa. 2007. "Full-Scale Verification of Dynamic Properties from Short Duration Records," presented at *Structures Congress 2007,* May 16-19, 2007.
12. Bashor, R. and A. Kareem. 2007. "Efficacy of Time-Frequency Domain System Identification Scheme Using Transformed Singular Value Decomposition," presented at *12th International Conference on Wind Engineering*, July 1-6, 2007.