

## FULL-SCALE MONITORING OF WIND-INDUCED RESPONSE OF TALL BUILDINGS

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### Abstract

Despite the extensive research and model testing of high-rise structures, there is still a significant degree of uncertainty associated with the estimation of the response of tall buildings under dynamic excitations. To reduce this uncertainty, a suite of accelerometers and Global Positioning Systems (GPS) are installed to monitor the accelerations and displacements of three tall buildings in Chicago to determine the response due to wind excitation for different structural systems and materials. Using various system identification techniques, the natural frequency and damping in each building is determined. In addition, the amplitude dependence of frequency and damping is also investigated under typical Chicago wind conditions. This paper compares the dynamic properties obtained through the analysis of the accelerometer and GPS data with the predicted values assumed during the design of these buildings in an attempt to reduce the uncertainty associated with the estimation of the response of high-rise structures to wind excitation. The comparison of full-scale and model scale responses are presented elsewhere.

### 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, have yet to be systematically validated in full-scale. In particular, as state-of-the-art structural analysis software and wind tunnel testing are advancing rapidly, the accuracy and validity of their results needs to be calibrated with respect to actual performance. Understandably, since the development of full-scale models for this type of structure is not feasible, monitoring the performance of actual structures becomes the most viable means for verification and improvement of current design practices and analytical modeling approaches. The latter becomes particularly important to ensure satisfactory performance, economy and efficiency of future designs with increased complexity and height. Though monitoring has now become commonplace in seismic zones in the United States, the tall buildings community has unfortunately not followed suit.

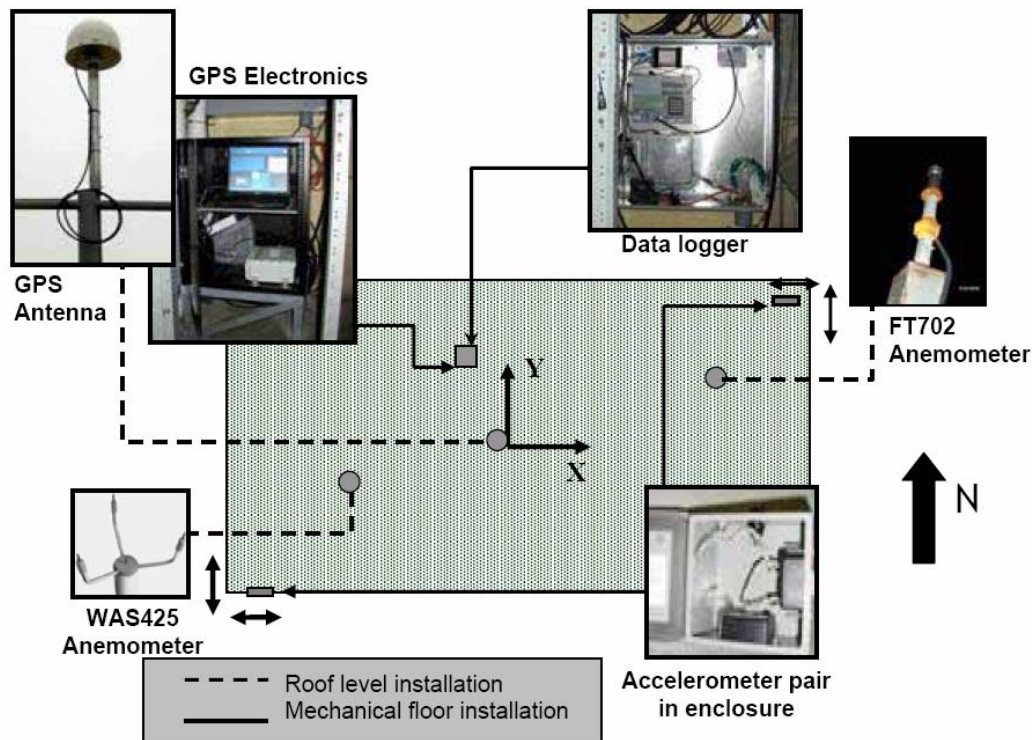
In response to this need, a partnership between the University of Notre Dame (UND), the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario (UWO) and Skidmore, Owings & Merrill LLP (SOM) in Chicago was established to initiate the Chicago Full-Scale Monitoring Project, which utilizes both traditional monitoring techniques (accelerometers) and Global Positioning Systems (GPS) Through the program, the actual performance of three tall buildings in Chicago is compared to predictions, both by finite element and wind tunnel models, thereby providing an important missing link between analytical modeling and actual behavior. Based on these comparisons, sources of discrepancies are identified to allow enhancement of current design practice. These evaluations also examine the in-situ periods and damping ratios of the buildings under a variety of wind conditions and over a range of response amplitudes, which will prove vital for expanding the existing databases of full-scale dynamic properties.

### Overview of Chicago Full-Scale Monitoring Project

#### *Description of Instrumented Buildings*

Currently, three tall buildings representing structural systems common to high rise design, all located in the same general locale of downtown Chicago, have been instrumented. As considerable time and effort were invested in establishing relationships with the building ownership, the anonymity of each building must be assured to guarantee continued access for the life of the program. Thus the buildings will be

generically referred to as Buildings 1, 2, and 3. The primary lateral load-resisting system of Building 1 features a steel tube comprised of exterior columns, spandrel ties, and additional stiffening elements to achieve a near uniform distribution of load on the columns across the flange face, with very little shear lag. In Building 2, a reinforced concrete building, shear walls located near the core of the building provide lateral load-resistance. At two levels, this core is tied to the perimeter columns via reinforced concrete outrigger walls to control the wind drift and reduce overturning moment in the core shear walls. The steel moment-connected, framed tubular system of Building 3 behaves fundamentally as a vertical cantilever fixed at the base to resist wind loads. The system is comprised of closely-spaced, wide columns and deep spandrel beams along multiple frame lines. As each building is rectangular in plan, with the primary axes aligning with North and East, subsequent discussions will reference sway response as North-South (N-S) or y-sway and East-West (E-W) or x-sway for simplicity, as shown in Figure 1.



**Figure 1: Generalized sensor array on generic floor plan with inset photographs of equipment (Kijewski-Correa et al. 2006).**

### *Instrumentation Overview*

Each building is equipped with the same primary instrumentation system that features four Columbia SA-107 LN high-sensitivity force balance accelerometers mounted in orthogonal pairs at two opposite corners of the ceiling at the highest possible floor in each building, as shown in Figure 1. The outputs of these sensors are sampled every 0.12 seconds and archived by a 15-bit Campbell CR23X data logger. The primary instrumentation systems were respectively installed in Buildings 1, 2, and 3 on 6/14/02, 6/15/05, and 4/30/03. Though wind-induced displacements are characterized by both background (quasi-static) and resonant components, only the latter can be recorded by the aforementioned accelerometer system. Therefore, it was of interest to monitor both of these contributions in full-scale using GPS.

The use of GPS is a relatively new technology for monitoring dynamic displacements of Civil Structures. As such, an extensive controlled calibration program was conducted prior to full-scale deployment

(Kijewski-Correa and Kareem 2003). These studies revealed that the Leica MC 500 GPS could track simulated tall building motions with RMS errors under 10% when used in a differential configuration with an Earth-based reference point. This has been confirmed in full-scale through the comparison of GPS displacements, twice differentiated, and the recorded acceleration data (Kochly 2006). Given the harsh environment and interference levels associated with monitoring in urban environments, the good correlation between new sensing technologies like GPS and existing technologies like accelerometers is quite promising. With appropriate diagnosis and removal schemes for urban multipath effects (Kochly 2006), this GPS technology has allowed the background component of wind-induced response to be observed in full-scale for the first time.

In addition, two ultrasonic anemometers were installed on masts 41 m above the rooftop of the tallest building in the program, Building 3, so that the reference wind speed and direction for each event may be measured at this site and reliably converted to represent the wind speed at the top of each instrumented building. In the meantime, an interim wind monitoring protocol was established. This interim data is collected at a NOAA GLERL meteorological station in Lake Michigan, elevated 75 feet above lake level and located 3 miles offshore of downtown Chicago. These data are extrapolated to gradient (taken as 300 m over open water) using methods to account for the influence of terrain roughness and fetch (ESDU 2001).

	Mode 1		Mode 2		Mode 3	
	Natural Frequency (Hz)	Damping	Natural Frequency (Hz)	Damping	Natural Frequency (Hz)	Damping
Building 1	<i>Y-axis translation</i>		<i>X-axis translation</i>		<i>Torsion</i>	
	0.14	1%	0.20	1%	0.50	1%
Building 2	<i>X-axis translation, slight torsion</i>		<i>Y-axis translation, slight torsion</i>		<i>Coupled Torsion</i>	
	0.15	1%*	0.16	1%*	0.22	1%*
Building 3	<i>Fully coupled x-translation</i>		<i>Fully coupled y-translation</i>		<i>Fully coupled torsion</i>	
	0.13	1%	0.13	1%	0.22	1%

\*1% used for accelerations, 1.5% used for base moments.

**Table 1: Natural frequencies and assumed damping levels in finite element models of buildings in Chicago Monitoring Project (Kijewski-Correa *et al.* 2006).**

#### *Finite Element Modeling*

For the buildings associated with this study, finite element models were developed using currently available commercial software: ETABS and SAP2000, based upon careful reference to the design drawings (ETABS 2002; SAP 2002). It was not the purpose of this study to apply a unique set of modeling assumptions to the FE models in order to mimic a known, in-situ measured result. Rather, all assumptions regarding the finite element representation of the buildings in the study reflect those commonly applied in design offices for serviceability assessment. Table 1 summarizes the resulting periods from the FE analyses conducted at SOM and the damping levels assumed by the original designers of the buildings (Kijewski-Correa *et al.* 2005b).

#### *Data Archiving and Distribution*

The program also takes advantage of JAVA-based applets for efficient processing and secured distribution of recorded data to the geographically dispersed project team through the program website (<http://windycity.ce.nd.edu>). While the JAVA applet interfaced with MATLAB on the server side denoises, decouples and displays the measured data as accelerations along each of the building's axes, a

database feature allows users to search the data archives for records associated with a specified wind velocity or response level (Kijewski-Correa *et al.* 2005a).

## Identification of Dynamic Properties

The analysis of full-scale data collected in this program provides valuable insight into a variety of response characteristics for tall buildings and permits the systematic validation of existing design practice through the comparison of analytical and wind tunnel response estimates with full-scale observations. To determine the natural frequency and damping of the three buildings under ambient vibrations, two system identification (SI) techniques assuming white noise inputs are utilized: a power spectral approach using the Half-Power Bandwidth Technique (HPBW) and the Random Decrement Technique (RDT). The latter approach has allowed the estimation of structural properties over a range of amplitudes to document the amplitude-dependence of damping. When considering the return period of events examined thus far and the trends in amplitude dependence, the in-situ values confirm the appropriateness of values assumed in the design for longer return period events (Kijewski-Correa *et al.* 2006). As both approaches invoked assumptions of stationarity, three separate stationarity tests were performed to investigate the validity of this assumption for the analyzed events. These tests included the Run and Reverse Arrangements Tests and a method proposed by Montpelier (1996). It was determined that passing at least two of the stationarity tests was sufficient and records satisfying these conditions were then used in subsequent system identification analyses.

### *Spectral Analysis*

Given the narrow-banded nature of the buildings in this study, the simultaneous reduction of bias and variance errors can be quite challenging, given the limited amount of data satisfying the stationarity checks conducted here. In light of this, spectral damping is generally overestimated and can have significant uncertainty in light of variance errors. Nevertheless, the identified stationary data was broken into segments of sufficient length so as to provide bias errors of less than -2% and the averaged to reduce variance as much as possible given the amount of data available.

### *Random Decrement Technique*

The stationary response data was first pre-processed by Butterworth bandpass filters to isolate each mode of interest before applying the Random Decrement Technique. Once the Random Decrement Signature (RDS) is obtained, it is fit using the Hilbert Transform to extract frequency and damping from the phase and amplitude of the analytic signal. Due to the sensitivity of trigger conditions on the number of segments captured, the reliability of the Random Decrement Technique can be improved through repeated localized triggering, as proposed in Kijewski-Correa (2003). Assuming a positive point trigger is specified as some multiple of the standard deviation of the acceleration response being analyzed ( $X_p = M\sigma$ ), then an array of triggers within a few percent of  $M$  are specified to generate multiple RDSs. From these, frequency and damping values can be estimated and subsequently averaged for the mean estimate of the dynamic properties associated with a trigger of  $M\sigma$  and their accompanying Coefficients of Variation (CoV).

## Example Results

An example of the measured response of all three buildings for a wind event on March 7, 2004 is now presented. Additional analyzed events can be found in Kijewski-Correa *et al.* (2005a; 2006) and Kochly (2006). Following the procedure outlined above, the available records for the March 7, 2004 for each building were tested for stationarity by the aforementioned methods. Records that did not pass the standard were not included in the subsequent System Identification. The remaining records were analyzed with both the Spectral Analysis and Random Decrement Technique described above. Table 2 lists the resulting estimated natural frequency and damping ratios, along with associated error measurements:

power spectral density variance estimates are provided for the HPBW and CoVs from the local trigger operation are reported for the RDT.

The natural frequencies agree well with the Finite Element predictions for Building 1. However, for Buildings 2 and 3 there are some discrepancies, which have been discussed in Kijewski-Correa et al. (2006) and Kochly (2006). The damping estimations do vary from predictions in many cases, not surprising since the values in Table 1 are assumed. As expected, CoVs on damping are considerably higher than those on natural frequency. Due to the difficulty in estimating damping, the higher CoVs are not surprising. While both methods (RDT and HPBW) agree well with respect to frequency, there is some considerable disparity in the damping values estimated by each. This is likely due to the limited data which influences the smoothness of the PSD estimate, resulting in higher uncertainty in the bandwidth estimates. In addition, the error associated with RDT is lower than that of HPBW due to the large number of segments averaged (in the thousands) as compared to the few segments averaged to create each PSD (less than 50). The results of this analysis follow the trends previously observed in Kijewski-Correa et al. (2005a): Building 1 has lower damping than either Building 2 or 3, while Building 2 has the highest damping. As the estimated damping for Building 1 is, for the most part, less than 1%, the assumed 1% damping value of this building is appropriate. However, for Building 2 and 3, the assumed 1% damping is lower than the in-situ damping, which would result in higher predicted response estimates.

		Building 1		Building 2		Building 3	
		Natural Frequency (Hz)	Damping (%)	Natural Frequency (Hz)	Damping (%)	Natural Frequency (Hz)	Damping (%)
X-Sway	HPBW	0.204	1.37	0.178	1.66	0.117	1.59
	(Error)	18.57		22.36		33.33	
	RDT	0.204	0.89	0.178	1.52	0.117	1.01
	(CoV)	0.13	12.61	0.31	11.33	0.15	10.18
Y-Sway	HPBW	0.141	0.88	0.176	2.53	0.117	2.01
	(Error)	26.73		22.36		33.33	
	RDT	0.141	1	0.176	2.95	0.116	1.44
	(CoV)	0.13	6.43	0.96	5.54	0.34	24.2
Torsion	HPBW	0.503	0.71	0.294	3.26	0.116	1.81
	(Error)	13.13		22.36		23.57	
	RDT	0.502	0.50	0.289	4.20	0.116	1.53
	(CoV)	0.11	6.08	0.49	5.04	0.19	8.83

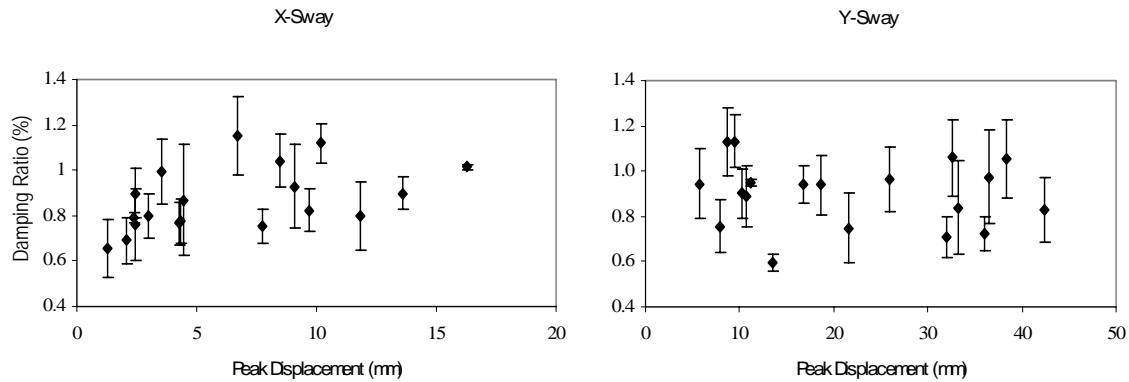
**Table 2: Estimated natural frequencies and damping levels from Half-Power Bandwidth and Random Decrement analyses of buildings in Chicago Monitoring Project.**

### Amplitude-Dependence of Damping

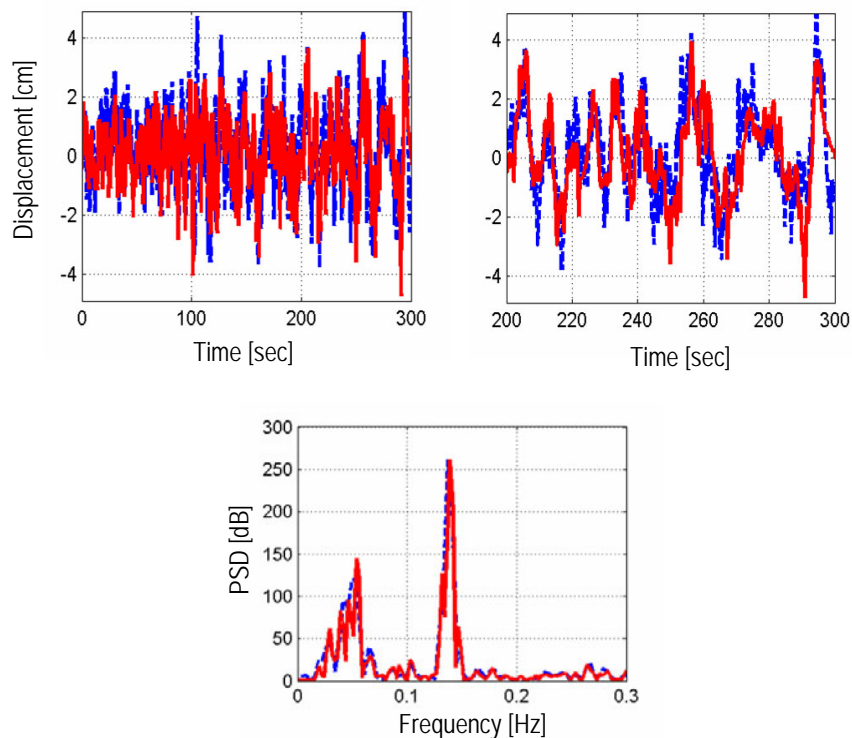
To examine the amplitude-dependent nature of the damping estimates obtained in the Chicago Project, the aforementioned averaging RDT scheme with localized averaging was applied to multiple wind events. It was determined that an 80% passing rate for at least two of the stationarity tests was sufficient to establish stationarity for a given record. Only wind events producing at least five hours of data satisfying this criterion were considered. The analysis here shall focus only with the two perpendicular axes of Building 1: x-sway and y-sway.

As only annual and sub-annual wind events have been observed to date, the resulting response levels tend to be in the lower amplitude range. As such, the high amplitude plateau may not yet be known for Building 1. As shown in Figure 2, the estimated damping levels over a range of amplitudes show no discernable amplitude dependence in light of the uncertainty associated with the estimated damping. This

level of uncertainty is again gauged from the CoV values associated with the localized triggering approach and are visually represented by the error bars in Figure 2.



**Figure 2: Damping estimates as a function of amplitude for Building 1 (Bashor et al. 2005).**



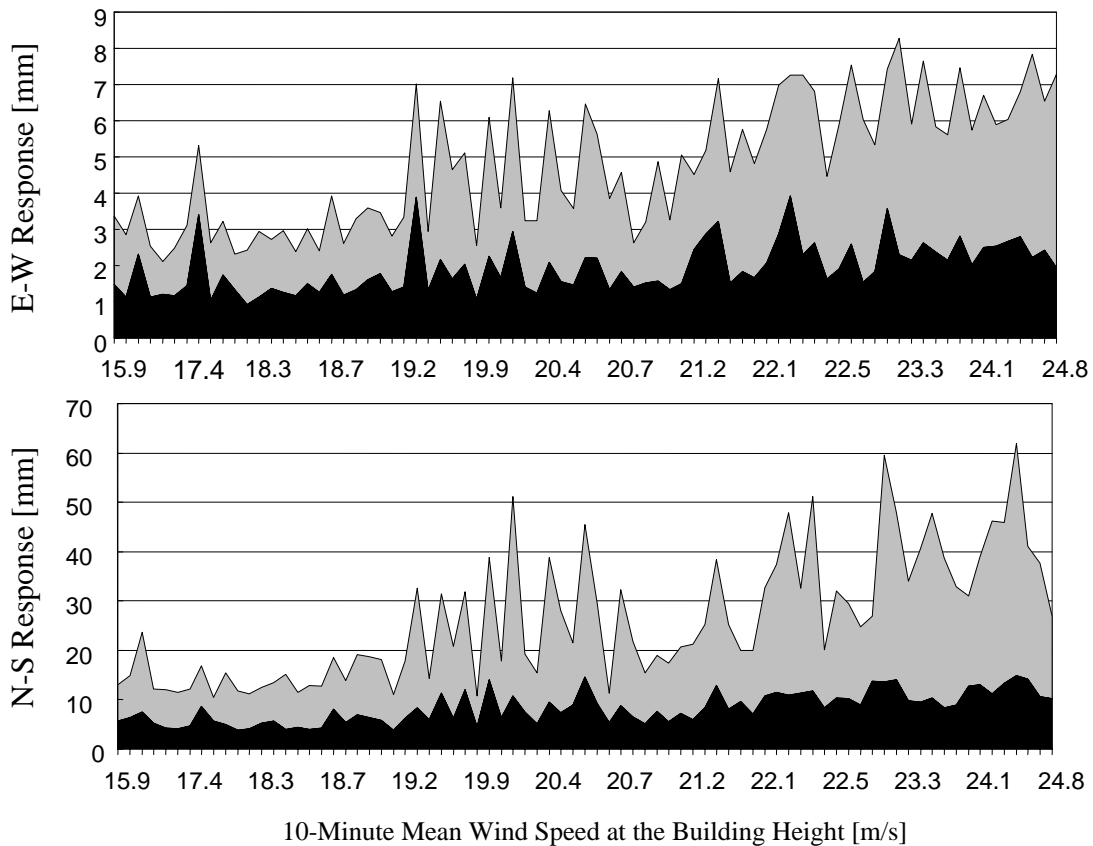
**Figure 3: Time history (top, left), zoom from 200–300s (top, right) and PSD (bottom) of GPS-measured full-scale displacements from a high-rise building, resimulated in field tests (GPS solid red, shake table dashed blue) (Kochly 2006).**

### GPS Performance Verification

The Chicago Full-Scale Monitoring Project offers an excellent opportunity to verify GPS technologies against traditional sensors in full-scale for resonant tracking capabilities as both systems are monitoring the same building simultaneously. Several comparisons of GPS with accelerometers have been made in full-scale, e.g., Kochly (2006) and Kijewski-Correa et al. (2006). The reader should refer to these for

additional details. These comparisons show that GPS is capable of measuring RMS accelerations with no errors greater than 10%.

In order to reliably verify the quasi-static tracking ability of the GPS units in full-scale, benchmark studies were performed using controlled field tests performed at Notre Dame (Kochly 2006). For this particular test, a record of the GPS-measured wind-induced full-scale displacement of Building 1 was fed into a shake table and then measured with the GPS. The displacement time history and its power spectral density are shown in Figure 3. As is demonstrated, the GPS is capable of tracking the motion with general accuracy as well as capturing the energy of both the background and resonant components of the response. Thus, through the use of both traditional monitoring techniques and GPS, the resonant and background components of the response can be obtained and ultimately compared with design predictions. This comparison was conducted in Kochly (2006) and again underscored the importance of effective removal of multipath effects to insure reliable estimations of background response components.



**Figure 4: Contributions of background and resonant RMS response (background in black, resonant in gray) to total displacements, neglecting the mean component (Kochly 2006).**

To demonstrate the relative contributions of background and resonant responses in full-scale, GPS displacements of Building 1 are decomposed into these components and plotted in Figure 4 (Kochly 2006). This plot displays how much each component contributes to the total response, neglecting the mean component. As is shown in the figure, the background portion of the response is significant for such lower return period wind events, increasing slightly at lower wind speeds in the alongwind (E-W) direction, where it encompasses half of the total response. Even at the higher wind speeds observed in these events, the background component contributes significantly to the alongwind response. Although not as dominant in the acrosswind direction, the background component is still noteworthy.

## Concluding Remarks

This paper discusses a study established to allow the first systematic validation of tall building performance in the US using both traditional monitoring techniques and GPS to compare the in-situ response of tall buildings with current design practices. For each of the three buildings currently monitored in the City of Chicago, instrumentation is overviewed and analytical modeling approaches are summarized. The in-situ dynamic properties for a specific wind event are compared with design predictions as well as with previous analyses. Using the same methodologies, the amplitude dependence of damping is examined. In addition, the performance of GPS is examined for measuring both resonant and background components of the response. Note that these efforts are presently being expanded for other observed wind events for a more comprehensive assessment of the design state-of-the-art.

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