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Wind-induced vibrations of buildings: role of transient events

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The design of tall buildings, in many cases, is governed by habitability limit states, where accelerations predicted from wind tunnel studies emulating stationary, boundary layer flows associated with synoptic winds are compared to accepted standards for occupant comfort. In both the accelerations predicted for these design limit states and the criteria they are evaluated against, tall building design practice has consciously neglected other types of responses that result from more transient wind events, such as thunderstorms, owing to their short duration. In fact, these types of events and the impulse-like responses they induce in dynamically sensitive structures were not even considered in occupant comfort tests on human subjects until very recently. However, full-scale monitoring programmes on tall buildings, and anecdotal reports from their occupants, have verified that these events do occur regularly and are capable of producing accelerations that exceed those generated by their stationary synoptic counterparts at comparable wind speeds, thus generating perceptible motions on more frequent recurrence intervals. Therefore, it becomes important to investigate the dynamic behaviour of tall buildings under transient wind events and to attempt to gain some understanding of the mechanisms causing these large acceleration responses. The present study attempts to do just that, developing analysis frameworks appropriate for non-stationary records and applying them to full-scale data to enable rare insights into the dynamics of tall buildings under transient wind events, particularly those buildings with marked amplitude dependence and coupling between lateral and torsional modes.

1. Introduction

As building systems become taller, more lightweight and efficient, they become increasingly sensitive to the effects of wind. As a result, habitability limit states often govern the design of tall structures, as wind-induced accelerations increase and become more perceptible to occupants. The evaluation of habitability is traditionally based on accelerations from wind tunnel testing on scaled models in boundary layer tunnels emulating stationary flows associated with synoptic winds. The resulting accelerations are compared to acceptable levels, so-called occupant comfort criteria, which were originally based on sinusoidal, uniaxial motion simulator studies employing human subjects. Only in recent years has research focus changed: wind loads and responses associated with transient wind events such as gust fronts, characterised by distinct boundary layer profiles and non-stationarity, are now being considered, while motion simulator studies are now examining the role of motion duration and peak factor to determine the effect of impulse-like motions on perception, human comfort and task disruption (Burton *et al.*, 2005).

Interestingly, anecdotal evidence from major cities in the USA has suggested that occupants of tall buildings have experienced discomforting sensations during transient wind events such as thunderstorms or gust fronts, where variations in wind speed and/or direction can be dramatic and rapid (Wakimoto, 2001). These reports have been corroborated by recent pseudo-full-scale occupant comfort surveys (Kijewski-Correa and Pirnia, 2009). In fact, full-scale investigations have even documented acceleration responses in these events that exceed the design predictions based on stationary, synoptic winds of comparable velocity (Bentz and Kijewski-Correa, 2009a). Thus while wind tunnel response predictions and habitability criteria at present do not account for such events, the levels of acceleration they can generate and the negative feedback from actual occupants perhaps suggest they should. This issue becomes particularly relevant in countries such as the USA, where it has been documented that gust front or thunderstorm events are quite common (Wakimoto, 2001) and actually drive the extreme wind climatology at many sites outside hurricane zones (Twisdale and Vickery, 1992). Given that the concern over these events was first noted in full-scale studies, full-scale monitoring continues to provide the best venue to investigate this phenomenon further. Unfortunately, even with full-scale data in hand, it can be difficult to determine the mechanisms causing these large-amplitude responses and the role that the structure's own dynamics plays in the process. This is primarily due to the limited system identification approaches available for accurately analysing full-scale, non-stationary response data.

1.1 State of the art in system identification for tall buildings

System identification methods have been used on full-scale data to compare in situ dynamic properties with those predicted in design. In particular, since there is no means to estimate damping effectively in the design stage, the earliest full-scale efforts were directed towards short-term monitoring of suites of buildings to develop damping databases (Davenport and Hill-Carroll, 1986; Jeary, 1986; Lagomarsino, 1993). Since then, monitoring efforts have grown increasingly long-term (Brownjohn *et al.*, 1998; Li *et al.*, 1998; Kijewski-Correa *et al.*, 2006) with the objective of observing the structure under a range of wind events to validate the design process more systematically, especially in extreme events such as typhoons (Li *et al.*, 2005; Xu and Zhan, 2001). In these studies, discrepancies between predicted and measured natural frequencies and damping ratios have been noted. Particularly in newer reinforced concrete structures, natural frequencies have been observed to be higher in situ, owing to assumptions of cracking in the finite-element model development that have yet to be realised in service, or owing to differing material properties in situ (Kijewski-Correa *et al.*, 2006). In other cases, discrepancies have indicated errant assumptions regarding the participation of gravity elements in the overall concrete lateral system (Erwin *et al.*, 2007) or a failure adequately to capture steel connection flexibility (Kijewski-Correa *et al.*, 2005). Similarly, inconsistencies between actual and predicted viscous damping ratios are commonplace, and it is often discovered that design values are unconservative (Li *et al.*, 2002), although it should be noted that in situ damping values reveal a significant amount of scatter (Satake *et al.*, 2003). This has much to do with the difficulty of estimating low levels of damping from wind-induced response data.

While there are a wide variety of system identification tools that have been applied to full-scale data from buildings, tall buildings excited by wind introduce a number of constraints that narrow the pool of viable methods (Kijewski-Correa *et al.*, 2008). First, owing to the spatio-temporal distribution of wind pressures over a structure, input forces cannot be monitored and researchers must rely on output-only system identification methods that extract dynamic properties from the measured responses only. As a result, system identification approaches must generally employ assumptions of stationary, Gaussian, white noise inputs to enable the substantial amounts of averaging necessary to eliminate the influence of the unmeasured input. Unfortunately, since tall buildings have long periods of vibration and low damping levels, these approaches require many hours of stationary data. An inventory of the Japanese full-scale damping database (Satake *et al.*, 2003) reveals that stationary time (e.g. random decrement technique) and frequency (e.g. half power bandwidth and least-squares curve fit) domain approaches have received equal attention by their researchers, and this tends to be an accurate microcosm of the literature on full-scale monitoring of other tall buildings.

Unfortunately, the stationary approaches based in the frequency domain using power spectral densities (PSDs) can have particular challenges when the structure's properties are not time invariant (Pirnia *et al.*, 2007). Specifically, simplifications are made in design to facilitate linear analyses of structures that are inherently non-linear. These subtle non-linearities then surface in full-scale observations as amplitude-dependent frequencies and viscous damping ratios. This is not evidence of damage, but rather a reflection of the fact that these systems have mildly non-linear features, primarily in their connections and non-structural elements. In fact, it is widely accepted that frequency decreases with increasing amplitude, even under service loads, as these elements slip more, in turn causing greater energy dissipation, with both behaviours plateauing at some point. These losses in stiffness are not permanent and the structure recovers once the excitation subsides. This amplitude dependence has been observed in situ for several tall buildings using stationary approaches such as the random decrement technique with varying trigger conditions (Kijewski-Correa and Pirnia, 2007; Li *et al.*, 2002, 2003, 2005). However, even with the ability to track mild non-linearities, these approaches still require substantial amounts of weakly stationary data and are ill-suited for short-duration events such as thunderstorms, where averaging is no longer possible owing to the non-stationarity of the event. Thus, it is necessary to seek analysis methods that preserve evolutionary details.

1.2 Study objective

This study will utilise acceleration data from an instrumented tall building that is part of the Chicago full-scale monitoring programme (Kijewski-Correa *et al.*, 2006) to underscore some of the unique dynamics associated with tall building response to transient wind events, using a wavelet-based approach to system identification. While wavelets have been used previously by the authors to visualise transient features (Bentz and Kijewski-Correa, 2009a; Kijewski-Correa and Pirnia, 2007), this study takes the wavelet analysis a step further by actually performing system identification within the wavelet framework. The composite building studied here, whose structural details and instrumentation are described in greater detail by Pirnia *et al.* (2007), is instrumented with three orthogonal pairs of accelerometers attached to girders on its 64th floor. The selection of this building in particular followed from a routine analysis of data that revealed a number of recent events with unusual response statistics, for example isolated occurrences of peak accelerations exceeding those previously observed in other wind events with comparable wind velocities. Furthermore, as this building had previously revealed evidence of amplitude dependence in its dynamic properties and coupling between its closely spaced modes (Kijewski-Correa and Pirnia, 2007; Pirnia *et al.*, 2007), it has unique dynamic characteristics worthy of additional investigation. After checking historical weather service data, these large-amplitude responses were found to be associated with thunderstorms. In these events, accelerations showed an impulsive-type character, as discussed by Bentz and Kijewski-Correa (2009a). These events are characterised by rapid increases in wind speed, often accompanied by erratic variations in wind direction, and tend to excite multiple modes with their broadband energy, as demonstrated in Figure 1, which shows the power spectral density

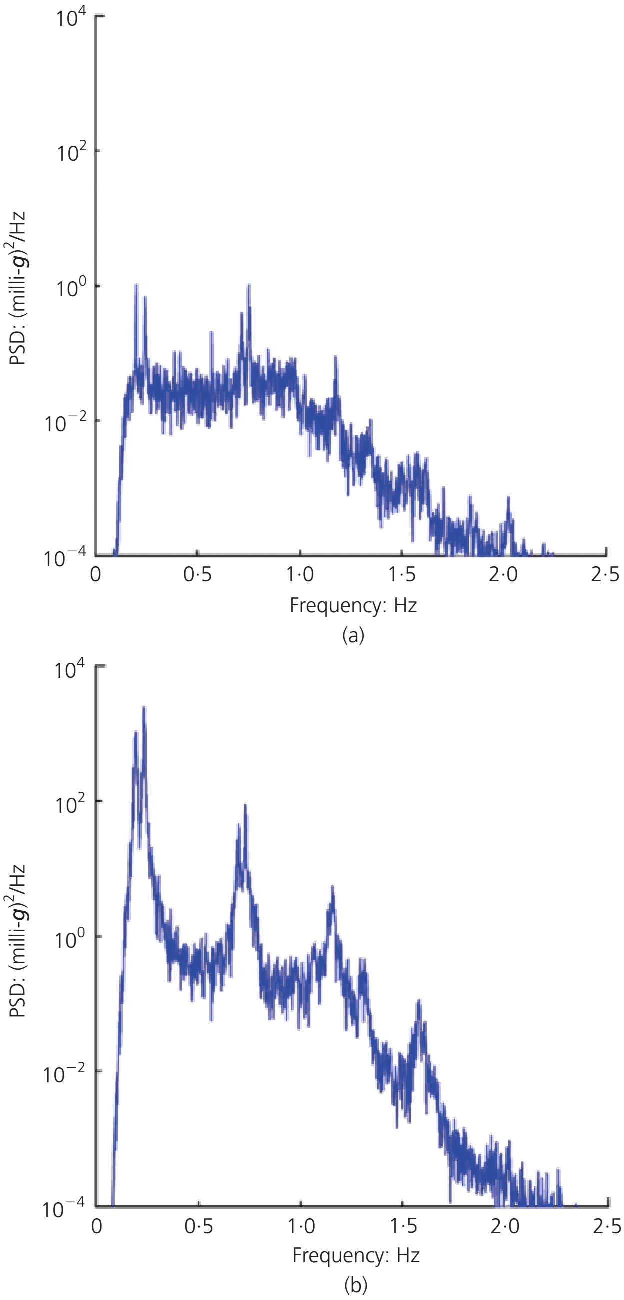

Figure 1. Comparison of power spectral densities of building accelerations in (a) stationary event and (b) transient event

for a recorded acceleration of this building in a stationary wind event and during one of these transient wind events.

2. Methodology

2.1 Wavelet framework

Stationary analysis tools such as the Fourier power spectral density cannot provide an adequate representation of these transient responses, requiring an analysis that retains temporal information, such as the Morlet wavelet analysis framework introduced by Kijewski and Kareem (2003). Wavelet transforms have been shown by the co-author and her collaborators to offer interesting perspectives on non-linear systems (Kijewski-Correa and Kareem, 2007) and tall buildings with unique dynamic characteristics (Kijewski-Correa and Pirnia, 2007), thanks to their ability to detect subtle variations in frequency over time. A brief primer on the Morlet wavelet is now provided.

The wavelet transform for signal $x(t)$ and its parent Morlet wavelet $g(t)$ are respectively given in Equations 1 and 2 below.

$$W(a,\ t) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(\tau)\,g^{*}\left(\frac{t-\tau}{a}\right)\mathrm{d}\tau \tag{1}$$

$$\begin{aligned} g(t) &= \mathrm{e}^{i2\pi f_0 t}\mathrm{e}^{-t^2/2} \\ &= \mathrm{e}^{-t^2/2}[\cos(2\pi f_0 t) + i\ \sin(2\pi f_0 t)] \end{aligned} \tag{2}$$

where f_0 is the central frequency of the wavelet, related to the dilation or scale parameter a by $a = f_0/f$, where f is the Fourier frequency. Thus this wavelet provides a Fourier-like analysis, but localised and translated in time, making it well suited for the analysis of transient dynamics. The central frequency of the wavelet is particularly important for tuning the analysis to enhance frequency or temporal resolutions. In this study, owing to the closely spaced nature of the modes, the former is desired, so f_0 was set to 4 Hz. Ensuing end effects were then remedied with reflective signal padding (Kijewski and Kareem, 2002). Once the wavelet coefficients are calculated from Equation 1, their squared magnitudes can be presented in an energy map (scalogram) with respect to Fourier frequency and time.

As the wavelet coefficients will take on their maximum values at the dominant frequency components at each instant in time, they provide clear ridges in the time–frequency plane that can be isolated and extracted to remove any redundant information in the scalogram (Kijewski and Kareem, 2003). This is effectively a tight bandpass filter around each mode. Through the use of analytic wavelets like the Morlet, the resulting wavelet coefficients along this ridge provide an important complex-valued representation: the analytic signal $z(t)$, which will later prove valuable for system identification (Kijewski and Kareem, 2003). Similarly, wavelet coefficients can be isolated at particular time instants by taking a slice of the scalogram, which produces an instantaneous power spectrum that will prove valuable for unlocking the contributing modes to various events within the responses. These manipulations of the scalogram are shown in Figure 2.

2.2 Impulse extraction

As discussed previously, the system identification conducted on full-scale, stationary wind-induced response data extracts dynamic properties from highly averaged response artefacts such

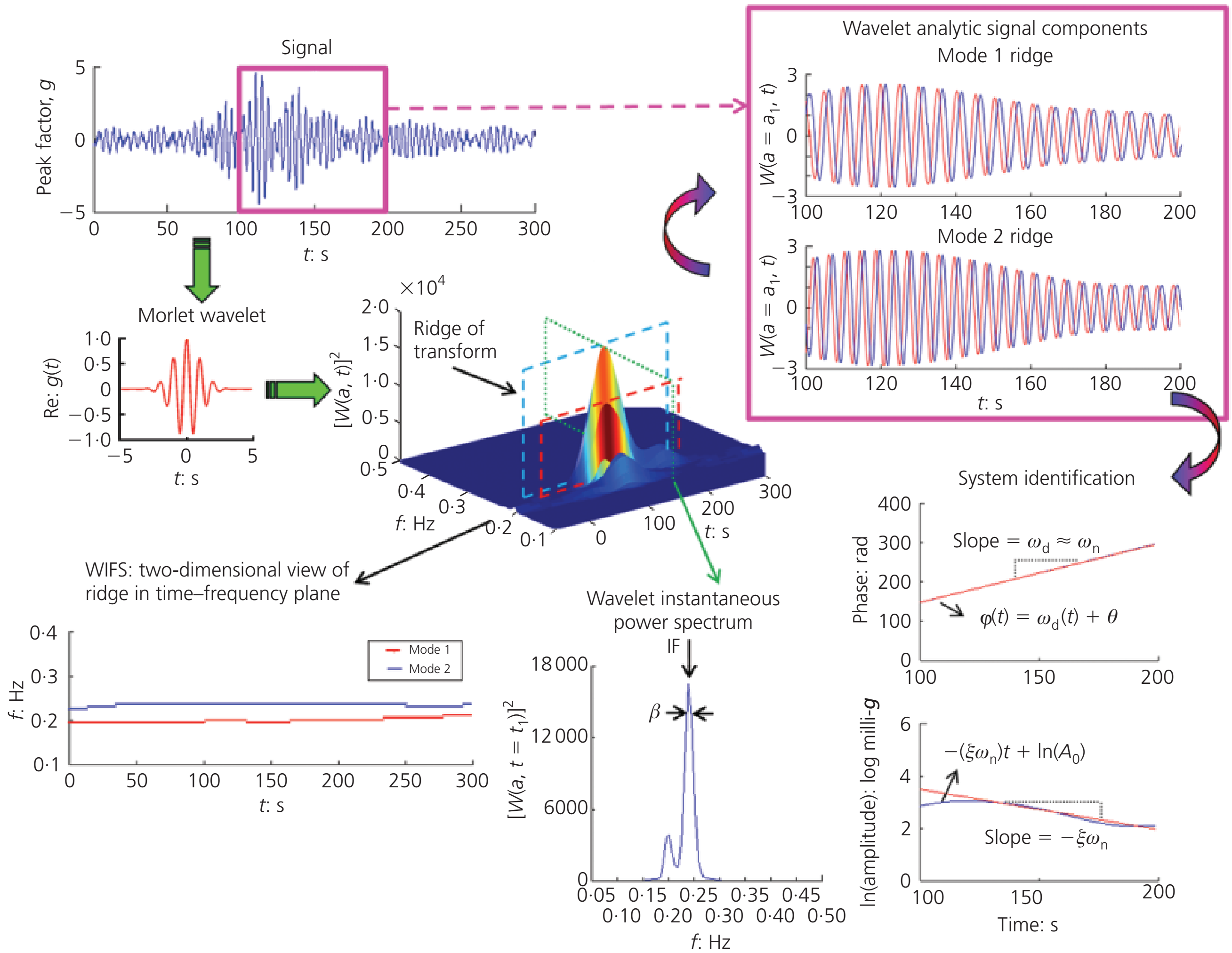

Figure 2. Schematic overview of wavelet analysis framework

as random decrement signatures or power spectral densities (Kijewski-Correa *et al.*, 2008). In a transient analysis, the option for averaging is no longer available, and the influence of input can no longer be eliminated in this way. However, it was previously noted in the application of the random decrement technique that a high number of averaged segments was not always necessary for good performance (Kijewski-Correa, 2003). In fact, averaged segments that initiate from the highest amplitudes in the signal were found, with little to no averaging, often to yield impulsive or free-vibration-like responses, particularly within a few cycles following the peak amplitude, despite the decrement theory that would suggest a large number of averages would be required to do so (Vandiver *et al.*, 1982). This finding should not be surprising, as a natural decay is more likely to follow the highest amplitudes of a randomly excited response. In particular, this type of impulsive response has been observed in the acceleration records from transient events. Therefore, the authors developed a separate wavelet analysis that could be used to diagnose impulse-like responses bedded in narrowband wind-induced accelerations. This was achieved by defining a new parent wavelet that mimics the impulse response function for a single degree-of-freedom oscillator

$$g(t) = e^{-\xi_i 2\pi f_i |t|}\cos(2\pi f_i t) \quad (3)$$

where f_i and ξ_i are set to the projected natural frequency and damping ratio of the building being analysed. Bentz and Kijewski-Correa (2009b) demonstrated that a wavelet transform employing this customised parent wavelet was capable of identifying impulses as concentrated energy bands in the wavelet scalograms. This was verified using extensive simulations to ensure that impulses could be clearly distinguished from other high-amplitude responses. This customised wavelet will be used in the present study to isolate viable impulses in the full-scale data that will be analysed in greater detail in the following sections to unlock the dynamic characteristics of the contributing modes during these transients.

2.3 System identification

The Morlet wavelet system identification approach used here is based on the earlier work by the authors, where decay responses were obtained from averaging stationary records (Bentz and Kijewski-Correa, 2009a; Pirnia *et al.*, 2007). The difference in this study lies in the fact that decay signatures will be directly extracted from identified impulse regions in the time histories, instead of being generated by the random decrement technique. For decays characterised by a single mode, responses are of the following form

4. $$x(t) = A_0 e^{-\xi\omega_n t}\sin(\omega_d t + \theta)$$

where ω_n is the natural frequency, ξ is the critical damping ratio and ω_d is the damped natural frequency. If this is then compared to the estimate of the complex-valued analytic signal, in this case furnished by the wavelet coefficients along the ridge associated with a given mode, a similar form will be found

5. $$z(t) = x(t) + i\tilde{x}(t) = A(t)e^{i\varphi(t)}$$

where $A(t)$ is amplitude and $\varphi(t)$ is phase. From these two expressions, the time-varying or *instantaneous* natural frequency can then be determined from the derivatives of the complex valued analytic signal phase

6. $$\phi(t) = \omega_d t + \theta$$

and once the natural frequency is determined by Equation 6, the damping can be estimated by a derivative operation on the analytic signal's amplitude

7. $$\ln[A(t)] = -\xi\omega_n t + \ln(A_0)$$

In summary, the overall system identification framework operates as follows.

(*a*) Impulses are isolated using the customised parent wavelet in Equation 3, along with a total of 5 min of response surrounding the impulse.
(*b*) These data are then Morlet wavelet transformed using Equation 1.
(*c*) Ridges are extracted from the scalogram of the selected impulses, corresponding to the dominant modes.
(*d*) The instantaneous dynamic properties in the impulse regimes are extracted from the wavelet coefficients along these ridges using Equations 6 and 7, as depicted in Figure 2.

As necessary, instantaneous power spectra can be extracted from the ascent approaching and descent following large impulses for investigation of instantaneously participating modes.

This approach is now applied to a specific event on 25 April 2008, discussed previously by Bentz and Kijewski-Correa (2009a), to demonstrate the importance of using appropriate system identification approaches on data from transient wind events. An impulse from this event was analysed by the wavelet analysis approach described here to yield the damping values in Table 1. These results, all less than 1% critical, are comparable to the damping levels observed in previous analyses of hours of stationary data from this same building (Bentz and Kijewski-Correa, 2009a; Pirnia *et al.*, 2007). For comparison purposes, a Fourier power spectral density was generated from the entire 1 h record containing the impulse in question, with spectral resolution sufficient to achieve −2% bias and generating four spectral averages to somewhat reduce variance. If the Fourier power spectral density was generated directly from the isolated impulse, bias would be overwhelming. Thus, considerably more data have to be utilised to obtain any reasonable result by this method, somewhat tainting the basis for comparison. Still, the damping estimates by half power bandwidth (HPBW) method and a least-squares fit (LS fit) to the power spectrum are reported in Table 1. Note that the HPBW results in particular are vulnerable to the high variance in this power spectrum and have been shown both to over- and underestimate damping (Erwin *et al.*, 2007). The resulting damping values are 1·5–2·5 times greater when the stationary analyses are applied, owing to the non-stationary characteristics of the event and specifically the amplitude dependence of the dynamic properties shown previously to inflate spectral bandwidths (Pirnia *et al.*, 2007). Clearly such approaches are not viable in the analysis of transient wind events. Thus the wavelet-based framework will be adopted to analyse the tall building's full-scale acceleration responses under six different transient wind events, observed over 16 months of monitoring, which consequently yielded 86 extracted impulses. These results will be presented in the following sections. Before doing so, it should be noted that all acceleration levels presented in this study are normalised, as mandated by owner confidentiality agreements that are a necessary consequence of this and many other full-scale monitoring programmes.

3. Results

3.1 Instantaneous dynamic properties from impulses

Figure 3 presents the instantaneous fundamental dynamic properties obtained from the proposed system identification framework, with an inset floor plan showing the sensor locations and the building's x and y axes. Results are presented for the x and y

	X-sway	*Y*-sway	Torsion
Wavelet analysis	0·71%	0·68%	0·59%
Fourier analysis: HPBW	1·60%	0·80%	0·80%
Fourier analysis: LS fit	0·97%	1·00%	0·92%

Table 1. Comparison of critical damping ratios estimated by wavelet and Fourier analyses for 25 April 2008 event

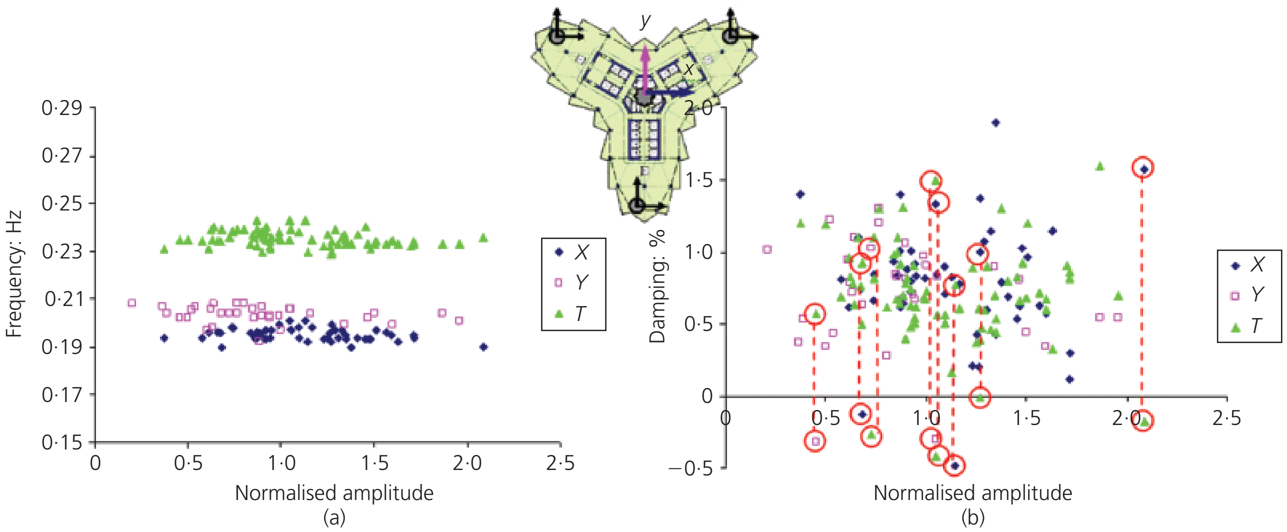

Figure 3. (a) Instantaneous frequency values as a function of normalised peak amplitude; (b) instantaneous critical damping ratio as a function of normalised peak amplitude, with negatively damped modal pairs interconnected by dashed lines

sway and for torsion (T). Considering the amplitude dependence that had been previously noted in this same building by Kijewski-Correa and Pirnia (2007), these results are presented with respect to the peak amplitude of the impulse, normalised by the wind tunnel's predicted annual accelerations. Clearly a majority of the events surpass the projected accelerations for this return period. As Figure 3(a) suggests, the building's fundamental frequencies of vibration are relatively closely spaced, and the building's fundamental modes are all known to be coupled (Pirnia *et al.*, 2007). The amplitude range canvassed here surpasses previous analyses of this building and confirms the reduction in natural frequency with amplitude initially observed by Kijewski-Correa and Pirnia (2007). Still there is appreciable scatter in these instantaneous frequency estimates, which in part may be attributed to the variance inherent to this system identification method that cannot benefit from averaging, but also to the dynamics of the problem, as the next section will demonstrate.

With respect to instantaneous damping, the scatter is quite dramatic, which is not surprising. Even within stationary analyses, damping can show wide variability: the analysis of this same building under stationary wind events revealed damping values for the x-sway of 0·84% and y-sway values of 0·5% (Pirnia *et al.*, 2007), while a separate study of different stationary events showed these damping levels to be 0·83% and 0·99%, respectively (Bentz and Kijewski-Correa, 2009a). As later sections will comment on further, the y-sway shows more variability due to its potential coupling with the adjacent torsional mode. The latter study also found the torsional damping ratios to be between 0·70% and 0·91% critical (Bentz and Kijewski-Correa, 2009a). Indeed while the instantaneous damping ratios in Figure 3(b) tend to cluster in the range noted previously for all three response components (between 0·5% and 1·0%), there is still significant scatter. Of particular interest are occurrences of damping values more than twice those previously observed in this building. While acknowledging that the amplitudes of response observed here are appreciably higher, many of these occurrences of high damping ratios are associated with coupled responses between a given lateral mode and the torsional mode. In some cases, one mode in that couple is negatively damped, while its companion mode is not only positively damped, but damped at levels much higher than previously observed. These instances resulting in negative damping are marked in Figure 3(b) by circles with dashed lines connecting the companion modes. In these cases, the net damping of the two modes is always positive and tends to cluster along with the other observations. Less extreme companion pairs, with no mode experiencing negative damping, can also be noted within the data: cases where damping values of one mode are less than 0·5%, while the partnering mode's damping values are greater than 1%. This interesting phenomenon would seem to support the hypothesis of energy being exchanged between coupled modes so that one mode 'benefits' at the expense of the other. In general, the highest damping levels were found to be associated with situations where sway and strong coincident torsion are present.

3.2 Insights borrowed from instantaneous spectra

To explore further this notion of energy exchange in coupled modes during transient wind events, consider the information presented in Figure 4. Figure 4 shows acceleration–time histories, normalised by each record's root mean square (r.m.s.) value, for a pair of high-amplitude events. At specific locations demarcated by dashed lines, an instantaneous power spectrum is offered. Inset in these power spectra are estimates of the natural frequencies

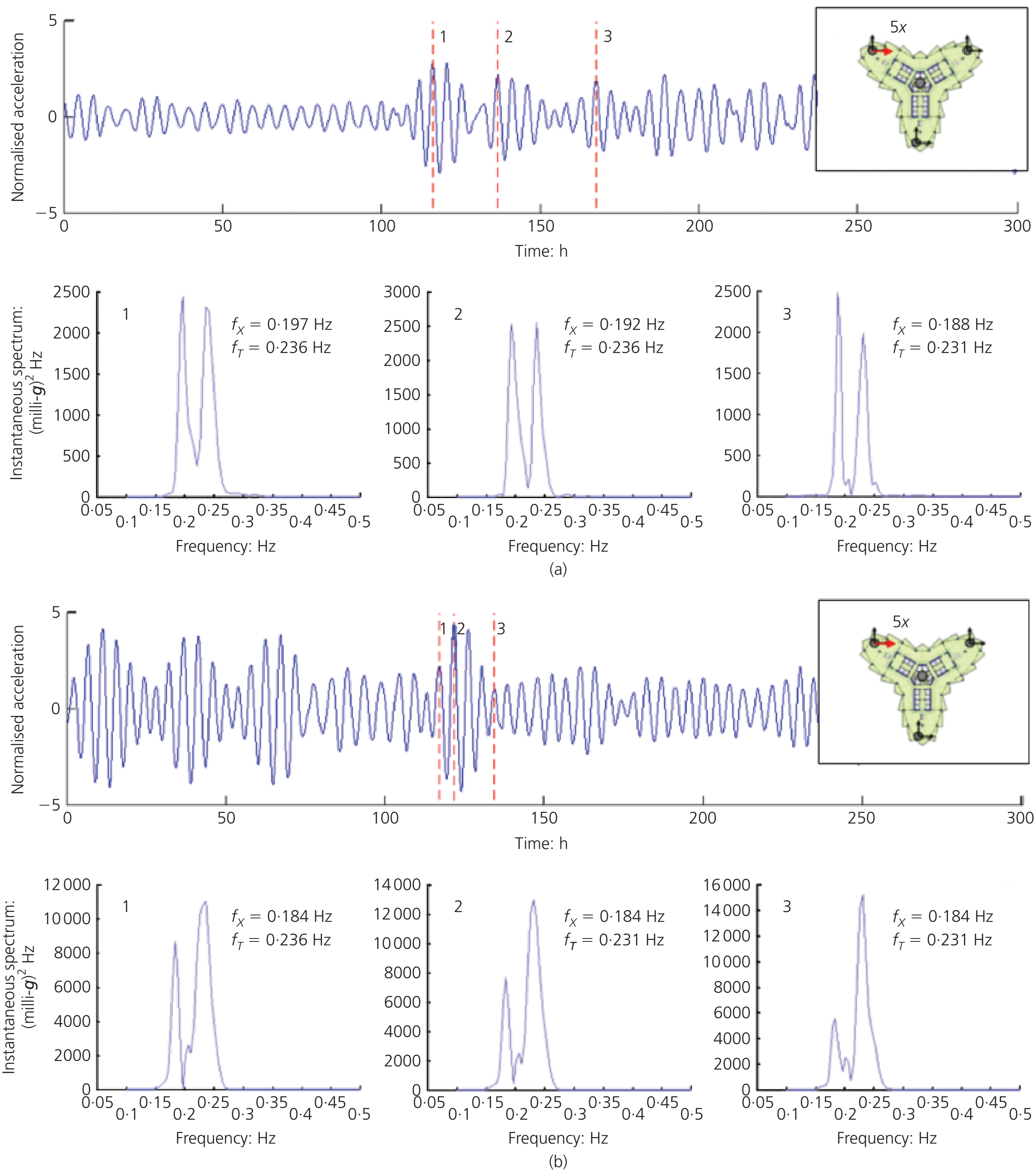

Figure 4. Time history of *x*-direction acceleration response and selected instantaneous power spectra for two events (a) and (b). Sensor location and direction shown by inset figure; instantaneous frequency values are superimposed on each spectrum

garnered from the locations of the instantaneous power spectrum's peaks. The inset figure shows, as an enlarged arrow, the location of the sensor measurement under consideration (5*x*). Figure 4(a) represents a time history that more than doubles in amplitude over just a few cycles of oscillation. In the course of this process, the frequency of the fundamental *x*-sway mode begins to lessen from 0·197 Hz down to 0·188 Hz and is eventually accompanied by a reduction of the torsional frequency from 0·236 Hz to 0·231 Hz. Note also that in the highest amplitude component of the time history, in spectra 1, the peaks have a broad characteristic and particularly in the *x*-sway mode, show asymmetry towards the higher frequencies associated with non-linear behaviour. This type of bandwidth inflation due to amplitude-dependent frequency had been previously noted for this building as a cause for overestimation of damping (Pirnia *et al.*, 2007). This evidence suggests that lateral response coincident with strong torsional motions can produce significant energy exchange between modes, amplifying damping levels in either one or both of the modes, in support of the observations in Figure 3(b). As may be expected, this is further enhanced as the presence of torsion grows. To explore this behaviour further, consider the event producing the largest damping value (1·9% in the *x*-direction, as shown in Figure 3(b)). This event, shown in Figure 4(b), has an r.m.s. acceleration that is 1·5 times greater than that in Figure 4(a) and initiates with a strong presence of sway and torsion. With each cycle of oscillation, as the amplitude of the response decreases, the presence of the sway mode swiftly diminishes, while an intermediate mode emerges and slowly shifts towards the torsional mode. In such larger amplitude events, *x*-sway frequencies have been observed to reduce further to 0·184 Hz, with a similar progressive reduction of the torsional frequency and increase in its spectral bandwidth. The rapid deterioration of the *x*-sway mode resulted in this irregularly high level of damping when analysed in the time domain. Asymmetries in the torsional spectral peaks further support the evidence of amplitude dependence in frequency.

The implications of this behaviour are even more pronounced for the *y*-sway, most susceptible to strong coupling with the torsional response, as demonstrated in Figure 5, where the acceleration–time history is normalised by its r.m.s. value. Here note again a reduction of the *y*-sway frequency with increasing amplitude of response; even more noteworthy is the strong coupling and exchange of energy between the *y*-sway and torsional responses in this event. In particular, at the highest amplitude in this record, the two modes share significant spectral bandwidth. Again this is consistent with the observations in Figure 3(b), which further suggest that the benefits of this exchange can transfer energy from torsion to sway and vice versa. It is not surprising then to note that Kijewski-Correa and Pirnia (2007) documented higher uncertainty in the estimates of damping in the *y*-mode, even in stationary wind events, likely to be due to the effect of coupling.

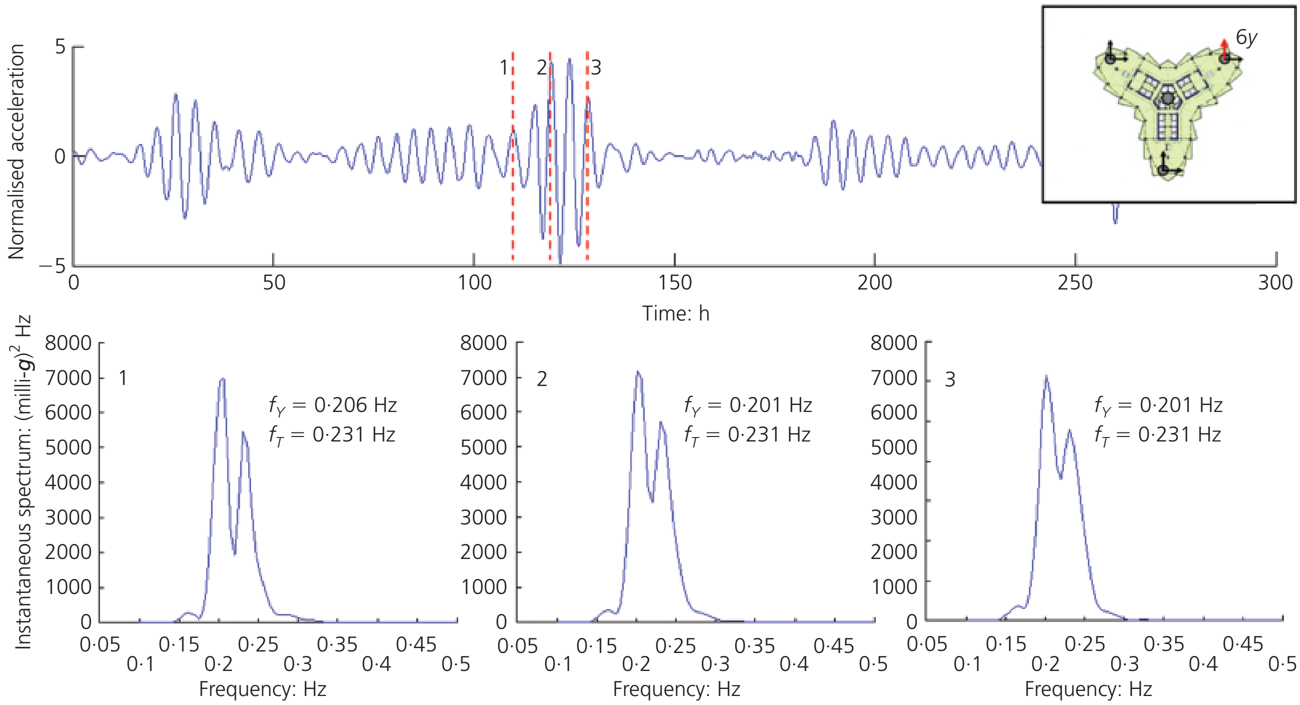

Figure 5. Time history of *y*-direction acceleration response and selected instantaneous power spectra. Sensor location and direction shown by inset figure, instantaneous frequency values superimposed on each spectrum

4. Discussion

4.1 Implications of dynamic coupling

The previous example of a highly damped *x*-sway mode in Figure 4(b) is not an artefact of the instantaneous impulse analyses conducted here. In fact, this finding is entirely consistent with the levels of damping observed in stationary random decrement analyses of low-amplitude sway modes by Kijewski-Correa and Pirnia (2007). That study found that as amplitude levels dropped, these sway modes could show particularly large damping values. Reasons for this behaviour, however, were not entirely understood and attributed to noise interferences. However, the instantaneous spectral analyses in this study help to underscore the role of torsional response in this phenomenon, and the potential for energy exchange between coupled modes, even at low amplitudes of response. This effect is particularly noteworthy for the *y*-sway component. In the absence of torsion, the *y*-sway response shows a reduction of frequency, as isolated by Figure 6(a), which, like Figure 3, shows accelerations normalised by the annual wind tunnel predictions. In the presence of significant torsion (Figure 6(b)), the *y*-sway response shows higher scatter and takes on some of its lowest levels due to the influence of torsion. Clearly the potential for interaction between these modes and ensuing energy exchange is further enhanced by amplitude dependence, which may further reduce the frequency of the torsional mode, moving it towards the *y*-sway mode, particularly for the higher amplitude events considered here. This was observed distinctly in another torsionally sensitive building in Boston, which found that damping can be increased by a factor of 2 in the presence of a beating mode (Kijewski-Correa and Pirnia, 2007). This same study also affirmed that the presence of coupling increases amplitude dependence of the dynamic properties. Indeed the *x*-sway response, which is spectrally further separated from the torsional mode, does not appear to show the same effect (Figure 6(b)).

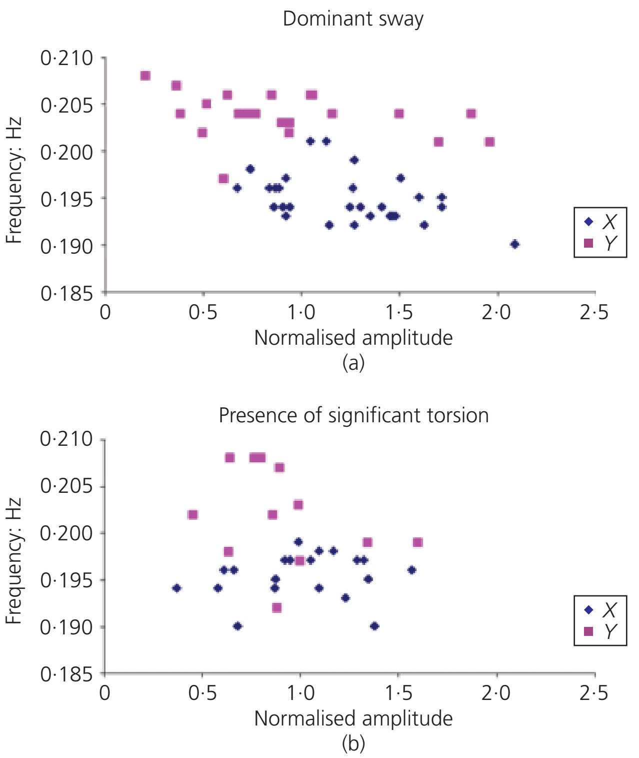

Figure 6. Frequency as a function of normalised amplitude for (a) sway responses with no significant torsion and (b) sway responses with significant torsion

4.2 Role of transient excitations

Clearly there are some unique dynamic characteristics of this building that played an important role in these responses; however, those characteristics alone did not previously generate this level of acceleration – these behaviours have only been observed in the presence of transience in the wind field. To demonstrate the effect this transience can have on a structure with these unique dynamics, consider Figure 7. At each location where accelerations are acquired, the acceleration–time histories normalised by each record's r.m.s. value are displayed for a particularly energetic event, which was characterised by very rapid changes in wind direction. Accompanying this is an *x*–*y* plane trace of the response at that location. The boxes denote a response area of interest in the time history, following a series of wind direction shifts. The dark lines on the *x*–*y* plane traces at each location show the response during this time of interest. In the span of 30 s, wind directions switched from the southeast to the northeast twice, with net wind direction shifts of over 90° within this time frame. Similar swings were not noted before or after this event. This implies that the event began with approaching winds from the wing of the building marked as location 2, switched towards the wing marked as location 6 and back again. Thus for the majority of the event, the third wing (location 5) can be considered the 'leeward face'. Thus it is interesting to note the red traces at location 2, which develops a particularly strong across-wind response, completely different from its behaviour at other times in the event, as the wind switches to the northeast. This then exaggerates the fishtailing effect at location 6 for a brief time, leading to the highest accelerations detected in this storm. Similar fishtailing had been noted in another torsionally sensitive building in Boston (Kijewski-Correa and Pirnia, 2007). In particular, the rapid variation in wind direction in these transient events, leading to instantaneous imbalances in the pressure fields on the building that can enhance the torsional response, may explain how these events have a more dramatic effect on accelerations than wind tunnel predictions would suggest for wind velocities of this level. It could further be argued that, for a building without predisposition to strong torsional response and coupling, similar effects would not be noted for the same magnitude of wind event.

4.3 Interface to practice

The observations presented by this study primarily highlight the importance of considering the role of transient events as an additional limit state if perceptible motions are of concern to the

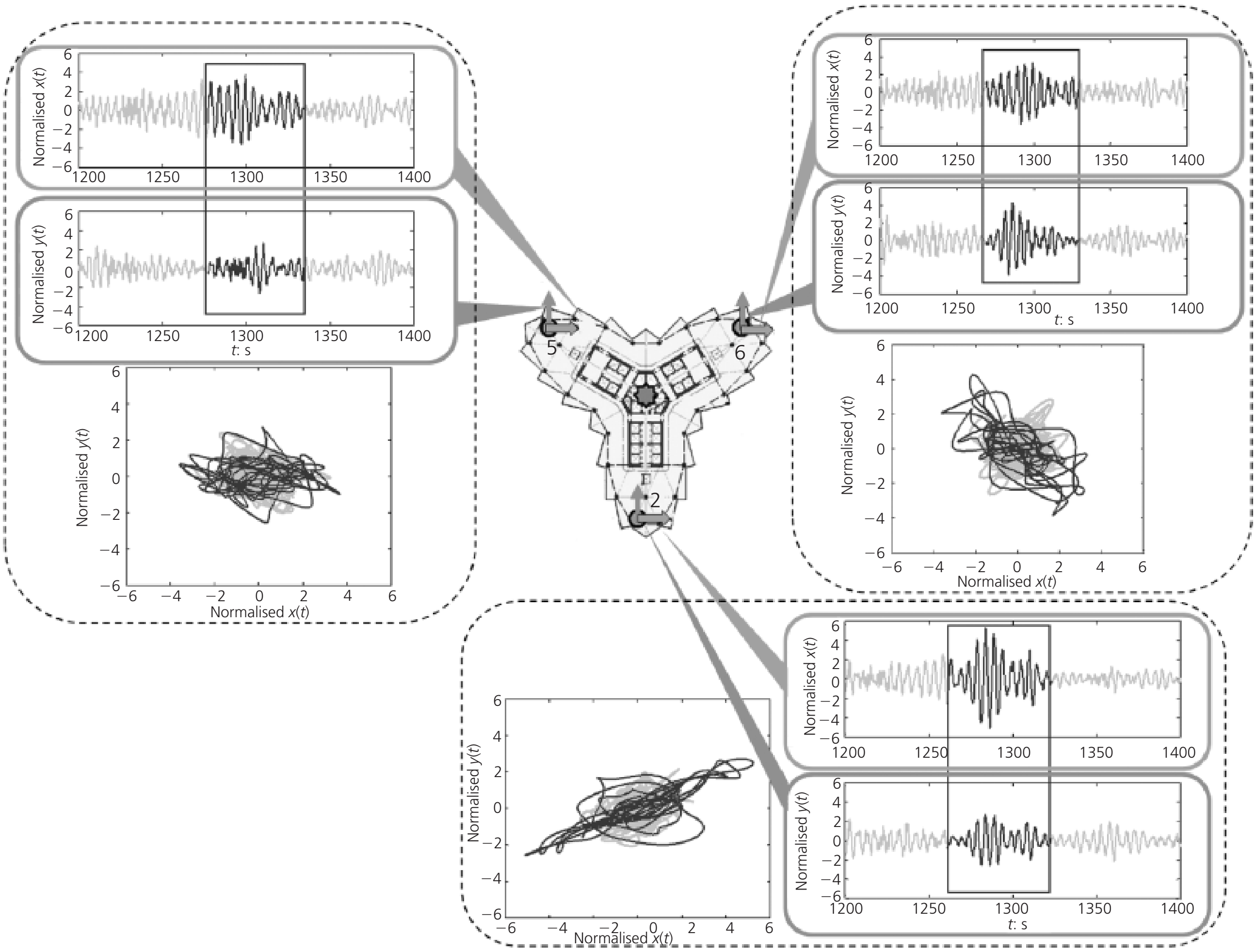

Figure 7. Effect of transience on response at three instrumented locations on building floor plan: at each location, normalised acceleration time history in *x*- and *y*-directions is shown along with trace in *x*–*y* plane (grey lines); box indicates high-amplitude response of interest and *x*–*y* plot dark line indicates response associated with this region of interest

tall building designer. While recent motion simulator studies have suggested that impulse-like motions are not task disruptive or sufficient to induce nausea (Burton *et al.*, 2005), likely because of their short duration, these studies do not capture some of the unique dynamics of transient wind events. In these events, as shown by this study, rapid changes in wind direction can cause dominant motions suddenly to switch their primary axes (see Figure 7) and stimulate significant amounts of companion torsion that, in the case of buildings with coupled modes, can lead to rapid increases in acceleration. Particularly since these situations involve torsional accelerations that have been noted to be especially disturbing to occupants (Kareem *et al.*, 1999), they represent an in situ condition that has yet to be replicated by motion simulator studies used to define perception criteria. In fact, these events may constitute a missing element of current design practice to minimise perceptible motions, as anecdotal evidence indicates that thunderstorm events in particular, owing to their sudden onset and rapid changes in amplitude and direction, cause perception issues in tall buildings (Bentz and Kijewski-Correa, 2009a). Clearly, transient events are capable of inciting dynamic behaviour that is fundamentally different from that simulated in wind tunnels as the basis for predicted accelerations in design and emulated in motion simulator studies to establish perception criteria.

As damping remains the single most effective structural property to reduce accelerations, it plays a vital role in a design's ability to meet habitability limit states. An overestimation of structural damping levels in the design stage will result in a structure with potentially excessive accelerations and likely perception issues.

Current practice generally assumes constant viscous damping levels of 1%, 1·5% or 2% critical for steel, composite and concrete structures, respectively, based on limited full-scale observations of mostly low- to mid-rise buildings. However, it is often the case, both in this study and in other buildings (Bentz and Kijewski-Correa, 2008), that in situ damping values for tall buildings are beneath these levels. While efforts are under way to develop more meaningful predictive models for damping in tall buildings (Bentz and Kijewski-Correa, 2008), the literature to date has been constrained by stationary analyses that offer glimpses of amplitude-dependent damping. Specifically, as discussed at the beginning of this paper, most system identification approaches applied to tall buildings under wind seek to estimate dynamic properties from hours of averaged, stationary data. Even when approaches are used that can document the degree of amplitude dependence in dynamic properties, for example the random decrement technique, they can only do so for modest amplitude levels of the order of a few milli-***g***, as the higher amplitude responses generally occur only a few times in the response and thus do not create the necessary pool of segments required by this method for averaging. Thus, if amplitude-dependent dynamic properties are to be observed in full scale, designers wish to know the values associated with the highest amplitudes, those at 10, 15 and 20 milli-***g***, which occupy the range of 10-year perception criteria used in practice. Unfortunately, this is the range stationary approaches are not equipped to handle. Therefore, any information on the damping ratios at high amplitude levels is especially valuable and can now be extracted using the system identification framework presented here.

5. Conclusions

This study employed a non-stationary analysis of full-scale acceleration data from a tall building subjected to transient wind events, following the observation that acceleration levels in these events surpassed those observed in stationary wind events with comparable wind velocities. Through the use of a customised parent wavelet, the authors were able to isolate impulsive responses in these events and, using a secondary Morlet wavelet analysis, the various contributing modes were observed as they evolved with time. This system identification framework then allowed estimates of dynamic properties at high amplitudes of response and revealed the mechanisms facilitating these responses. Of particular interest was the observation of companion pairs of sway and torsional modes that exchange energy in the course of the event, as evidenced by negatively damped modes coupled with irregularly high, positively damped modes. The study further demonstrated how this exchange of energy in coupled modes can be enhanced by amplitude dependence in the dynamic properties, shedding new light on the root causes of damping variability, even in stationary analyses.

This study also demonstrated how high damping levels and impulsive-like responses are only observed in the presence of substantial torsion, which is facilitated in this case by the instantaneous pressure imbalances caused by rapidly changing wind directions in these transient events. It is unlikely that the same acceleration levels would be observed in the absence of either of these two conditions, and analysis of this building in other wind events confirms this. Regardless of the mechanism, as current design philosophies for tall buildings do not consider the effect of transient wind events in either the prediction of accelerations or the occupant comfort criteria they are evaluated against, it is unlikely that these responses would be predicted or considered, even though they may potentially affect occupant perception. Thus the role of transient wind events and their influence on the dynamics of tall buildings from the perspective of habitability will require further exploration.

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REFERENCES

Bentz A and Kijewski-Correa T (2008) Predictive models for damping in buildings: the role of structural system characteristics. *Proceedings of the 8th Annual Structures Congress, 18th Analysis and Computation Specialty Conference, Vancouver*, CD-ROM.

Bentz A and Kijewski-Correa T (2009a) Wind-induced vibrations of tall buildings: the role of full-scale observations in better quantifying habitability. *Proceedings of IMAC-XXVII: A Conference and Exposition on Structural Dynamics, Orlando,* CD-ROM.

Bentz A and Kijewski-Correa T (2009b) A wavelet-based framework for system identification of tall buildings under transient wind events. *Proceedings of Joint 2009 ASCE–ASME–SES Conference on Mechanics and Materials, Blacksberg, VA*, CD-ROM.

Brownjohn JMW, Pan T and Cheong H (1998) Dynamic response of Republic Plaza, Singapore. *The Structural Engineer* **76(11)**: 221–226.

Burton M, Hitchcock P, Kwok K and Roberts R (2005) Acceptability curves derived from motion simulator investigations and previous experience with building motion. *Proceedings of the 10th Americas Conference on Wind Engineering, Baton-Rouge, LA*, CD-ROM.

Davenport AG and Hill-Carroll P (1986) Damping in tall buildings: its variability and treatment in design. In *Building Motion in Wind* (Isyumov N and Tschanz T (eds)). American Society of Civil Engineers, Reston, VA, pp. 42–57.

Erwin S, Kijewski-Correa T and Yoon S (2007) Full-scale verification of dynamic properties from short duration records. *Proceedings of Structures Congress 2007, Long Beach, CA*, CD-ROM.

Jeary AP (1986) Damping in tall buildings – a mechanism and a predictor. *Earthquake Engineering and Structural Dynamics* **14(5)**: 733–750.

Kareem A, Kijewski T and Tamura Y (1999) Mitigation of motion of tall buildings with specific examples of recent applications. *Wind and Structures* **2(3)**: 201–251.

Kijewski T and Kareem A (2002) On the presence of end effects and associated remedies for wavelet-based analysis. *Journal of Sound and Vibration* **256(5)**: 238–245.

Kijewski T and Kareem A (2003) Wavelet transforms for system identification in civil engineering. *Computer-Aided Civil and Infrastructure Engineering* **18(5)**: 339–355.

Kijewski-Correa T (2003) *Time-frequency Perspectives in System Identification: From Theory to Full-scale Measurements*. PhD thesis, Department of Civil Engineering and Geological Sciences, University of Notre Dame.

Kijewski-Correa T and Kareem A (2007) Nonlinear signal analysis: time-frequency perspectives. *Journal of Engineering Mechanics, ASCE* **133(2)**: 238–245.

Kijewski-Correa T and Pirnia JD (2007) Dynamic behavior of tall buildings under wind: insights from full-scale monitoring. *The Structural Design of Tall and Special Buildings* **16(4)**: 471–486.

Kijewski-Correa T and Pirnia JD (2009) Pseudo-full scale evaluation of occupant comfort in tall buildings. *Proceedings of the 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico*, CD-ROM.

Kijewski-Correa T, Young B, Baker WF *et al.* (2005) Full-scale validation of finite element models for tall buildings. *Proceedings of the CTBUH 7th World Congress, New York, NY*, CD-ROM.

Kijewski-Correa T, Kilpatrick J, Kareem A *et al.* (2006) Validating the wind-induced response of tall buildings: a synopsis of the Chicago full-scale monitoring program. *Journal of Structural Engineering* **132(10)**: 1509–1523.

Kijewski-Correa T, Taciroglu E and Beck JL (2008) System identification of constructed facilities: challenges and opportunities across hazards. *Proceedings of the Structures Congress, Vancouver*, CD-ROM.

Lagomarsino S (1993) Forecast models for damping and vibration periods of buildings. *Journal of Wind Engineering and Industrial Aerodynamics* **48(2–3)**: 221–239.

Li QS, Fang JQ, Jeary AP and Wong CK (1998) Full scale measurements of wind effects on tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics* **74–76**: 741–750.

Li QS, Yang K, Zhang N, Wong CK and Jeary AP (2002) Field measurements of amplitude-dependent damping in a 79-storey tall building and its effects on the structural dynamic responses. *The Structural Design of Tall Buildings* **11(2)**: 129–153.

Li QS, Yang K, Wong CK and Jeary AP (2003) The effect of amplitude-dependent damping on wind-induced vibrations of a super tall building. *Journal of Wind Engineering and Industrial Aerodynamics* **91(9)**: 1175–1198.

Li QS, Xiao YQ and Wong CK (2005) Full-scale monitoring of typhoon effects on super tall buildings. *Journal of Fluids and Structures* **20(5)**: 697–717.

Pirnia JD, Kijewski-Correa T, Abdelrazaq A, Chung J and Kareem A (2007) Full-scale validation of wind-induced response of tall buildings: investigation of amplitude dependent properties. *Proceedings of the 7th Annual Structures Congress, Long Beach, CA*, CD-ROM.

Satake N, Suda K, Arakawa T, Sasaki A and Tamura Y (2003) Damping evaluation using full-scale data of buildings in Japan. *Journal of Structural Engineering* **129(4)**: 470–477.

Twisdale LA and Vickery PJ (1992) Research on thunderstorm wind design parameters. *Journal of Wind Engineering and Industrial Aerodynamics* **41(1–3)**: 545–556.

Vandiver JK, Dunwoody AB, Campbell RB and Cook MF (1982) A mathematical basis for the random decrement vibration signature analysis technique. *Journal of Mechanical Design* **104(2)**: 307–313.

Wakimoto RM (2001) Convectively driven high wind events, severe convective storms. *Meteorological Monographs* **28(50)**: 225–298.

Xu YL and Zhan S (2001) Field measurements of Di Wang Tower during Typhoon York. *Journal of Wind Engineering and Industrial Aerodynamics* **89(1)**: 73–93.

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