Full-scale study of the behavior of tall buildings under winds

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ABSTRACT

This study chronicles the first stages of an ongoing research initiative to monitor several tall buildings in Chicago under the action of wind. From these measurements, comparisons with predicted analytical values and wind tunnel tests will provide valuable insights into the accuracy of current design strategies, highlighting areas for improvement to advance the state-of-the-art in tall building design. This paper overviews the entire project with detailed treatment of the current phase: the instrumentation of the four buildings.

Keywords: wind-induced motion, tall buildings, full-scale monitoring, GPS

1. INTRODUCTION

While high-rise construction serves as one of the most challenging projects undertaken by society each year, tall buildings are one of the few constructed facilities whose design relies solely upon analytical and scaled models, which, though based upon fundamental mechanics and years of research and experience, has yet to be systematically validated in full-scale. As high-rise dwellings gain more prominence worldwide, their impacts upon the global society and economy will become more pronounced, necessitating a new frontier in tall building design fully equipped to address the emerging issues of performance, economy and efficiency.

As tall-building projects push the envelope to greater heights, designers are faced with the task of not only choosing a structural system to carry the lateral loads, but also insuring a design that meets serviceability and occupant comfort requirements under complex wind environments. This latter issue strongly affects the potential economic viability of tall building projects. An additional limitation in tall building design is the inability to provide accurate estimates of structural damping in the design phase, which is critical to insure that the structure can meet both serviceability and habitability requirements. Although the building stiffness may be accurately quantified, inherent damping values are typically assumed in the design stage, resulting in estimates of response characteristics that may have significant inaccuracies. Thus, the accurate prediction of inherent damping for a given design becomes yet another critical consideration.

In light of such challenges facing tall building designers, the full-scale validation and advancement of existing design procedures becomes paramount in order to facilitate the next generation of high-rise structures. Thus, a detailed study of several tall buildings whose structural systems are most commonly used worldwide in high-rise design is being undertaken. The instrumentation of four buildings in Chicago, each within close proximity to one another, to measure response characteristics under the action of wind is currently underway. This effort includes not only building accelerations, but also structural displacements through the use of Global Positioning Systems (GPS). To facilitate unhindered access to real-time measurements, a Java-based Internet framework will be developed, permitting the multi-faceted project team, and its international advisory board of designers, consultants, and interested researchers, analysis capabilities from any remote location.

The subsequent analyses, in total, will form a necessary bridge between the measured response with the predicted response of structures, obtained via analyses performed as part of the design process and wind tunnel testing. Based upon these findings and additional sensitivity studies, modern analytical approaches and wind tunnel testing procedures will be calibrated systematically for the first time using full-scale data in order to provide more reliable predictions for future design. Associated with these efforts, the extraction of amplitude-dependent frequency and damping estimates using Wavelet-Based System Identification will shed new light on the dynamic characteristics at varying response levels. Not only will this give valuable insight into the design community's current ability to estimate the dynamic properties and response of a structure

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under the action of wind loads, but it will also uncover areas of deficiency and suggest modifications to current design approaches, including the assessment of current standards for occupant comfort through a subjective survey of occupants following significant wind events. Thus, the contributions of this work will help to revolutionize the growing state-of-the-art in tall building design.

In the case of high-rise construction there have been limited full-scale monitoring projects, typically undertaken following some performance concerns. Although there have been noteworthy studies[1-4], the circumstances surrounding many of these studies prohibited the academic community's access to the measured data. Perhaps this explains the reservations that previously precluded extensive full-scale monitoring of buildings in the United States. By embarking on a study of buildings with proven performance, the misconceptions regarding full-scale monitoring can be arrested, reassuring owners and occupants that the presence of monitoring devices in a structure is not necessarily indicative of a troubled building, but rather is representative of a commitment on the parts of owners and the engineering community to improve the understanding of structures and thereby techniques for their design, thus improving the habitability of the built environment. In particular, the use of a simplified user interface and Internet technologies in this study enhances this initiative by permitting a select group of researchers and owners to access daily reports of building performance, actively involving them in the health monitoring of these structures. This will promote the use of health monitoring of major buildings and pave the way for the potential applications of smart materials and advanced technologies to control building performance in the United States. It is only through such a commitment to full-scale monitoring and validation that the standards for high-rise construction can advance, resulting in more efficient, reliable designs.

2. OVERALL PROJECT OBJECTIVES

The primary objective of this study is to correlate the in-situ measured response characteristics of tall buildings, representing a host of typical structural systems under a wide range of wind environments, with computer-based analytical and wind tunnel predictive models for the advancement of the current state-of-the-art in tall building design. To address all aspects of this effort, a multi-faceted team, including members from academia (University of Notre Dame), a consulting laboratory (Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario, Canada), and practicing structural engineers (Skidmore, Owings and Merrill, LLP of Chicago, IL), are pooling their unique perspectives, experiences and resources throughout this project. In addition, the project team is collaborating with an advisory board of leading designers, researchers and organizations, who have been involved in a wide range of projects associated with tall buildings around the world, to provide regular reviews and consultations. The end result will be the first systematic validation of existing design practice for tall buildings in the US, followed by appropriate calibrations of existing wind tunnel and analytical models, with modifications to current design practice, where applicable. Such an endeavor requires the selection of several buildings in the same general locale, for which design information and building access are available. Thus, several tall buildings in Chicago, representing different generic types of structural systems and materials, are being instrumented so that the response characteristics and wind conditions may be ascertained.

The tasks associated with this effort shall include:

- Establishment of real-time monitoring of tall building response during significant wind events with measured wind speed and direction, providing a comparison of actual response to predicted response estimates.
- Investigation of the sensitivity of in-situ dynamic characteristics of tall buildings based on the level of response, foundation type, materials of construction, age and condition of the building, and wind environment.
- Development and introduction of advanced instrumentation systems, including GPS, for in-situ structural monitoring, real-time data access and analysis via Java-Based web interface, promoting the use of full-scale monitoring of tall buildings in the United States.
- Comparison of measured response and predictive models for tall buildings with actual occupant perception of performance through tenant interviewing process.

Relationships have been established with the owners and designers of each building to permit instrumentation and comparison of the resulting full-scale response with the actual design estimates supplied by the original design firms, along with complete structural details.

3. BUILDINGS INVESTIGATED

The four buildings selected for this study represent a variety of typical structural systems employed in the construction of high-rise structures, such as the steel moment-connected bundled tubular system, exemplified by Building 1. The structure is intended to behave as a vertical cantilever fixed at the base to resist wind loads, with a skeleton comprised of a structural steel frame, pre-assembled in sections and bolted in place on site. The two interior frames of the structure connect opposing facade frames at two intermediate points reducing the shear lag effect in the flange frames and the material premium for height considerably. Foundations are comprised of straight shaft reinforced concrete caissons extending to bedrock.

The braced steel tube concept of Building 2 has proven highly efficient in high-rise construction, relying on a steel tube comprised of the exterior columns and spandrel beams as its primary lateral load-resisting system, stiffened by its diagonal members. The diagonals tie to the structural floors and corner columns, functioning as a continuous system for the transmission of axial loads. The intersection of these diagonals at the corner columns permits the direct transfer of wind shear, carried as axial loads in the web side diagonals, to the flange side diagonals. The lateral load of the structure is resisted primarily by cantilever action (80%) with frame action carrying the remainder of the load. This behavior is primarily a result of the diagonals insuring a near uniform distribution of load on the columns across the flange face, with very little shear lag. The structure rests on foundations of straight shaft reinforced concrete caissons to bedrock.

While structural steel is commonly used for high-rise construction, comparative performance of reinforced concrete structures will also prove beneficial in this study. Thus, Building 3 is examined as an example of a concrete shear wall/outrigger system. The structure is rectangular at its lower levels, approaching a square shape at the 59th floor as the result of a series of plan setbacks on the north and south faces. Above the 59th floor, the building begins to taper into a sculptured cone, topped by an 82 ft. architectural spire. Four shear walls located at the core of the building provide lateral load-resistance. At the 40th and 59th floors, the core is tied to the perimeter columns at two locations via reinforced concrete outrigger walls to control the wind drift and reduce overturning moment in the core shear walls. The structure's foundation utilizes reinforced concrete straight-shaft caissons extending to rock.

The use of reinforced concrete can significantly increase the level of damping inherent to the structure, enhancing performance; however, this still may not be enough to insure acceptable performance for especially slender structures. Though not especially prevalent in the United States, the use of auxiliary damping devices offers one remedy. Thus, to further enrich the breadth of this study, Building 4 is also being considered as it incorporates such technologies. The high-rise features a reinforced concrete framed tube with shear walls and relies on reinforced concrete caissons extending to limestone bedrock strata.

4. INSTRUMENTATION AND DATA COLLECTION

The primary aim of this study is to establish a real-time monitoring of tall building responses during significant wind events correlated with measured wind speed and direction. Thus, a continuous monitoring period of approximately three years is necessary to capture several significant windstorms and allow the evaluation of the buildings under different wind loads and at various response amplitudes. While specific details of the sensors involved are detailed in the subsequent sections, it should be noted that the final phase of the data acquisition scheme would include an Internet portal, permitting analysis by various groups worldwide. Recent advancements not only facilitate the transmission of data from remote computing stations to a host computer, but the emergence of Java-based applets[5] and ActiveX Control now permit data retrieval and analysis by authorized users worldwide through the use of commercially available software. (Passwords necessary for access may be assigned and would be restricted to authorized individuals with the permissions of all parties involved.) Such secured access over the Internet becomes particularly attractive for the current project, as the data from the four instrumented buildings may be reviewed, downloaded, processed and analyzed, with complete access to all applications on the host computer, from any location by the research team or advisory board members at their respective locations worldwide. In particular, the use of Internet technologies and a simplified user interface will encourage the active involvement of owners as well. Since most users are already equipped with a working understanding of the Internet, as well as the appropriate hardware and software, Internet-based monitoring becomes an inexpensive tool to facilitate long-term monitoring initiatives in the US. The following sections detail further the current phase of the study focused on the instrumentation systems.

4.1 Anemometer

As documentation of tall building response under significant wind conditions is limited, it is imperative that quality wind speed and direction data accompany the measured responses. While wind speed and direction measurements are recorded at

Figure 1: Ultrasonic anemometer used.

Chicago's surrounding airports, they give little indication of the observations within the city. Since wind-induced accelerations are typically proportional to the wind velocity cubed and uncertainties in the wind speed are very much amplified by building response, it becomes essential to have a reliable measure of wind speed and direction in the downtown area. By establishing a reliable wind measurement station atop the tallest building in the study, a reference wind speed and direction for each storm may be measured at approximately the gradient height and reliably transferred to each of the instrumented buildings.

Though Building 1 is the tallest of the buildings being considered, its rooftop is cluttered with a variety of communications antennae and other equipment. Based on wind tunnel testing, the interference to a rooftop anemometer was deemed to be quite significant and required the anemometer to be elevated above the rooftop. To resolve these concerns, the anemometer is instead mounted atop one of the antennae of Building 1, placing it well above any significant interference.

Due to this unique location, the anemometer installed has to be robust enough to withstand the harsh conditions at this elevation without requiring any repairs, as access to this location is not conventional. For this reason, an ultrasonic wind sensor was selected, shown in Fig. 1. The ultrasonic wind sensor, lacking any moving parts, does not suffer from minimum friction thresholds and delays of traditional propeller-type units. Further, its accuracy is inherently more stable, being dictated by the distance between the transducers, which remain fixed. The specific properties of the ultrasonic wind sensor are provided in Table 1.

Table 1: Specifications of ultrasonic anemometer.

Wind Speed			Wind Direction			Output	
Range	Accuracy	Resolution	Range	Accuracy	Resolution	Rate	Temperature Range
0-50 m/s (0-112 mph)	±1% or 0.5 m/s (1.1 mph)	0.1 m/s (0.2 mph)	$0-360°$	±3°	1°	1 Hz	$-30°C$ to $55°C$ ($-22°F$ to $131°F$)

Considering the harsh winter environments in Chicago, icing and snow accumulation was an added concern. Fortunately, by virtue of the small size and fixed orientation of the sensor, internal heater units were available to prevent icing. Understandably, the physical construction of the sensor itself provides some obstacles to the wind flow, modifying the velocity within the three-transducer configuration. However, as this configuration is redundant, it provides a means to check the validity of the measured velocity. The influence of turbulence on the measurements increases with velocity; however, this redundancy allows the sensor to fill in the holes created by turbulence and extends the accuracy range of the sensor up to a maximum 140 mph. Though the resolution of the sensor is sacrificed to achieve this robust velocity range, it was essential to have a sensor capable of capturing the maximum potential wind speeds during a significant event.

4.2 Instrumentation of Buildings 2-4

As shown by Fig. 2, buildings 2-4 are each being instrumented with three accelerometers to monitor the two fundamental sway modes and the fundamental torsional mode[6]. The accelerometers are being mounted in protective enclosures at the highest mechanical floors in each building, a few floors from the roof. The acceleration data, sampled at 10 Hz, is passed through an analog filter, A/D converted and subsequently digitally filtered. In the analysis component of the system, a

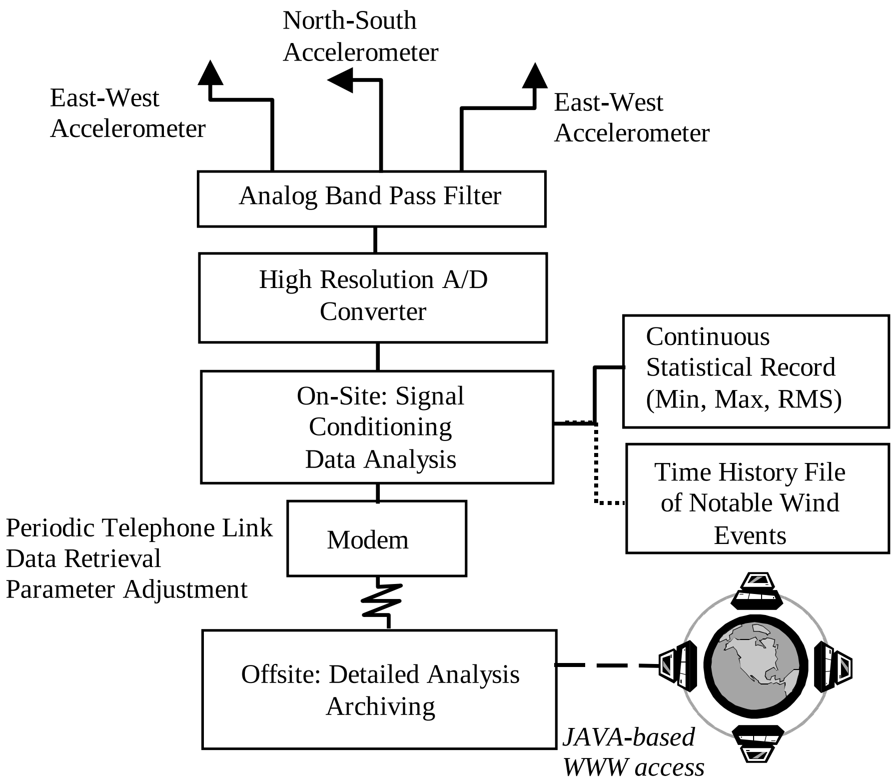


Figure 2: General data acquisition system for Buildings 2-4.

continuous statistical record is logged, chronicling the minimum, maximum and RMS accelerations over a 10-minute averaging interval. As shown by the dotted lines in Fig. 2, acceleration time histories are captured during critical wind events for subsequent dynamic analysis. A trigger automatically engages this option at a prescribed acceleration threshold and continues to record the entire response until it falls back below the prescribed threshold for sequential 10-minute intervals.

Frequently, seismic accelerometers with piezoelectric crystals as the secondary transducer are used for structural monitoring. While these accelerometers are capable of performing under a wide range of frequencies, they cannot accurately detect motion near DC. Often, the low-frequency performance is sacrificed in these devices to provide quicker recovery to changes such as a loss of power or overload. Clearly, this is an advantageous feature; however, considering the low-frequency nature of the buildings under consideration, low-frequency performance becomes critical. For these reasons, servo force balance accelerometers are used to provide high accuracy outputs even down to DC. Further, considering the low-amplitude responses manifested under the action of wind, sensitivity and signal resolution became critical considerations in obtaining accurate response data, further necessitating the use of the servo force balance accelerometer, as the model features a sensitivity of 75 V/g and a 0.0001 milli-g resolvable signal, assuming a 10:1 signal to noise ratio.

4.3 Instrumentation of Building 1

Previously, the measurement of relative displacements for the assessment of drift and stress conditions was difficult, especially in the cases of permanent displacements, which cannot be recovered from accelerometer measurements. Furthermore, the idea of measuring relative displacements in real-time was thought to be unrealizable; however, GPS technologies[7] have not only made it possible to measure relative displacements, but to do so in real-time. GPS have advanced to levels that now permit the measurement of displacements at 10 samples/second, adequate to monitor long period structures such as tall buildings. In fact, recent applications of GPS to long span bridges in Japan have illustrated the feasibility and promise of this technology[8, 9]. The development of such systems to accommodate accurate, real-time monitoring will prove vital data for future studies, improving design and code methodologies, and even health monitoring, repair and retrofit projects.

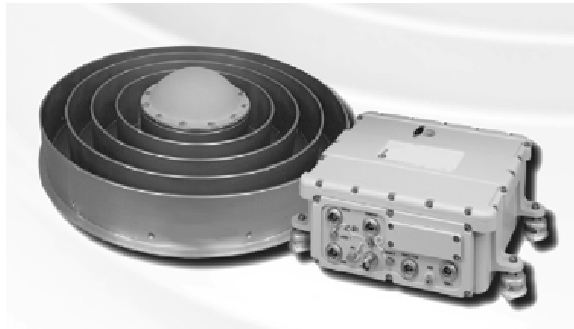


Figure 3: GPS antenna and receiver unit.

Thus, to supplement the acceleration data, a rugged GPS is also being installed on the roof of Building 1 with a stationary reference placed on the roof of a low-rise building less than 5 miles away. The system at each location is comprised of a gold anodized choke ring antenna and GPS receiver, as shown in Fig. 3. The system has an accuracy of 5 mm + 2ppm (RMS) and recovery time of 120 nsecs, sampling displacement data of the building at 10 Hz.

The acquisition system being installed in Building 1, by virtue of the added instrumentation, has a slightly different configuration than the previous system (Fig. 4). The outputs of the ultrasonic anemometer and GPS are integrated with the conditioned acceleration data. The same statistical record is performed, considering now accelerations, displacement and wind speed and direction. For notable wind events, the simultaneous recording of acceleration response, displacement response and wind speed and direction is retained for detailed dynamic analysis at a later time, under the triggering conditions specified previously. This permits the opportunity to correlate not only the wind speeds with observed response but also allow a comparison of displacements recovered from the acceleration records to be compared with the GPS result.

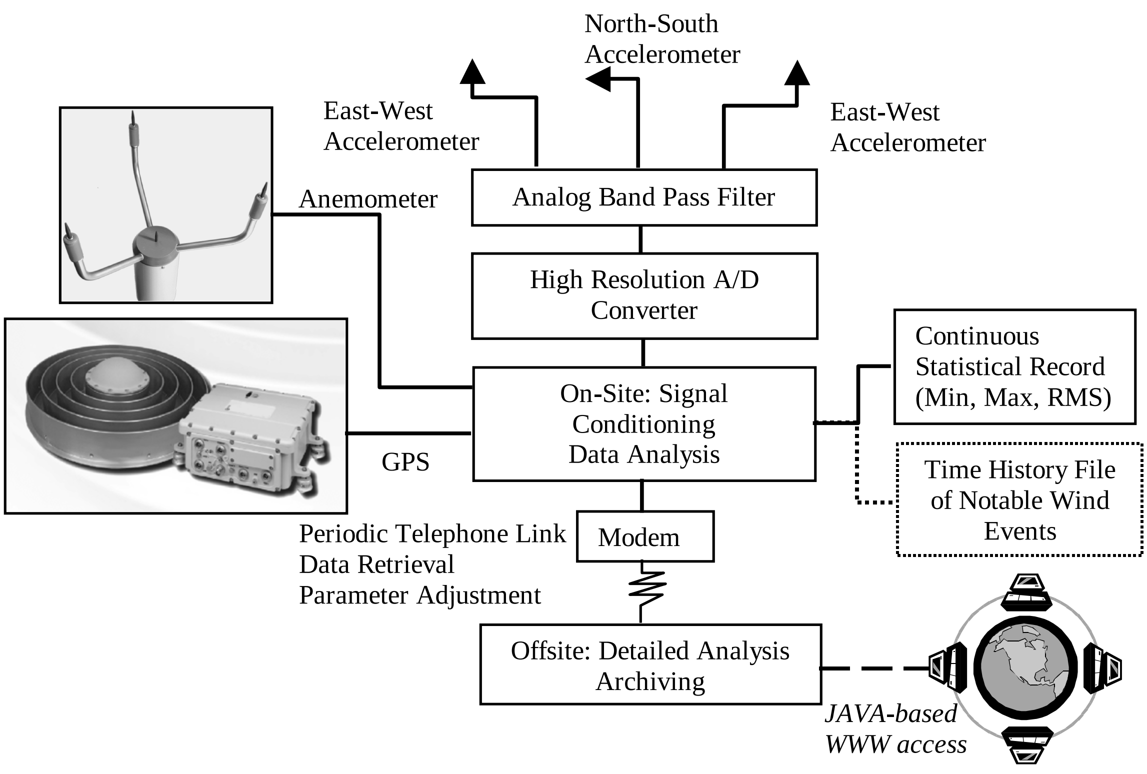


Figure 4: General data acquisition system for Building 1.

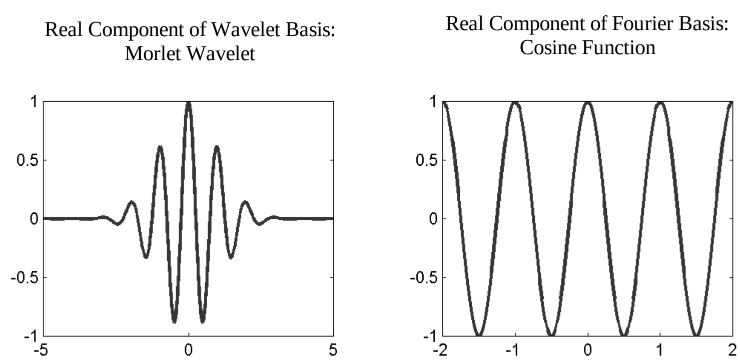
5. WIND TUNNEL TESTING

The next phase of the effort will be concerned with determining the responses of each of these buildings under wind events with known wind speeds and directions through detailed wind tunnel studies. While wind tunnel tests have been conducted for most of the buildings, modifications to the near field effects due to blockage or interference of neighboring buildings have changed the conditions modeled in previous wind tunnel studies. The inclusion of these changes in the surrounding environment, along with recent advances in wind tunnel testing techniques, will produce superior wind tunnel results, providing state-of-the-art wind loading and structural analyses to accompany the full-scale monitoring of the four buildings. The implementation of high-frequency force balance model tests will provide a consistent baseline for each of the buildings. These predictions will be obtained using best estimates of in-situ dynamic properties, as well as the dynamic properties obtained by analytical methods. This will provide a valuable indication of the variation of wind-induced behavior of tall buildings due to inherent uncertainties in the actual dynamic properties. These predictions will be updated as the in-situ dynamic properties of each building are determined. Wind tunnel tests will be conducted at BLWTL, since original tests in the design phase were conducted there.

6. DYNAMIC ANALYSIS

The next phase of the project will focus on determining the actual dynamic characteristics of the buildings, i.e. their natural periods and modal damping. While system identification technologies have made considerable advancements, the most accurate means to estimate stiffness and damping properties require the measurement of the input to the system, in addition to response quantities at a number of locations, making such approaches ill-suited to the wind-excited problem, for which exact system inputs are not known. While traditional analysis techniques such as Fourier analysis can be invoked, this study will consider and develop alternative approaches.

The Random Decrement Technique[10, 11] has emerged as a popular choice for time-domain analysis of ambient wind response data, due to its ability to produce reasonable estimates of the decay signature associated with the autocorrelation function of mechanical oscillators. The decrement signatures are obtained by overlaying segments of the structural response to ambient loads that initiate with the same initial conditions, averaging out the random components of the response. The method is particularly attractive since the user defined initial condition thresholds permit referencing of dynamic properties over varying response amplitudes[12].
Assuming amplitude-dependent levels of frequency and damping, accurate techniques for tracking the levels of damping and natural frequency can be achieved through the use of wavelet-based extraction schemes on the resulting decrement signatures[13, 14]. The reliability of the estimated damping and natural frequency determined by this approach may be accessed



Transform	$W(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)g^{*}\left(\frac{t-b}{a}\right)dt$	$X(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty}x(t)g(t)dt$
Basis Function	$g(t)=e^{i\omega_o t}e^{-t^2/2}$ $=e^{-t^2/2}\left(\cos(\omega_o t)+i\sin(\omega_o t)\right)$	$g(t)=e^{i\omega_o t}$ $=\cos(\omega_o t)+i\sin(\omega_o t)$

Figure 5: Comparison of transforms & basis functions for Fourier and Wavelet Transforms.

using a Bootstrap-based resampling scheme[15, 16]. Unlike traditional Fourier-Based Analysis, which relies on infinite basis functions of sines and cosines, the wavelet transform decomposes signals with respect to finite, localized bases, as illustrated by the example of the Morlet Wavelet in Fig. 5. Though strikingly similar to the Fourier Basis, the Morlet Wavelet is enveloped by a Gaussian Function, yielding a localized basis capable of capturing time-varying characteristics of the system. As the wavelet provides a representation optimized in both time and frequency (or scale), the analysis of multi-mode data is simplified, as the response of a given mode is contained within a distinct frequency band associated with a particular frequency over the entire time axis. Using this transform, in conjunction with the standard techniques for modal parameter estimation based on the approximation of the signal by a complex analytic signal, extraction of the time-varying phase and envelope is possible. These may be directly related to the instantaneous frequency and damping of the system analogous to the Hilbert Transform-based approach.

7. SENSITIVITY OF BUILDINGS TO VARIOUS FACTORS

It has long been hypothesized by some members in the structural engineering design community that the inherent damping and overall stiffness of tall buildings may vary considerably from those assumed for structural analysis and wind tunnel prediction, and may vary somewhat depending on the magnitude of individual wind events. It has also been thought that the size and type of foundations, cladding systems, and internal partitioning may have a significant impact on the basic structural characteristics of damping and stiffness actually realized in constructed tall buildings. A determination of the level of inherent damping for each building during wind events of varying magnitude is a primary evaluation goal for the study. As the study program includes a range of buildings with different structural materials, ages, foundations, and exterior cladding systems, the measurement and analysis of in-situ damping levels will represent an important contribution to the state-of-the-art in the structural engineering of tall buildings. Each building will be evaluated in terms of the measured inherent damping in comparison to the damping ratios normally assumed by tall building structural engineers for the type of material and lateral load resisting system for that particular building.

The availability of the original computer-based structural engineering analysis and design for each building in the study, as well as in-situ measured data, will permit an evaluation of the sensitivity of each building’s performance to various factors. Some of the factors to be considered will be the level of building response for a given magnitude of wind event, level of inherent damping and stiffness, and age. As some very limited full-scale data for the natural periods, damping, and accelerations of Buildings 1 and 2 (see ref. 17) were recorded soon after their construction, comparisons with measurements collected in this study will permit some evaluation of the effects of aging on the dynamic properties of these buildings. The implications of differences in the measured response and in-situ structural characteristics from that used for structural analysis and wind tunnel testing will be determined and presented in the results of the study. Further, the study will seek to identify factors contributing to the discrepancy between predicted and observed values.

8. VALIDATION/MODIFICATION OF EXISTING DESIGN PROCEDURES

The comparison of building performance predictions under winds with full-scale data will provide validation for existing design procedures and/or highlight their deficiencies and provide insight into the modifications necessary to insure that current design practices reflect the actual response of the built structure[18, 19]. Occupant comfort is an important consideration, often serving as the limiting factor in this design process, as excessive motions of tall buildings in wind have been observed to cause discomfort to the structure’s occupants and trigger responses analogous to those associated with motion sickness[20]. While the response of each person varies, symptoms may range from concern, anxiety, fear, and vertigo to extreme responses of dizziness, headaches, and nausea. As a result, a limited number of studies have been devoted to determining the thresholds marking the onset of these sensations, based on the response of individuals to tests using motion simulators[21-24]. In most cases, such experiments rely on sinusoidal excitations; however, there appear to be some discrepancies between these testing environments and those of actual structures[25]. Since the motion of the structure is narrowband in nature inducing bi-axial and torsional responses, the use of uni-axial sinusoidal motions is questionable[26]. In addition, the absence of visual and audio cues in the test environment neglects critical stimuli, particularly for torsional motions, which are known to trigger visual stimulus. Since full-scale occupant perception threshold data is lacking, this program provides the unique opportunity to obtain subjective data from building occupants.

As the structures considered in this study function as both residential and commercial facilities, monitoring their performance will permit evaluation of habitability standards at both occupancy levels in real wind environments. Over the course of this three-year study, significant events may be observed, since most high-rises experience annual events leading to discomfort. Following each occurrence, occupant surveys will be distributed the next business day to scientifically sampled occupants, aiding in the quantification and definition of acceptable wind-induced motions of tall buildings. Such a baseline of acceptable performance would be extremely valuable for confirming and, if appropriate, modifying existing motion perception criteria for tall buildings. It is recognized that motion perception is a sensitive issue and any building occupant surveys will be carefully coordinated with the individual building owners.

Further, as accelerations will be measured for each building under significant wind events, the performance of each lateral system will be evaluated with respect to existing guidelines for occupant motion perception. The study will thus constitute an important contribution to the structural engineering of tall buildings, as the actual building response and occupant tolerance to motion will be evaluated and compared against that predicted by wind tunnel testing and against current design criteria.

9. CONCLUSIONS

Over the course of three years, this study will address the deficiencies in current tall building design practice by correlating the actual performance of constructed buildings with predictions made during their design, thereby providing an important missing link between predictions and actual behavior. As state-of-the-art structural analyses and wind tunnel testing are advancing rapidly, the accuracy and validity of their results needs to be calibrated with respect to actual performance. This will be the focus of this project. This study will provide substantive information with respect to this correlation and create an important database for the development of future prediction techniques. Furthermore, it will contribute to existing international databases by providing valuable information on the dynamic characteristics of high-rise buildings, as well as revealing modifications to dynamic properties as the result of aging. The current phase of this project is focused on the instrumentation of the four high-rise buildings, which includes a GPS, accelerometers and anemometer. Following this phase, detailed dynamic analyses, wind tunnel testing and sensitivity studies will provide valuable lessons to shape the future state-of-the-art of high-rise design. With improved understanding of tall building performance, the next generation in design can truly evolve from the perspectives of performance, economy and efficiency to advance the burgeoning development of tall buildings around the globe.

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REFERENCES

1. R.J. Hansen, E.H. Vanmarcke, and J.W. Reed, “Human response to wind-induced motion of buildings,” *Engineering Journal of American Institute of Steel Construction* **16**(3), pp. 66-74, 1979.
2. F.H. Durgin and R.J. Hansen, “Full-scale on-site wind-induced data from a tall building,” *ASCE Dynamics of Structures, Proceedings of Sessions at Structures Congress ’87*, Orlando, FL, 1987.
3. F.H. Durgin, T. J. Gilbert and J. R. Macachor, “Available full-scale on-site wind-induced data from a major tall building,” *Journal of Wind Engineering and Industrial Aerodynamics* **36**, pp. 1201- 1215, 1990.
4. N. Isyumov, A.G. Davenport and J. Montbaliu, “CN Tower, Toronto: model and full-scale response to wind,” *International Association for Bridge and Structural Engineering (IABSE) 12th Congress*, Session VI, September 30, Vancouver, B.C., 1984.
5. C.M. Ballard and S.S. Chen, “An internet structural monitoring system,” *Intelligent Civil Engineering Materials and Structures*, ASCE, pp. 229-242, 1997.
6. N. Isyumov and D.P. Morrish, “Full-scale measurements to assure performance and quality of buildings and structures,” *Proceedings of ASCE Structures Congress ‘97*, Portland, Oregon, April 14-16, 1997.
7. M. Çelebi, “GPS and/or strong and weak motion structural response measurements – case studies,” *Proceedings of Structural Engineering World Congress*, San Francisco, July 19-23, T193-1, 1998.
8. S. Nakamura, “GPS measurement of wind-induced suspension bridge girder displacements,” *Journal of Structural Engineering* **126**(12), pp. 1413-1419, 2000.
9. S. Kashima, S. Okano, M. Takeguchi and K. Mori, “Monitoring system for the Akashi Kaikyo Bridge,” *Workshop on Research and Monitoring of Long Span Bridges*, University of Hong Kong, 26-28 April, 2000.

10. J.K. Vandiver, A.B. Dunwoody, R.B. Campbell, and M.F. Cook, "A mathematical basis for the random decrement vibration signature analysis technique," *Journal of Mechanical Design*, ASME **104**, pp. 307-313, 1982.
11. A. Kareem and K. Gurley, "Damping in structures: its evaluation and treatment of uncertainty," *Journal of Wind Engineering and Industrial Aerodynamics* **59**(2,3), pp. 131-157, 1996.
12. Y. Tamura and S. -Y. Suganuma, "Evaluation of amplitude-dependent damping and natural frequency of buildings during strong winds," *Journal of Wind Engineering and Industrial Aerodynamics* **59**, pp. 115-130, 1996.
13. M. Ruzzene, A. Fasana, L. Garibaldi and B. Piombo, "Natural frequencies and dampings identification using wavelet transform: application to real data," *Mechanical Systems and Signal Processing* **11**(2), pp. 207-218, 1997.
14. W.J. Staszewski, "Identification of non-linear systems using multi-scale ridges and skeletons of the wavelet transform," *Journal of Sound and Vibration* **214**(4), pp. 639-658, 1998.
15. T. Kijewski and A. Kareem, "Reliability of random decrement technique for estimates of structural damping," *Proceedings of 8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability*, University of Notre Dame, July 24-26, CD-ROM, PMC2000-294, 2000.
16. T. Kijewski and A. Kareem, "On the reliability of system identification: applications of bootstrap theory," *Proceedings of ICOSSAR Conference*, Newport Beach, June17-22, 2001.
17. A.G. Davenport, M. Hogan and B.J. Vickery, "An analysis of records of wind-induced building movement and column strain taken at the John Hancock Center," *Boundary Layer Wind Tunnel Laboratory Report BLWT-10-1970*, 1970.
18. T. Kijewski and A. Kareem, "Comparative study of provisions in codes and standards with wind tunnel data," *Wind and Structures* **1**(1), pp. 77-109, 1998.
19. Y. Zhou and A. Kareem, "Along-wind load effects on tall buildings: a comparative study of major international codes and standards," submitted to *Journal of Structural Engineering*, ASCE, 2000.
20. F. Khan and R. Parmalee, "Service criteria for tall buildings for wind loading," *Proceedings of 3rd International Conference on Wind Effects on Buildings & Structures*, Tokyo, 1971.
21. P.W. Chen and L.E. Roberston, "Human perception threshold of horizontal motion," *Journal of Structures Division*, ASCE **98**, pp. 1681-1695, 1973.
22. T. Goto, "Studies on wind-induced motion of tall buildings based on occupants' reactions," *Journal of Wind Engineering and Industrial Aerodynamics* **13**, 1983.
23. A. Irwin, "Perception, comfort and performance criteria for human beings exposed to whole body pure yaw vibration and vibration containing yaw and translational components," *Journal of Sound and Vibration* **76**(4), 1981.
24. AIJ, *Guidelines for the Evaluation of Habitability to Building Vibration*, Architectural Institute of Japan, Tokyo, 1991.
25. N. Isyumov, "Criteria for acceptable wind-induced motions of tall buildings," *International Conference on Tall Buildings*, Council on Tall Buildings and Urban Habitat, Rio de Janeiro, 1993.
26. A. Kareem, "Serviceability issues and motion control of tall buildings," *Proceedings of Structures Congress*, San Antonio, 1992.