Full Scale Validation of the Predicted Response of Tall Buildings: Preliminary Results of Chicago Monitoring Project

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ABSTRACT: The wind-induced responses of three tall buildings in Chicago are being measured and compared to wind tunnel tests and finite element models. Preliminary results from only one of the buildings are presented herein, due to space limitations. These findings indicate amplitude dependent damping slightly lower than assumed in the design phase, but fundamental frequencies consistent with predicted values. Preliminary analysis of selected data gathered to date indicates that the measured full-scale accelerations are consistent with the wind tunnel predictions.

1 INTRODUCTION

Even though the performance of tall buildings affects the safety and comfort of a large number of people in both residential and work environments, 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 a result, the ongoing monitoring program described in this study seeks to correlate the measured characteristics of tall buildings under a wide range of wind environments with the behavior predicted via analyses performed as part of the design process and wind tunnel testing. In this NSF-sponsored program, collaborators at the NatHaz Modeling Laboratory at the University of Notre Dame (UND), the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario (UWO), and Skidmore Owings and Merrill (SOM) LLP in Chicago are pooling their resources and expertise for the first systematic validation of existing design practice for tall buildings in the US, followed by appropriate modifications of those standards, if necessary. The results of this effort will also provide much needed evaluation of the performance of common structural systems for tall buildings in real wind environments and will supplement existing international databases by providing valuable information on the dynamic characteristics of high-rise buildings over a range of amplitudes.

2 MONITORED STRUCTURES

The monitoring program detailed in this paper features three tall buildings in downtown Chicago, representing a variety of typical structural systems employed in high-rise design and construction. Since a major component of the project was spent in establishing relationships with the building owners to allow access to the buildings, their anonymity and privacy of the data must be assured to guarantee continued access for the life of the program. The structures are among the tallest of their respective types in the world and will be generically referred to as Building 1 (a steel tube with additional stiffening elements), Building 2 (a reinforced concrete shear wall/outrigger system) and Building 3 (a steel moment-connected, tubular system). All three structures are rectangular in plan and their primary axes aligning with North and East. Therefore, discussions referencing the sway response relative to a given axis will be appropriately described as North-South (N-S) sway or East-West (E-W) sway for simplicity.

3 PRIMARY INSTRUMENTATION

Each of the buildings is equipped with the same primary instrumentation system featuring four Columbia SA-107 LN force balance accelerometers, capable of accurately measuring accelerations down to 0 Hz, making them well-suited for monitoring these long-period Civil Engineering structures. These accelerometers are mounted to the ceiling in orthogonal pairs (Fig. 1b) at two opposite corners of the highest possible floor in each building. The outputs of these sensors are sampled every 0.12 seconds and archived by a 15-bit Campbell CR23X data logger (Fig. 1a). Considering the sensitivity of the accelerometers, this results in an overall system accuracy of approximately 0.001 milli-g. The logger is programmed to capture 10-minute statistics of these accelerometer outputs (min, max, and rms), and when motions exceed a user-selected threshold, the system switches to a continuous acquisition mode to capture hour-long time-histories for as long as the threshold levels are surpassed. The algebraic sum and difference of these four accelerometer outputs yields estimates of the N-S and E-W sway responses and two sources for estimation of the torsional response. These time histories are currently being investigated by the project team to determine the dynamic properties of these structures under a range of wind events, though this study presents only a sampling of this data. The data loggers are interrogated by phone using a remote interface established at a communications hub housed by SOM and are then uploaded onto an FTP server for access by the geographically dispersed project team. These systems were installed on June 14 and 15, 2002 in Buildings 1 and 2, respectively, while Building 3 was instrumented on April 30, 2003.

4 SUPPLEMENTARY INSTRUMENTATION: GPS & ANEMOMETERS

Global Positioning System (GPS) sampling capabilities currently provide the ability to track dynamic displacements of objects with high-accuracy (on the order of millimeters), while capturing the static and quasi-static displacements contributed by the background component of wind-induced response, thermal displacements, and even settlement. These could not be previously recovered by a double integration of accelerometer data, particularly in real-time. The evolution of Real-Time Kinematic (RTK) GPS makes this now a reality, and therefore, a differential RTK, GPS sensor pair was installed on Building 1 and on a nearby stationary reference station on August 26, 2002 to explore the effectiveness of GPS as a sensing technology. The choke-ring, GPS antenna, affixed to a rigid mount and topped by a protective radome (Fig. 1c), was installed at the centerline on the penthouse rooftop of Building 1 to capture building sway. The GPS receiver, supporting electronics, and on-site laptop, which is remotely interrogated via modem to trigger the system and download data, are housed indoors in an enclosure nearby the data logger system discussed previously. In this differential configuration, the Leica MC 500 sensors used in this study are capable of achieving a resolution, in terms of RMS background noise, down to 5 mm based on calibrations in [1], though this resolution is realistically 7.6 mm due to the baseline separation between Building 1 and the reference station.

Building 3 was also instrumented in July 2003 with a pair of ultrasonic anemometers on masts at opposite corners of the rooftop, approximately 41 m above roof level. An interim wind monitoring protocol was established while the final installation of these anemometers was coordinated at Building 3. This interim data is collected at the city's two airports (Midway and O'Hare) and from a NOAA meteorological station in Lake Michigan, elevated 75 feet above lake level and located 3 miles offshore of downtown Chicago.

5 IDENTIFICATION OF DYNAMIC PROPERTIES

While the data processing and analysis is on-going, preliminary system identification from Building 1 accelerations are presented herein. The analysis is directed toward a notable wind event that initiated on the morning of February 11, 2003 at 09:00 CST and escalated over the course of the day, as discussed later in Section 8. The following day was characterized by a more stationary response, as the wind direction stabilized around 315° and the mean hourly surface level wind speeds were constrained to 10-11 m/s, providing approximately 20 hours of data for analysis. A power spectral analysis would require spectral resolutions of 0.001 Hz for the E-W sway, 0.00051 Hz for the N-S sway, and 0.002 Hz for torsion to mitigate the spectral bias. Given the amount of stationary data during this event, this implies that the power spectra have 65 averaged raw spectra for E-W sway, only 22 averages for N-S sway and 149 averages for torsion. These spectra, an example of the time histories contributing to them, and a schematic of the oncoming wind relative to the building axes are shown in Figure 2. Note that the torsional spectrum is characterized by a separated peak, reflecting that the torsional response of the structure is not uniformly separated from the sway through the algebraic manipulation of accelerometer outputs. Therefore, identification of frequency and damping is not conducted herein for the fundamental torsional mode, as the physical significance of such estimated properties are somewhat questionable. The frequency (f_n) and damping (ξ) estimated by a half-power bandwidth of the power spectrum [2] are listed in Table 1 along with the RMS accelerations for each response component. The frequencies predicted from the structural analysis of the building are listed as well, along with the damping levels assumed in wind tunnel testing. The power spectra are biased and overestimate the level of damping, a fact reiterated by the analysis of the same data set by Random Decrement Technique (RDT) [2]. Through the use of a RDT with positive point trigger (i.e. capturing segments whenever a specified amplitude level X_p is identified) and relaxing the correlation condition to allow overlapping segments, 1000-6000 segments can be identified for the varying trigger conditions, defined as multiples

(M) of the standard deviation (σ) of the acceleration response as listed in Table 1. To minimize the trigger sensitivity identified in [1], the frequency and damping identified from Random Decrement Signatures resulting from a vector of triggers within 10% of the selected amplitude range (X_p = [0.9 M σ: 0.1 : 1.1 M σ]) are averaged to produce the frequency and damping estimate linked to a given acceleration level M σ. These estimates confirm that, while an amplitude-dependence in frequency is not apparent, the amplitude dependence of damping can be observed. Observed damping values appear, when considering spectral bias, to be less than the assumed levels. Damping was not estimated for triggers beyond M = 2.5 since the number of segments averaged in the decrement signature diminishes for higher amplitude levels, compromising the accuracy of system identification [1].

Table 1. Estimated dynamic properties for Building 1 in fundamental modes.

Response Component	RMS accelerations (milli-g)	Design Predictions		Power spectrum		RDT (M=1, 1.5, 2, 2.5)	
		f_n (Hz)	ξ	f_n Hz)	ξ	f_n (Hz)	ξ
E-W Sway	0.151	0.204	0.010	0.206	0.0121	0.207, 0.206, 0.206, 0.206	0.0073, 0.0076, 0.0082, 0.0094
N-S Sway	0.355	0.142	0.010	0.142	0.0098	0.142, 0.142, 0.142, 0.142	0.0086, 0.0076, 0.0076, 0.0080

6 EXAMPLE OF GPS DISPLACEMENT DATA

To demonstrate the ability of GPS to monitor the displacements of Building 1, a sample of data taken on January 7, 2003 is presented. The sample shown in Figure 3a was acquired between 15:00 and 15:30 CST. During the monitoring interval, the mean hourly wind speed was approximately 13 m/s at the aforementioned NOAA monitoring station and approaching from the west-northwest at 290°. The data was filtered using a second-order Chebyshev filter to separate the quasi-static or background components from the resonant response, also shown in Figure 3a. The displacements in the background components are on the order of a few of centimeters, more pronounced along the more flexible N-S axis of the structure. The enhanced flexibility along this axis is clearly reflected by the Fourier power spectra in Figure 3b-c, where the fundamental sway frequency along this axis was identified as 0.142 Hz, in comparison to the stiffer E-W axis at 0.205 Hz. Despite the resonant displacements along the E-W axis being beneath the resolution limits of the sensor, the frequency of the system is still accurately identified. The continued collection of GPS data and its assessment throughout this project will allow the identification and treatment of multipath error sources [1], the identification of noise threshold levels [1], and the ability to reliably correlate GPS displacements against the predicted displacements of the structure under varying wind events.

7 WIND TUNNEL MEASUREMENTS

While aeroelastic model testing can provide direct information on aerodynamic damping effects and contributions of higher modes of vibration to the response, the force-balance method was chosen for the wind tunnel tests in this study to allow some flexibility in analysis, since differences between the in-situ and predicted structural properties of the towers are more easily reconciled in the force-balance method. Force balance tests on 1:500 scale models of all three buildings, modeled with all surroundings within a 750m radius, were conducted at the BLWTL at UWO in the fall of 2002. The test data were combined with a wind climate model of Chicago, based on statistical analysis of wind measurements from O'Hare and Midway airports. Mode shape corrections were applied to obtain improved estimates of the generalized forces for prediction of building accelerations [3].

The variation of Building 1 sway accelerations with azimuth, calculated at the locations of the instrumentation described in Section 3, are presented in Figure 4 for varying return periods and azimuths. The data in the figure assumes the return period (*R*) wind speed may occur from any azimuth. Note that the data presented in Figures 4-6 have been normalized by the predicted accelerations along each building axis for a specified return period (see respective captions). These predicted accelerations reflect the likely response levels considering the Chicago wind climate. This ensures the anonymity of the building while still allowing the relative accuracy of the wind tunnel tests to be evaluated. The across-wind response of the building is quite strong in both the E-W and N-S building axes, as indicated in Figure 4.

8 COMPARISONS WITH WIND TUNNEL RESULTS

Preliminary results of the comparison of full-scale measurements and model scale predictions from the force-balance for Building 1 are presented herein. The predicted responses are based on an assumed damping of 0.01 and frequencies of vibration predicted from a finite element analysis of the building, which were consistent with the full-scale observations (see Table 1).

A complication in the present study is the lack of a rooftop anemometer on Building 1 to simultaneously record upper level wind speeds with the building responses through the data logger system. As noted in Section 4, this problem is being addressed by ultrasonic anemometers mounted at roof level on Building 3, which will provide an excellent source of upper level wind speed estimates for future comparisons. Currently however, gradient wind speeds are estimated from the interim protocol discussed in Section 4. Wind speeds at the airport meteorological stations are 2 minute averages measured on the hour, and have been extrapolated to gradient height using the BLWTL wind climate model. Wind speeds at the NOAA met station are sampled once every 5 seconds, and 5 minute averages are recorded continuously. These data are extrapolated to gradient (approximately 300 m over water) using methods [4] to account for the influence of terrain roughness and fetch. Corrections to account for averaging time for all stations were made using ASCE 7-98 [5]. A minor correction to the wind azimuth [6] was also applied to account for the rotation of the velocity vector with height. Gradient wind speed estimates are reasonably consistent between all three stations, though the data presented in the following figures are based on the measurements from the NOAA met station, as this is the sensor nearest downtown Chicago.

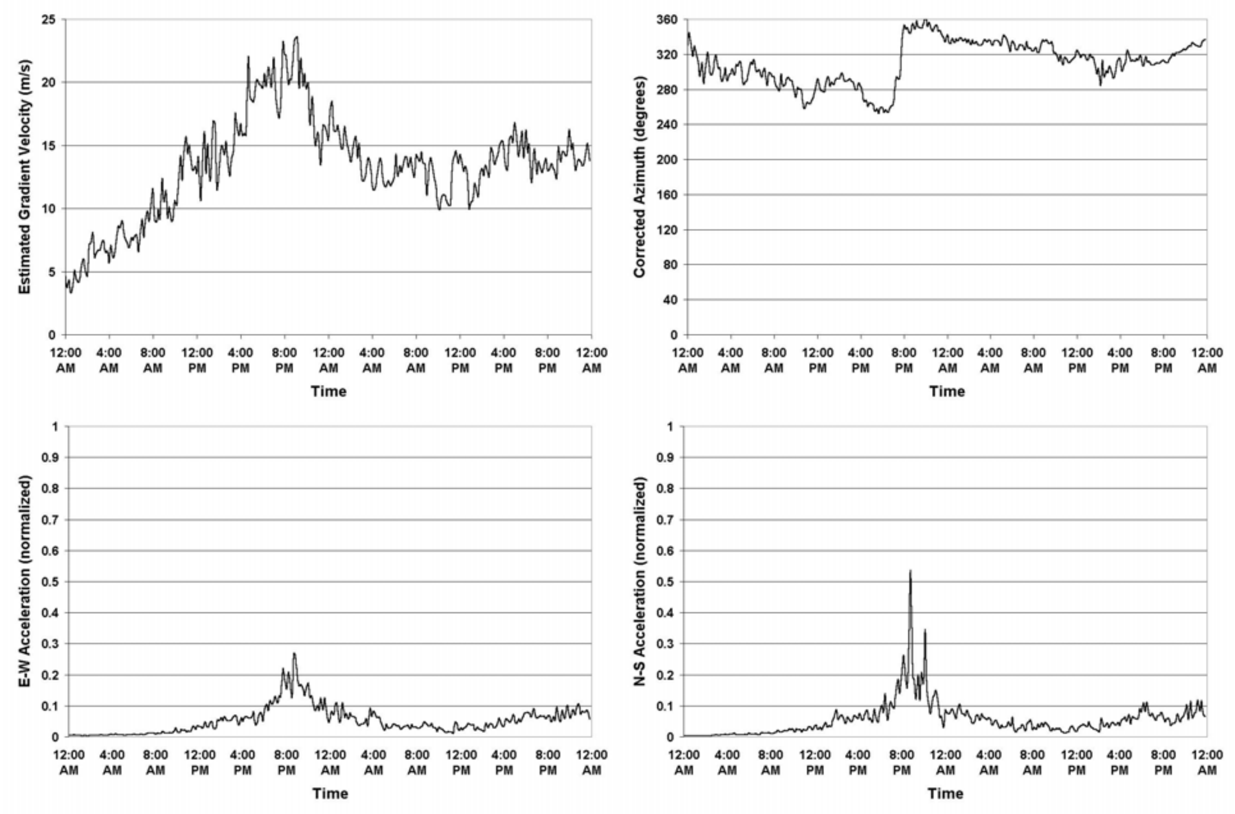

Figure 5. Variation of estimated gradient wind speed, direction, and normalized RMS response in E-W and N-S building axes during February 11th and 12th , 2003 wind event. Accelerations normalized by predicted annual RMS acceleration in respective axes.

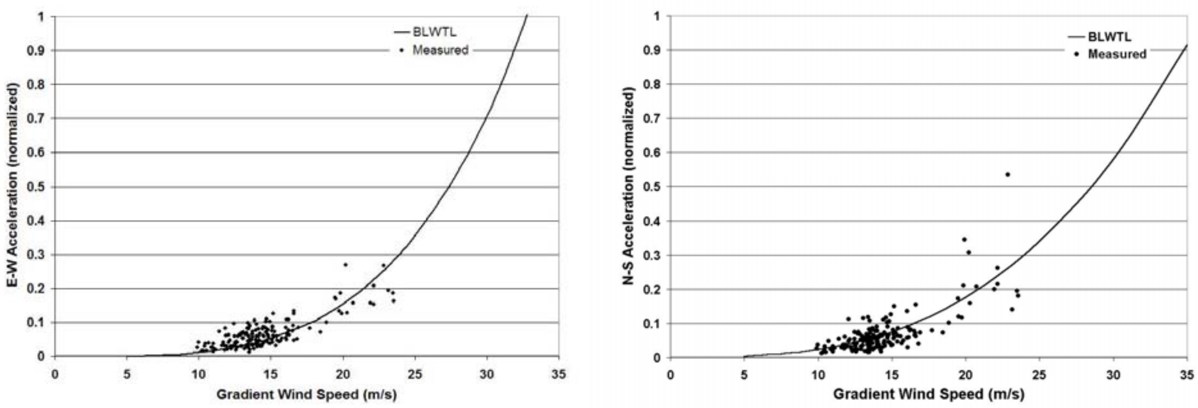

Figure 6. Relationship between estimated gradient wind speeds and measured RMS acceleration response in E-W and N-S building axes with wind tunnel predictions. Accelerations normalized by predicted annual RMS acceleration in respective axes.

A comparison of full-scale data with wind tunnel predictions is made for the strong wind event occurring on February 11th and 12th, 2003. Estimated gradient wind speeds and direction during the 48 hour period are shown in Figure 5, along with normalized RMS building accelerations in the E-W and N-S building axes. Measured RMS responses in the E-W and N-S direction are plotted against gradient wind speed and the wind tunnel predictions in Figure 6. The RMS acceleration data are normalized by the wind tunnel's predicted annual extreme acceleration in the E-W and N-S axes, respectively, again to assess the quality of the prediction while preserving anonymity. The full-scale data in Figure 6 correspond to the 10 minute averaged RMS values recorded from approximately 8:00PM on February 11th until the end of February 12th during which time the estimated gradient wind direction was relatively stable from the NW - NNW.

9 CONCLUSIONS

This study was established to allow the first systematic validation of the observed full-scale performance of tall buildings in the US against wind tunnel and finite element models used in design. As indicated by the normalized data presented in Figure 6, the maximum RMS responses of Building 1 measured to date are less than the annual values predicted from the wind tunnel studies. Given the relatively limited amount of data collected thus far, this is hardly surprising. While there is a good deal of scatter about the wind tunnel predictions, particularly at the higher wind speeds, the limited full-scale measurements to date appear to be consistent with the predictions from the wind tunnel tests. Difficulty estimating the gradient wind speeds from surface level wind and directionality measurements may partly explain the scatter. However, a clearer understanding will be gained with the continued monitoring and analysis of Buildings 1-3, presently ongoing, as well as the recent addition of rooftop anemometers at Building 3, which should alleviate some of the difficulties involved with estimating the gradient height wind speeds. Further, the ongoing collection of GPS data and its assessment throughout this project will address the unique challenges facing its application in urban environments and allow for comparisons with accelerometer outputs and permit the reliable correlation of GPS displacements against the predicted displacements of the structure under varying wind events. Preliminary system identification of the dynamic properties of the Building 1 indicates that fundamental frequencies were accurately predicted by the finite element models, as expected, and that damping values displayed some amplitude-dependence and were slightly lower than the levels assumed during design. The continued monitoring and analysis will enable a more complete description of damping over a range of amplitudes.

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