BEST PRACTICES IN FULL-SCALE MONITORING OF TALL BUILDINGS

A Report to SEI Tall Buildings Committee

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The Tall Buildings Committee created this subcommittee with the charge of assembling best practices with respect to full-scale monitoring of tall buildings. This document represents the end-result of this effort. Major sections of this report include the origins and benefits of monitoring, state-of-the-art in instrumentation and minimum requirements, signal processing issues, data management and processing techniques, a summary of full-scale efforts to date and lessons learned. While all are in agreement that full-scale monitoring of tall buildings is incredibly vital for validating in-situ performance of some of society's most expensive investments, access to these buildings is given only at the discretion of owners who often have more to lose than gain from the findings. Thus without proper incentive, continued access and expansion of monitoring programs are in jeopardy.

Figure 1: Rationale for Full-Scale Monitoring

ORIGINS

The monitoring of buildings, as summarized in Figure 1, has historically been tied to the need to understand in-situ behaviors, often spurred by suspect performance, as in the case of the infamous

Boston Hancock Tower (Durgin and Gilbert 1994). The prevalence of full-scale monitoring in subsequent decades was largely tied, at least in Asia, to the proliferation of auxiliary damping devices, where sensors served a variety of purposes from actual feedback mechanisms in active control to a means to document the performance of these supplementary devices during earthquakes and typhoons (Kareem, Kijewski, Tamura 1999). In parallel, monitoring efforts in seismically active zones within the United States received similar emphasis at this time for enhanced understanding of overall behavior and performance (California Strong Motion Instrumentation Program), while the wind engineering community turned its full-scale efforts toward developing databases of in-situ dynamic properties crucial to habitability limit states (Satake and others 2003). Efforts in full-scale monitoring for both of these hazards have also enabled correlations between the predicted and as-built structure to effectively update models and design approaches (Kijewski-Correa and others 2006b). Today, while monitoring efforts worldwide continue the task of in-situ validation of dynamic properties, dynamic load effects, and response characteristics, added emphasis on rapid assessment and evaluation in the larger venue of structural health monitoring (SHM) has the promise to expand opportunities for full-scale monitoring of tall buildings, particularly in seismic zones.

BENEFITS OF MONITORING

While the catastrophic losses in seismic zones have provided substantial fiscal and public confidence incentives for owners to invest in monitoring systems, the same incentives do not exist for wind-induced excitations that are commonly of greatest concern for tall buildings. Outside of seismic zones, owners may be reluctant to install instrumentation systems as the fiscal benefits are not always apparent or out of fear that this may somehow tarnish the reputation of their buildings. However, it is important to acknowledge why full-scale monitoring of tall buildings is so vital.

Even though the performance of tall buildings affects the safety and comfort of a large number of people in both residential and office 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 received only limited systematic validation in full-scale (Li and others 2004) (Kijewski-Correa and others 2006a). In fact, a large amount of the full-scale observations in the literature to date focus on low to mid-rise structures (Satake and others 2003) with a lack of information on super-tall buildings known to be the most dynamically sensitive. In particular, as state-of-the-art structural analysis software and wind tunnel testing are advancing rapidly, the accuracy and validity of their results need 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 of increased complexity and height. Particularly since limiting motion perception by building occupants is often a controlling structural engineering design parameter for tall buildings, even in moderate wind climates, there is a definite need for more reliable estimates of a building's damping in the design stage – something that can only be achieved through more full-scale observations of tall buildings. Still, as the estimated damping design values have a coefficient of variation of up to 70%, there may be significant uncertainty in the resulting response quantities, which are vital to insure that the design satisfies occupant comfort criteria.

These early perceptions and attitudes are starting to change with the advent and acceptance of "smart" building systems made realizable by major advances in instrumentation and computer technology. It is now possible to install instrumentation that continuously monitors the structural system and provides ongoing feedback on its performance, tracking the evolution of dynamic properties as indicators of global behaviors or even local behaviors (strains at an area of interest) to monitor for aging or damage to the structure. As the in-situ dynamic properties may differ somewhat from those assumed at the design stage, this information is not only valuable feedback on the effectiveness of design procedures, but is also critical when auxiliary damping devices are employed that require tuning with the structure's in-situ natural frequencies. Furthermore, in-situ observations can allow calibration of the finite element models used in design to allow continuous evaluations of the structure that are highly valuable in situations where the structural system is altered, for example, more stories are added to a building, or in situations where it becomes necessary to assess the impact of possible damage to the structure.

In summary, the principal reasons motivators for full-scale monitoring of tall buildings include:

- Feedback to the design process to improve techniques for modeling various structural systems and determining dynamic load effects.
- Capability for rapid assessment of possible damage to the structure and/or the consequence of some other unexpected action.
- Continuous status of building motions to enhance day-to-day operations, e.g., effective operation of elevator systems and observation decks, rooftop operations, etc.

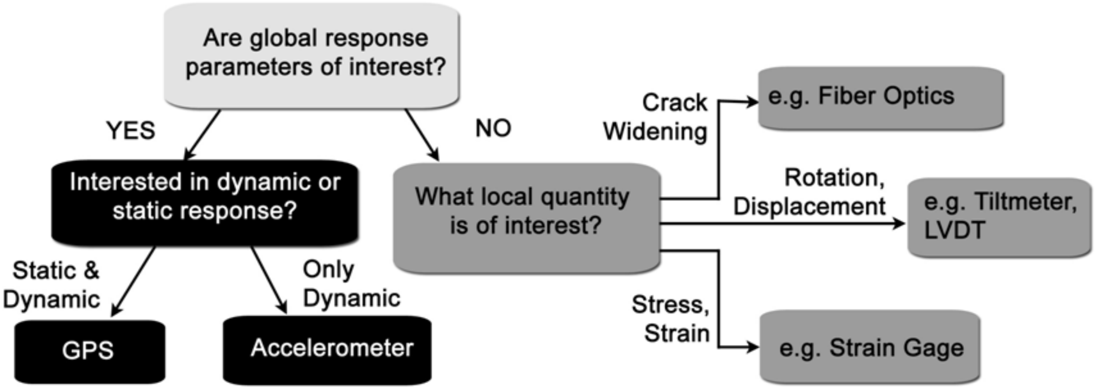

Figure 2: Decision Tree for Selecting Sensors (Kijewski-Correa 2005)

INSTRUMENTATION

The instrumentation used in full-scale monitoring of tall buildings can be classified into the category of **response** or **excitation sources**. While there are a wide variety of sensors on the market for either category, a general overview of the most common sensing elements for tall buildings is presented herein. Because the application of local sensing requires no unique treatment when extended to tall buildings, these subjects will not be treated herein and focus will instead be placed on the two response sensors most common in tall buildings: accelerometers and, more recently, GPS.

Response Measurements

Figure 2 provides a decision tree that can be used to determine the type of instrumentation required to record the responses of a tall-building. Generally speaking, there has been limited funding for full-scale monitoring of tall buildings, leading to very sparse sensor arrays. With limited resources, most monitoring efforts will focus on capturing global response quantities on the highest possible floor (for accelerometers) or roof (for GPS antenna). At minimum, two orthogonal accelerometers or one global positioning system (GPS) antenna would have to be installed at the building's centroid to monitor the two lateral responses. A third accelerometer of GPS antenna can be placed on the perimeter to capture torsional motions. An alternate approach would be to place pairs of orthogonal accelerometers or GPS antennae in each wing of non-rectangular buildings or at two extreme corners of rectangular buildings. This allows observation of lateral and torsional responses with redundancy, as shown in Figure 3. If funds permit, additional arrays of accelerometers should be deployed over the height of the building to capture in-situ mode shapes. Sadly, this density of response measurements is not often seen in tall building applications.

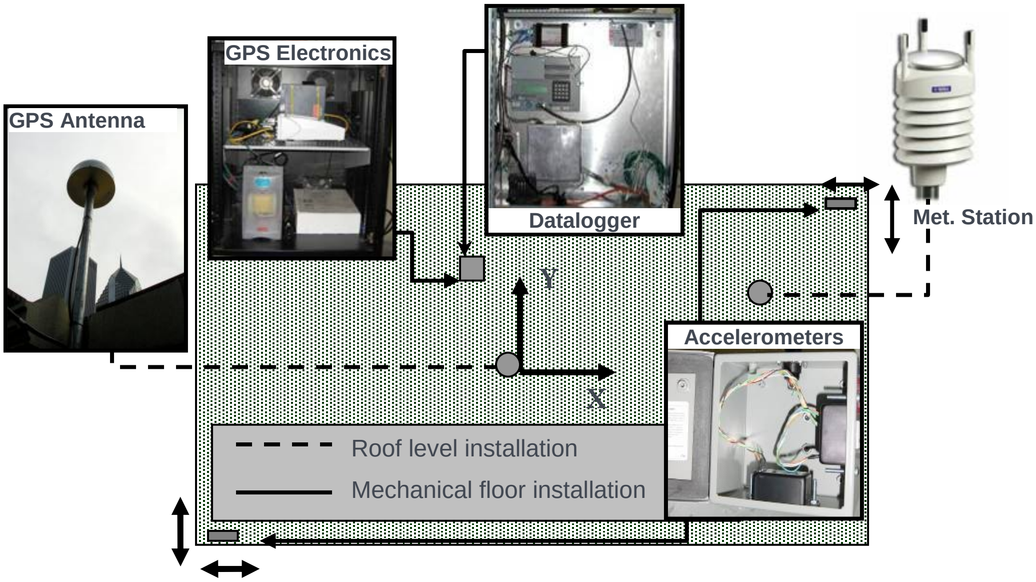

Figure 3: Schematic Representation of Sensors Used in the Chicago Full-Scale Monitoring Program (after Kijewski-Correa and others (2006))

Accelerometers

The most trusted and proven sensor for measuring response is the accelerometer. The accelerometer concept requires a primary transducer or inertial element that oscillates under applied accelerations and a secondary transducer that converts the displacement of this seismic mass into an electric signal. The primary transducers can be a single-degree-of-freedom vibrating mass (**seismic sensor**) or a **flexural/beam** element. The seismic mass sensors are particularly vulnerable to drift. There are a wide variety of secondary transducers in accelerometers, though the most common are **piezoelectric** (quartz or ceramic crystals) and **servo or force balance** devices. The piezoelectric have the lowest sensitivity and cannot measure into the low frequency range, but are very robust and inexpensive. Conversely, the force balance accelerometers are more expensive, but provide the highest sensitivity, lowest noise and the capability of measuring down to 0 Hz. While accelerometers have seen wide usage in the civil and mechanical fields for the measurement of vibrations, the unique requirements of tall buildings significantly narrows the field of viable accelerometers according to the following requirements:

Amplitude Range: Many accelerometers are marketed for high-g measurement (> 1g) ranges, and while this is attractive for avoiding damage due to shock or for monitoring mechanical systems, this results in a diluted level of precision for tall buildings. Given their accelerations are often on the sub-milli-g level, devices with ranges in the low-g (±1 or ±2 g) and sub-g (±0.1 g or ±0.5 g) level are required. The former ranges may be necessary for seismic applications, while the latter would be more appropriate for the wind applications. Note that this will create sensors that are not shock-tolerant and thus must be handled with care in shipment and installation.

Sensitivity: By selecting sensors with large operating ranges or low-precision components, sensitivity is directly compromised. While applications in other fields (mechanical systems) are capable of employing sensors with 1 V/g sensitivities, due to the comparatively lower amplitude responses observed in tall buildings, sensitivities should be as high as possible while remaining within the necessary amplitude range. Devices with sensitivities up to 40 V/g are currently available on the market (force balance variety).

Frequency Range: In a related manner, traditional accelerometers of the piezoelectric class have frequency response (transfer) functions that roll off in the low frequency range, thus limiting their application for structures with frequencies of vibration less than 0.5 Hz. While these sensors generally have better responsiveness to shock or overload, tall building applications often necessitate the use of force-balance accelerometers capable of measuring responses with high fidelity down to 0 Hz.

Noise: Again due to the required sensitivity for the tall building application, differential output devices with low noise circuitry is essential for this application. This can be achieved again through the use of force-balance accelerometers with a servo or feedback feature minimize noise and enhance sensitivity.

Analog vs. Digital Devices: The traditional accelerometers are analog in nature, outputting a voltage in proportion to the acceleration levels they detect. Presently, digital devices are making their way into the market place. These devices enable a far greater “plug and play” capability and can be directly interfaced with a laptop using serial or USB connections for rapid deployment. These devices generally have lower sensitivity than the highest quality analog devices on the market, achieving only up to around 5 V/g and are designed for higher amplitude ranges.

Global Positioning Systems

The displacement response of any structure can be characterized by three components: a mean component that does not vary with time, a background component that does vary with time, but at a slow rate, and a resonant component that also varies with time but at faster rate, oscillating at the natural frequencies of the structure. Depending on the nature of the excitation, a structure may display all three of these response components; however, in earthquakes, generally only resonant responses are observed. As a result, many monitoring applications focused on seismic effects attempt to recover displacements and even interstory drifts by double integrating recorded accelerations. In this process, two constants of integration are neglected, corresponding to the aforementioned mean

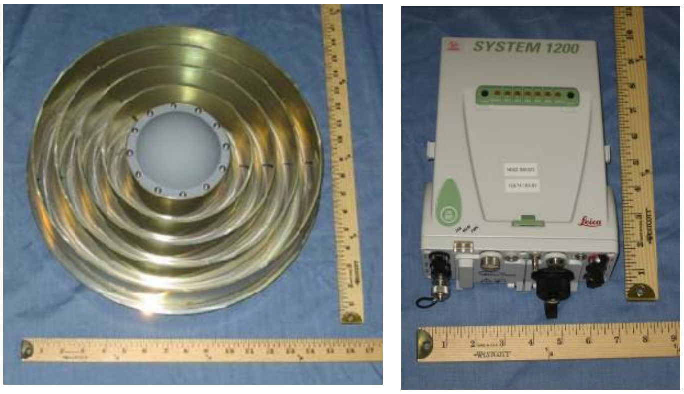

Figure 4: GPS Choke Ring Antenna (left) and Receiver (courtesy of Kijewski-Correa)

and background components, which cannot be fully recovered from accelerometers. Again, since earthquake response is largely resonant in nature, this loss of these other two response components is negligible. However, when monitoring the wind-induced response of tall buildings, all three components are present and can be quite important. In fact, studies have shown that the background response contributions can be as high 20-80% for some structures in certain wind events. The only way to completely recover these components is by directly measuring displacements in full-scale. Unfortunately, until recently, there were no reliable means to do so.

While other terrestrial positioning systems have been evaluated (imaging techniques, laser-based sensors), their applicability to tall building monitoring does not appear to be practical at this time due to line-of-sight issues or challenges in operating under all weather conditions. GPS, on the other hand, can operate continuously in all weather conditions to provide near-real time displacement data using all-digital technologies. GPS operates on the basic premise of triangulation to determine the position of an object on earth using the known positions of orbiting satellites overhead. Thus a three dimensional unknown position, accounting for clock bias, requires four satellites to determine the building's position.

As these satellite transmissions can be interfered with by upper atmospheric disturbances (solar flare activity), **dual frequency GPS** must be selected. Further, in the lower atmosphere, local weather disturbances can cause similar distortions, requiring GPS operating in a **differential mode**: processing the positions of the structure against a stationary **reference** GPS in the general locale (within a few miles) of the building being monitored (called the **rover**). The most considerable error sources in high precision GPS remains the multipath effect, which results when satellite signals bounce off or neighboring reflective objects – a significant issue in urban zones. These effects appear as sinusoidal oscillations on the order of minutes in period. While the use of **choke ring antennas** (Fig. 4) can diminish this effect, additional corrective algorithms in the GPS software or off-line processing by the end user may be required. Because of the need for so many corrections, most applications of GPS to tall buildings use commercial software packages to process the data feeds from the reference and rover receivers to produce the position of the building in a local coordinate system. These algorithms cannot, however, correct for occasional losses of satellites as they move past obstructions or out of range. Despite all these considerations, the systems have proven to be very effective in monitoring full-scale displacements, including quantifying the background and resonant components of wind-induced response (Kijewski-Correa and Kochly 2007). While the background and resonant components are readily identified, once any multipath effects are removed, a static baseline position of the structure in the local coordinate system must also be estimated in order to isolate mean components of response due to wind or thermal effects.

Capabilities: These feeds, processed in a so-called **real-time kinematic (RTK)** mode, traditionally were exchanged between the receivers and the processing hub by long range radio, but now many receivers offer direct interface to the internet (Fig. 4). Thus while some units can now resolve displacements at rates of 10 and even 20 Hz, bandwidth of the internet connection now becomes the limiting constraint. In terms of accuracy, testing has confirmed these high-sensitivity, differential GPS can detect displacements with an accuracy of 5 mm (RMS), though this accuracy diminishes as the distance between the reference and rover increases (Kijewski-Correa, Kareem, Kochly 2006). While costs of this hardware are on the order of thousands of dollars per receiver, the performance in full-scale environments plagued by RF interference has been extremely encouraging, correlating well with existing technologies like accelerometers (Fig. 5).

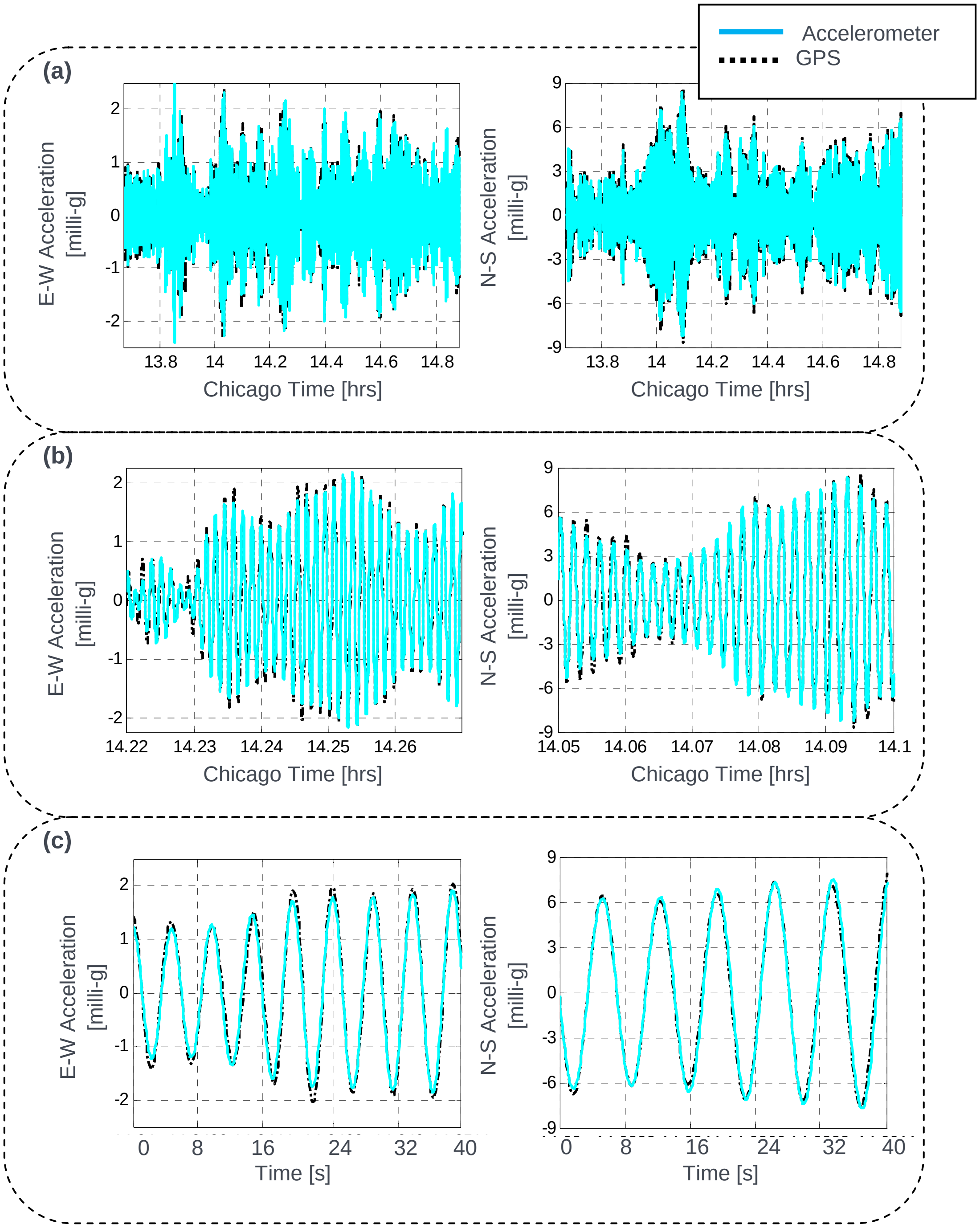

Figure 5: Full-Scale Accelerometer Data vs. GPS-Derived Accelerations from Chicago Full-Scale Monitoring Program: (a) One Hour Time History, (b) Zoom-In of 3-Minute Window, (c) Zoom-In of 40-Second Windows (Kijewski-Correa Kochly and Kareem 2006)

Excitation Sources

While the excitation source generally of interest is wind, in some situations potential seismic excitations must also be monitored. Thus a truly multi-hazard system would have the capability of monitoring either phenomenon and triggering the response sensors accordingly. For seismic ground motions, reliable accelerometers, primarily of the force-balance variety, can be mounted triaxially in three orthogonal directions to monitor nearfield ground motions on-site. These accelerometers will require a larger range than those used for the structure.

The situation is not so favorable for wind forces on structures. Due to the spatio-temporal variations of wind pressures over the surface of the structure, it is impossible to quantify the wind forces in full-scale. Despite this, it is preferable to have an on-site wind field measurement given the variability of wind speeds in urban zones and the high likelihood that wind velocities at the regional airports will be significantly different from those on site. As meteorological sensing is a well-established field, only limited details are provided here.

Wind Velocity Measurement

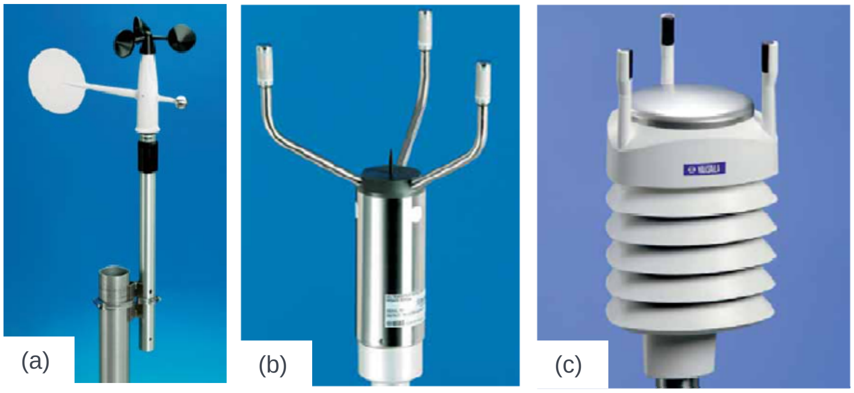

Figure 6: (a) Cup and Vane Anemometer, (b) Ultrasonic Anemometer and (c) Meteorological Station (Courtesy of Vaisala)

The most traditional approach is a propeller or rotating cup anemometer measuring wind speed with a vane to quantify direction (Fig. 6a). Wind speed can be quantified by pulse counting or by recording the time between successive pulses, potentially providing better resistance to interference by other rooftop signals (RF fields). While modern devices of this type are made of durable, lightweight materials and consume very little power, the utilization of moving parts raises some concerns for icing and mechanical wear in long-term deployments.

For about double the cost, users can upgrade to ultrasonic anemometry (Fig. 6b), which provides high fidelity wind speed and direction without moving parts, though consuming more power and requiring heating elements in cold environments. The ultrasonic devices generally employ three equispaced transducers that produce ultrasonic signals. Wind speed and direction are determined by measuring the time it takes for the ultrasonic signal from one transducer to reach the others. For only marginal additional cost and only minor loss in measurement range, a full ultrasonic meteorological station (Fig. 6c) can be deployed to measure wind speed and direction, precipitation, temperature, barometric pressure, and relative humidity. These devices are far more compact in form, and without a rotating vane, do not require the clearances of the cup and vane devices. Some devices on the market also provide the flexibility to specify analog or digital outputs in a variety of formats, which can be again an important consideration if interference is a concern. High quality devices of either the cup and vane or ultrasonic variety can measure maximum wind speeds of 60-70 m/s.

Regardless of the type of anemometer employed, the far more critical issue will be its placement on the building rooftop. This should of course avoid any close proximity to obstructions that could cause interference. Further, to ensure that the sensor is not within the separation zone of the flow as it passes over the rooftop, it should be installed on a mast as high as possible above the rooftop. Ideally this installation should be a few meters above the rooftop at minimum. Another important consideration for these and any other rooftop installations (like GPS antennas) is appropriate grounding practice and the use of in-line surge protection to ensure lightning strikes do not propagate through the cabling and damage the other instrumentation.

Wind Pressure Measurement

In some cases, information on wind pressures over the building envelope can be acquired, though they generally do not achieve the density necessary to make any legitimate speculation on the wind forces acting on the structure, but can provide important insights to the pressures acting on the cladding system. MORE FROM JON

Data Acquisition and Archiving

The process of data acquisition involves the translation of sensor outputs, often in analog form (voltages) to physical engineering measurements in a digital form (binary or ASCII). Figure 7 shows a visualization of this process, and often involves anti-aliasing (AA) filters, which will be discussed in a subsequent section. This section will discuss some important considerations about how to acquire, transmit and archive data, as well as the hardware required.

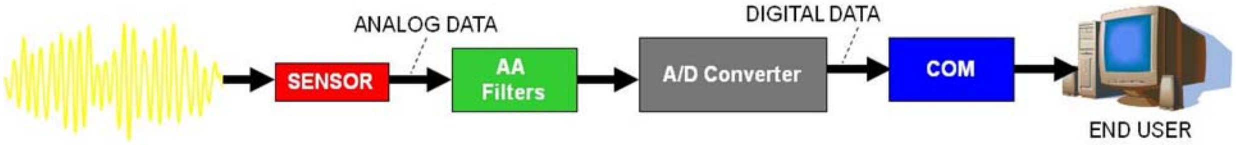

Figure 7: Schematic of Data Acquisition Process

Triggering

This process first requires some decision about how often data will be collected or sampled and whether to continuously record data or only retain data during significant events. The latter is almost always preferred. In the case of wind-induced excitations, the responses of the building are generally used as the triggering mechanism. To avoid occasional electrical spikes from erroneously triggering the system, the response statistics (RMS) are monitored over short intervals (10 minutes) and archived. When these 10-minute statistics surpass a particular threshold, the system is then triggered and responses of the structure as well as wind field data, if available, are recorded continuously for some period of time (one hour). This process continues as long as the motions remain above the threshold level.

In the case of seismic events, the decision to trigger the response sensors must be made quickly and is signified by the detection of accelerations in the near field base station that again surpass a particular threshold, which in this case cannot be based on statistics calculated over extended time intervals due to the transience of ground motions. Thus distinctly different triggering mechanisms are necessary for different hazards.

Acquisition Hardware

For short term deployments of sensors on tall buildings, the use of laptops running data acquisition software like LabView in conjunction with a data acquisition (DAQ) board is sufficient, and perhaps even preferable if digital sensors are being employed. However, stability of computers, security issues, and software updates make this an unsustainable hardware configuration for long term, unattended monitoring. In such applications, dataloggers (Fig. 8a) would be the preferred hardware for monitoring accelerations and wind field characteristics. GPS, on the other hand, must be processed by a computer and can directly output a digital signal to the internet, so on-site acquisition is not required and a computer can be maintained at an off-site location for processing reference and rover data. With either a computer and DAQ board or datalogger, a few important considerations should be made in selecting hardware:

Number of Channels: Each unique quantity output by a sensor must be wired into a channel of the data acquisition system. Units are specified by the number of single-ended or differential inputs (channels) they can accommodate. When possible, differential inputs should be used as they will produce lower noise measurements, particularly when cable runs are 3 m or more. The sampling rates posted for a piece of hardware will be affected by the number of channels that must be "scanned" on a given pass, but given the very high speed sampling currently available on the market (easily in the kHz level), sampling rate will not be a limiting factor for tall building applications, even for a high number of channels.

Number of Bits: In the process of data acquisition, analog signals (voltages) are sampled at discrete time intervals and quantized and digitized through a process called analog to digital (A/D) conversion. The accuracy of this quantization (or resolution of the signal's amplitude) is a function of the number of bits in the A/D converter. 24-bit A/D conversion is relatively standard on the market.

Input Types: Data loggers often can accommodate multiple input types, such as pulse counters and even side by side digital and analog interfaces. When monitoring only accelerometers, which will generally be analog, this capability is not important, but will become relevant if other sensor types are used.

Input Ranges: Most data acquisition systems will offer several voltage ranges they can operate over. Based on the expected voltage outputs for the sensors involved, the range should be selected to be as close as possible to the anticipated maximum voltage output by these sensors, keeping in mind that occasionally noise or other unexpected actions can produce larger voltages that the system will need to be able to accommodate without clipping. However, selecting a voltage range that is too large will dilute the resolution of system, so range selection must balance these two concerns.

Cabling: Long lengths of cabling essentially serve as "antennas" that intercept noise sources that can be quite prevalent at the mechanical floors where instruments are often placed. Thus the use of shielded or doubly shielded cable, sound grounding practice, and differential inputs is essential. Even with this practice in hand, the length of cable runs should be limited as much as possible, as excessively long cable runs may reduce signal strength and even require in-line signal boosting. In some instances where cables are run in the false ceiling of buildings, plenum-rated cable will required for fire protective purposes.

Alternative Architectures

The issues surrounding noise penetration into cables and the labor cost and inconvenience of running them to sensors distributed over the plan and even elevation of a building, have helped to motivate the development of wireless sensing paradigms for civil infrastructure. These miniaturized

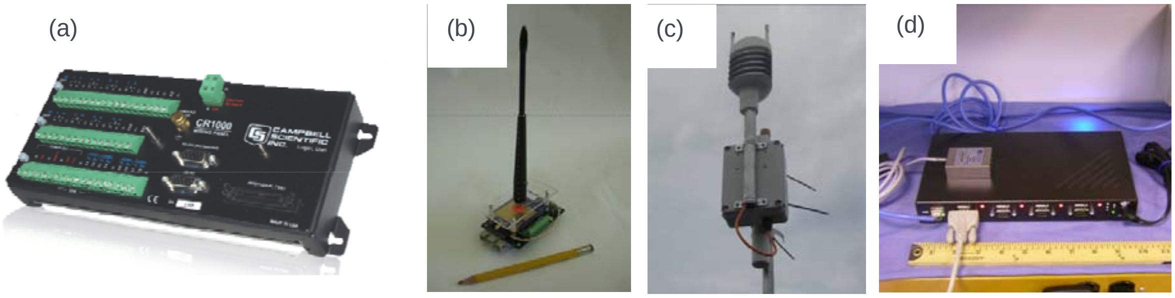

Figure 8: (a) Datalogger (Courtesy of Campbell Scientific), (b) Chasqui Wireless Mote and (c) Deployed Meteorological Station Interfaced with Chasqui Mote (Courtesy of EmNet LLC), (d) DAQ over LAN Interfaced with Digital Accelerometer (Courtesy of Kijewski-Correa).

devices (Fig. 8b) transmit data wirelessly through high powered radios, can even self-organize into ad hoc networks, and re-route data in the presence of interference. This hardware has been prototyped using the Berkeley Mote and now commercialized by Crossbow and a number of other small companies, but the hardware limitations on these devices and the radio bandwidths and resulting network congestion may prohibit applications to tall building monitoring where lengthy time histories must be acquired, locally stored and transmitted, but they have been used to transmit meteorological data as shown in Figure 8c.

DAQ over LAN (data acquisition over local area networks) is a new architecture that is particularly useful in situations where measurements are to be taken at multiple distributed locations – a prohibitive scenario for cable runs to a single logger. These technologies are now being promoted by companies like National Instruments and are capable of interfacing both analog and digital (Fig. 8d) sensors. Provided the number of bits, on-board analog filtering, and reliability and bandwidth of modern building LANs continue to mature, these systems will be viable for use in tall buildings. However, the data management of these systems is not “off-the-shelf” and considerable software and IT issues must be mastered to fully synchronize distributed devices, and the number of sensors supported by this solution is limited by the LAN capacity.

Storage and Communications

The transmission of acquired data to an off-site server has dramatically improved with advances in the reliability and affordability of consumer Internet services. Previously, data loggers employed on site storage modules on the order of several MB capable of storing days of triggered time histories. This data then is automatically downloaded to the server on a pre-defined schedule, previously through telephone modems, which could accumulate significant long distance expense if servers are far removed from the building being monitored. With affordable and reliable DSL services, these systems can now be upgraded with network interfaces and DSL modems for high-speed and even real-time data transmission. Even with the capability for real time and high speed transmission, sufficient on-site storage should be retained in case of communication outages that disrupt download schedules.

SIGNAL PROCESSING

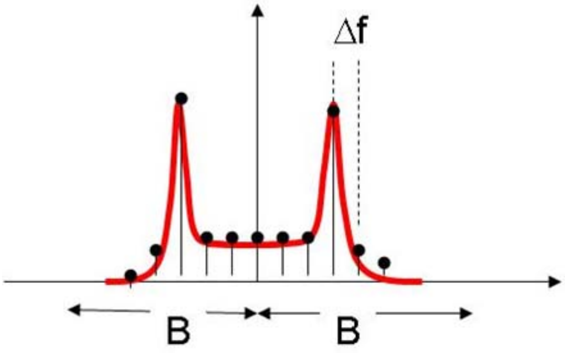

Figure 9: Schematic Demonstrating Frequency Resolution of Power Spectrum

After hardware and triggering mechanisms have been identified, additional electronics and settings will be dictated by signal processing concerns. Specifically, the need for processing full-scale data in the frequency domain (by Fast Fourier Transform) necessitates that the data is acquired and processed with care. These considerations are the result of acquiring analog data and subsequently converting it to a digital signal, as well as the fact that the infinite, continuous Fourier transform is ultimately applied to finite, discrete data.

Sampling Theory

Selecting too slow of a sampling rate will obscure key details of the signal, i.e., will fail to capture higher modes, while selecting a sampling rate that is too high will generate unnecessarily large amounts of data for processing and storage. An appropriate sampling rate can be determined by recognizing that the Heisenberg Uncertainty Principle dictates that, if N points are acquired in the time domain, then that data can be expressed at maximum by N points in the frequency domain, thus constraining the frequency resolution to $\Delta f=1/T$, where T is the length of the signal. As a result, if data is acquired every Δt seconds, the sampling frequency or rate is then $f_s = 1/\Delta t$ and T=N/fs. In short, this implies that if a building has a bandwidth of interest B (range of frequencies to be monitored or highest mode of interest), then the **minimum sampling rate is twice that: $f_s = 2B$.** (Note from Fig. 9 that the Fourier transform assumes a two-sided distribution of frequencies that are both positive and negative, though only the positive are generally considered). Thus at least two samples or points per cycle of oscillation are required to characterize the highest mode of interest.

Because the Fourier Transform has symmetry and repetitive properties, any content above $f_s/2$ is folded or mirrored into the frequencies below $f_s/2$ when the spectrum is implemented digitally (Fig. 10). Ultimately, an end user will have no ability to distinguish the content that physically resides below $f_s/2$ in the spectrum from that which is numerically deposited there by this **aliasing**

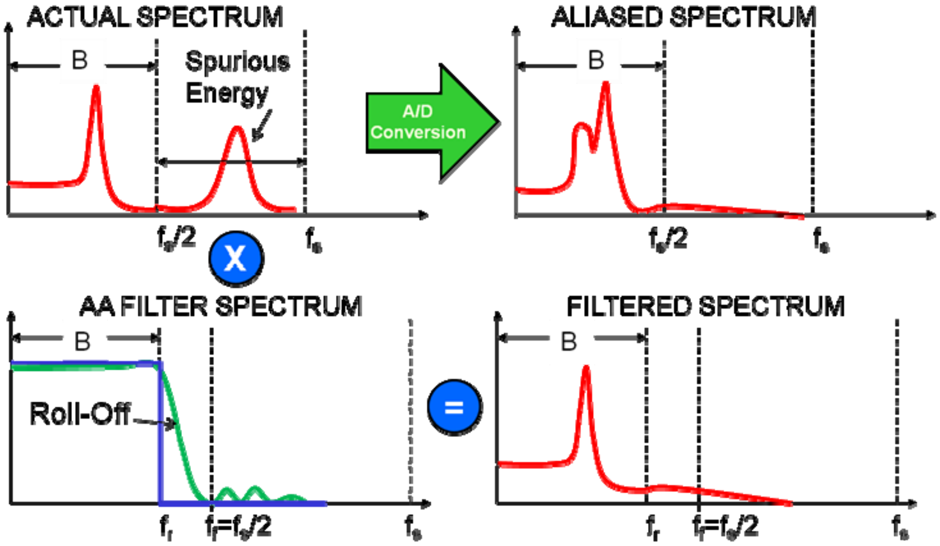

Figure 10: Schematic of Aliasing Phenomenon in Power Spectrum (top images) and Remedy by AA Filtering

phenomenon. Thus the frequency $f_s/2$ has special importance as the **Nyquist Frequency**. This aliasing occurs when data is transformed from analog to digital by A to D conversion. Once this conversion takes place, the aliased high frequency content cannot be removed.

There are two approaches to avoid aliasing in data. The first is to sample at an extremely high sampling rate, twice that of any known structural frequency or electrical/mechanical interfering noise. Often this is not practical, particularly due to the high frequencies of the latter contributions. More often, **anti-aliasing (AA) filters** are employed. These are analog filters that remove any frequency content above the bandwidth of interest before A to D conversion. While these filters would ideally truncate abruptly (see blue line in Fig. 10), this produces a number of undesirable behaviors in the time domain. Thus filters must gradually tend toward zero and the filter's frequency range (f_r) must span this bandwidth (B) and is essentially falls to zero by the filter cutoff frequency (f_f) (see green line in Fig. 10). The sampling rate (f_s) is then set as $2f_f$, and thus the use of an AA filter requires a higher sampling rate. There are several types of filters (Elliptic, Chebychev, Butterworth), though the Butterworth usually proves most versatile for the present application, though having a considerable roll off: $f_f \approx 7\ f_r$.

Noise, Quasi-Static Distortions and Discontinuities

Noise: Even with the use of AA filtering, acquired data can still have distortions that must be removed prior to analysis. Depending on the sampling rate and properties of the AA filters being utilized, the acquired signals may have some undesirable high frequency noise that may be removed by digital low pass filtering, again likely of the Butterworth variety.

Quasi-Static Distortions: Meanwhile in the low frequency range, **sensor drift** can occur, particularly with the use of seismic accelerometers, which leads to non-zero means in acceleration data. In cases where the drift is constant over the length of the acquired time history, this can be removed simply by subtracting the mean. In cases where the drift changes over the course of the time history, a moving average must be identified and subtracted or high-pass digital filtering can be applied to remove spurious quasi-static components. In the case of GPS data, another quasi-static distortion called **multi-path effect** is quite common due the reflection of a GPS satellite signal off of neighboring reflective objects. These distortions are periodic in nature, with periods on the order of minutes and can distort GPS signals by several centimeters. Various methods to diagnose and remove these characteristics have been offered (Kijewski-Correa and Kochly 2007).

Discontinuities: GPS displacement data can also experience large temporary swings due to the loss of a satellite, leading to an abrupt mean shift in the data. These can be removed by approaches similar to those used for multi-path effects or through the use of dead reckoning technologies that temporarily splice doubly integrated accelerometer data in place of distorted GPS displacements. Another common occurrence in full-scale monitoring, particularly with analog accelerometers, is **electrical spikes** which have instantaneous amplitudes much higher than the surrounding data points and must be removed through digital signal processing.

Verifying Stationarity

For many of the system identification approaches employed to analyze the response of tall buildings under wind, an implicit assumption of stationarity is imposed, which implies that the statistics of the response do not vary significantly with time. This assumption is especially critical in the application of the Fourier Transform to generate power spectra. Unfortunately, the assumption of stationarity is often made without any rational basis. For some, verification that the mean or even RMS values of the on-site wind speed and direction remains consistent over a period of time is often taken as sufficient test for stationarity. More rigorous tests are often not performed, though there are some standard statistical significance tests that can be employed, e.g., Run and Reverse Arrangements Tests (Bendat and Piersol 2000).

GENERATING POWER SPECTRA

After appropriately considering aliasing, sampling theory and stationarity, data is generally first processed by Fast Fourier Transforms to generate power spectra to evaluate the general frequency content of the signal. Specifically for the response of tall buildings under wind, it is assumed that the forces driving the structure are random white noise, so that a simple analysis of the response power spectrum reveals the frequency response function and thereby the dynamic characteristics of the building. The reliability of this method is thus heavily reliant on the accuracy with which the response PSDs are estimated, which depends upon how the Fourier Transform is discretely and finitely implemented according to:

$$S_{xx}(f_k) = \frac{1}{n_d T} \sum_{m=1}^{N_d} \left| X_m(f_k) \right|^2$$
$$f_k = \frac{k}{T} = \frac{k}{N\Delta t} = \frac{k}{N} f_s \quad k = 0,1,\ldots N_{FFT} - 1 \tag{1a,b}$$

where T is the length of the block of data being Fourier transformed, N_s is the number of spectra being averaged, and f_k are discrete frequencies at which the Fourier Transform is evaluated, as dictated by the sampling rate and number of FFT points (N_{FFT}) used in the analysis.

The number of FFT points or spectral lines used in the transform directly affects the bias of the power spectrum and thereby damping estimates. As a rule of thumb, the number of FFT points used for each spectral estimate should ensure a minimum frequency resolution (Δf_{min}) associated with at least four spectral lines in the half-power bandwidth (*HPBW)*, so that spectral bias errors are held to -2%:

$$\Delta f_{\min} = \frac{2\xi f_n}{4} \tag{2}$$

where ξ is the damping ratio, f_n is the natural frequency. Based on this, the required number of FFT points can be determined to the nearest power of two, based on the sampling frequency f_s:

$$N_{FFT} = 2^{ceil\left(\log_2\left(\frac{f_s}{\Delta f_{\min}}\right)\right)} \tag{3}$$

Once the N_{FFT} is determined, the stationary data is divided into blocks of N_{FFT} points with a length $T = N_{FFT}/f_s$ seconds Fast Fourier Transformed and averaged, according to Equation 1, to generate the power spectrum. This process is shown conceptually in Figure 11. The variance in this power spectral estimate is inversely proportional to the square root of the number of spectral averages and thus to generate a sufficiently smooth spectrum, tens of raw spectra often need to be averaged. For tall buildings, this can create a daunting situation due to the very low frequency and damping values commonly encountered in these buildings, which in turn generate very narrow half power

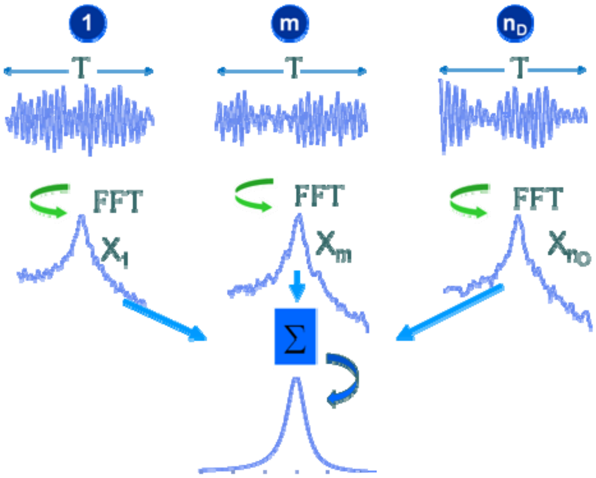

Figure 11: Schematic of Power Spectrum Creation via Fast Fourier Transform

bandwidths and require very fine frequency resolution. In some cases tens of hours of data may be necessary to generate reliable power spectra with low bias.

When this amount of stationary data is not available, users are often confronted with the competing demands of reducing bias and variance with what little data they have. To counter bias, one would increase frequency resolution and therefore the length of the blocks (T). This produces less raw spectra for averaging and increases variance. In general, if bias is not mitigated, damping will be overestimated. On the other hand, if variance is high, damping can be randomly over or underestimated depending on the jaggedness of the resulting spectrum. Thus it can be argued that users should first minimize bias by selecting N_{FFT} accordingly if limited amounts of data are available and either accept the variance or adopt techniques to extract dynamic properties from high-variance spectra, as discussed later.

The power spectrum generated in Equation 1, which is assumed to be proportional to the frequency response function, considers only the magnitude of what is a complex-valued function. Phase information is also available and can be utilized when sensors are distributed over the height of the structure to estimate mode shapes by noting the phase shifts between sensors at various locations on the structure and the amplitude of the power spectral peaks.

Leakage and Windowing

As the Fourier Transform assumes that the data in question is periodic, if the acquired time history does not take on the same value at the beginning and end of the record, i.e., $x(0) \neq x(T)$, then a phenomenon called leakage will occur. This can cause the spectral peak to be widened due to energy smeared from adjacent modes. Different windowing treatments, e.g., Hanning windows, can be applied to the acquired time history that taper the signal at its beginning and ends to insure the modified signal begins and ends at a zero value, i.e., $x(0) = x(T) = 0$, thus eliminating the problem of leakage. However, this tapering in turn reduces the power spectral amplitude and effectively damps the signal, leading to damping values that are over 50% larger. Furthermore, if any noteworthy content is in the end regions being tapered, this information is lost. Thus, when windows are used, it is common for power spectra to be estimated using overlapping blocks of data to make sure no content is "lost." Even with this measure in hand, the inflated damping issue still remains. However, if a relatively small frequency resolution (Δf) is adopted in the generation of power spectra, which requires longer lengths of data since Δf=1/T, the leakage issue can be effectively mitigated and damping values can be effectively preserved. This is addressed in greater detail in the discussion of spectral bias.

SYSTEM IDENTIFICATION TECHNIQUES

One obvious goal of most monitoring efforts is the identification of various response quantities, performance/damage metrics, and extraction in-situ dynamic characteristics such as periods of vibration, mode shapes and critical damping ratios. As today's buildings manifest diversity in both form and function, the properties best characterizing these systems are equally diverse. Coupling this with the varying constraints of practical data acquisition systems (e.g., limited instrumentation points, noise, sensor accuracy), it is no wonder that a broad spectrum of system identification methods have surfaced, which can be broadly categorized by the hazard they address (earthquakes vs. strong winds). Each of these hazards creates unique features and constraints on the identification problem, as summarized in Table 1.

Table 1: Features of Seismic and Wind-Induced Monitoring Efforts

Feature	Seismic Excitation	Wind Excitation
Input Forcing	Measured at the base, Nonstationary	Unknown, Spatially Distributed, Broadly Stationary
Response Type	Dynamic	Static, Quasi-Static, Dynamic
Model	Linear or Nonlinear	Linear
Sensor Density	Comparatively Higher	Generally Low

In order to understand the challenges associated with estimating dynamic properties in particular, one must first consider the role of dynamic properties in the overall response. The resonant response of a structure oscillates at the natural frequencies of the system. As a result, clear periodicity can be readily observed in time series. This indicates the significant role that natural frequency plays in shaping the response. As a result, natural frequencies are relatively easy to identify reliably from measured data. On the other hand, the amplitude of the response is largely shaped by the forces acting on the system as well as the rate at which the system can dissipate the energy imparted by that force. This energy dissipation capability is damping. The energy dissipation of most tall buildings under service conditions is relatively small, around 1% of the critical value. Thus, it plays a very minor role in the response. When a structure is excited by natural forces like wind, the exact amplitudes of the forces acting on the structure are unknown and impossible to measure. As a result, when examining the resulting response amplitudes, there is no way to differentiate the role of the loading from the very small levels of inherent damping in the system. Thus, established system identification approaches resort to extensive averaging to remove the random load effects and reveal the damping inherent to the system. This situation is further compounded by the fact that the taller the building (and the longer the time period), the more data is required to perform this averaging, as motivated earlier by the discussion of spectral bias. Thus, damping cannot be estimated reliably in from small amounts of data without an ability to measure the force acting on the system. The only situation where this is possible is the case of an earthquake, where the force acting on the building can be determined from the measured ground accelerations, allowing the force contribution to the response to be effectively isolated to reveal the true damping in the system without the need for significant averaging.

Applications to Wind-Induced Response

Due to the spatial distribution of wind pressures, exact measured inputs are never available for system identification, which sharply contrasts with the common situation in seismic zones, although those inputs are nonstationary and resulting responses are generally nonlinear. Further, given the comparatively lower amplitude responses encountered under wind, techniques must be capable of distinguishing responses from the noise floor in the data and extracting damping values that are smaller, again on the order of 1% compared to much higher levels (5%) commonly observed in earthquakes. These damping values potentially are the most valuable information extracted from full-scale data and has been demonstrated to show amplitude dependence. In such cases, to maintain faithfulness to the high-frequency base balance methodologies common to design practice, linear models are maintained in wind-resistant design, and frequency and damping values used in these evaluations are then adjusted for events of varying return period to account for their amplitude dependence. Finally, before discussing common methodologies, it should be emphasized that these applications sensor arrays are comprised generally of 2-6 accelerometers/1-2 global positioning antennae only on the uppermost floor/roof, thus limiting the approaches employed.

Frequency Domain Methods

By far, the most common approach to estimating dynamic properties relies on the power spectrum of the building's response with the assumption of white noise driving a linear system yielding stationary, ergodic responses. As evidenced by the Japanese Damping Database(Satake and others 2003) and summarized in Figure 12, approximately half the full-scale applications for wind or ambient vibration monitoring historically employed frequency domain identification techniques, such as half power bandwidth.

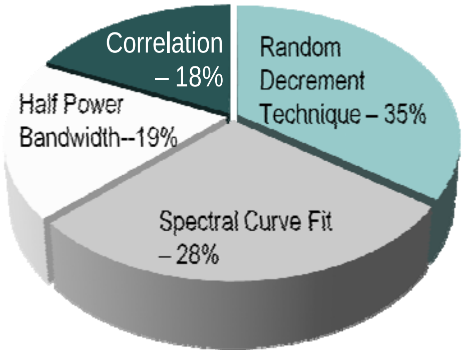

Figure 12: Summary of System Identification Methods Used in Japanese Damping Database (Based on Satake et al. 2003)

Still, there is significant reluctance to use frequency domain methods due to the aforementioned signal processing issues associated with Fast Fourier transforms. In particular, given the increased variance that often results when low bias spectra are generated, curve fitting methodologies(Lagomarsino and Pagnini 1995) like maximum likelihood estimators have been employed and were shown to produce lower bias and variance in their damping estimates than traditional methods like HPBW applied to high variance power spectra from a collection of over 60 buildings in South Korea(Erwin, Kijewski-Correa, Yoon 2007). Alternatively, techniques such as Frequency Domain Decomposition (FDD) employing curve fitting in the vicinity of the singular values has grown increasingly popular for frequency-domain identification, even in the presence of high variance with limited amounts of data. This method was employed for the long term monitoring of the first nine modes of the Tokyo International Airport and New Tokyo International Airport Control Towers using arrays of 27 accelerometers(Yoshida and Tamura 2005). This method proved especially advantageous in the evaluation of closely spaced modes in full-scale(Yoshida and others 2004).

Time Domain Methods

The inherent trade-offs between bias and random errors in power spectral estimates prompt some to employ time-domain methodologies. For example, autocorrelation functions can be fed into the Eigensystem Realization Method to extract the dynamic properties, but without sufficient data to accurately estimate the correlation functions, damping and mode shapes are not estimated with any reliability. Similar experiences with direct determination of autocorrelation functions(Davenport and Hill-Carroll 1986) has helped propel the random decrement technique (RDT) as an alternative for autocorrelation estimation. The primary advantages in this case are the ability to relax stationarity requirements and capture mild nonlinearities (amplitude dependence) in frequency and damping (Tamura and Suganuma 1996). This has been successfully applied to a number of buildings in China (Li and others 2003; Li, Xiao, Wong 2005b) and Chicago(Kijewski-Correa and Pirnia 2007); a sampling from the latter application is shown in Figure 13, where the degree of amplitude dependence in damping (Fig. 13b) and even exchange of energy between coupled modes (Fig. 13c) can be observed. It should be noted that the equivalent viscous damping ratios identified from Random Decrement Signatures using Hilbert Transforms (analytic signal theory), logarithmic decrement or direct curve fitting to the exponential decay are often less than their frequency domain counterparts. While this may be credited to bias in the power spectral estimates(Kijewski-Correa and Pirnia 2007),

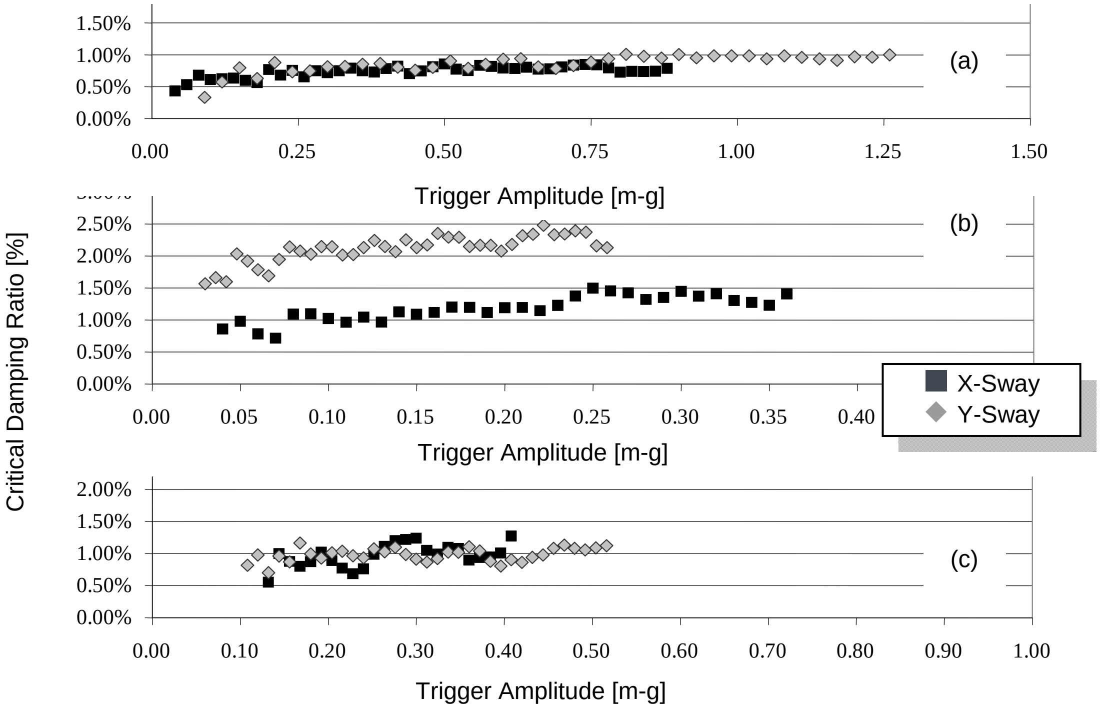

Figure 13: Amplitude-Dependent Damping from Buildings (a) 1, (b) 2, (c) 3 in Chicago Full-Scale Monitoring Program (Kijewski-Correa and Kochly 2007)

have demonstrated the role of amplitude-dependent frequency and modal coupling in “inflating” spectral damping estimates. Thus spectral methods should be used with caution and only when amplitude-dependence in frequency or damping is not suspected.

Time-Frequency Domain Methods

Given the amplitude dependence in dynamic properties and even transient wind events (thunderstorms) that can indeed affect tall buildings, it may be necessary to conduct analyses using time-frequency methods that do not require the verification of stationarity. While there are a number of methods that have been used, such has Hilbert Transforms with Empirical Mode Decomposition and Short Time Fourier Transforms, the Wavelet Transform has received the most attention in the application to tall buildings. Essentially this method replaces the infinite duration, sinusoidal bases of the Fourier Transform with finite-duration, compact bases (e.g., windowed sinusoids of the Morlet Wavelet). Thus the traditional power spectral perspective is replaced with a wavelet scalogram that shows energy content as a function of frequency and time. As shown in Figure 14, users can then focus their attention on the time-varying signals at particular frequency in the scalogram for the purposes of system identification(Kijewski and Kareem 2003) or at the energy over a range of frequencies at a given instant in time, to better understand the role of various modes in the response, their interaction, and exchange of energy between them(Kijewski-Correa and Pirnia 2007). Coupling these transforms with other approaches like singular value decomposition (WT-

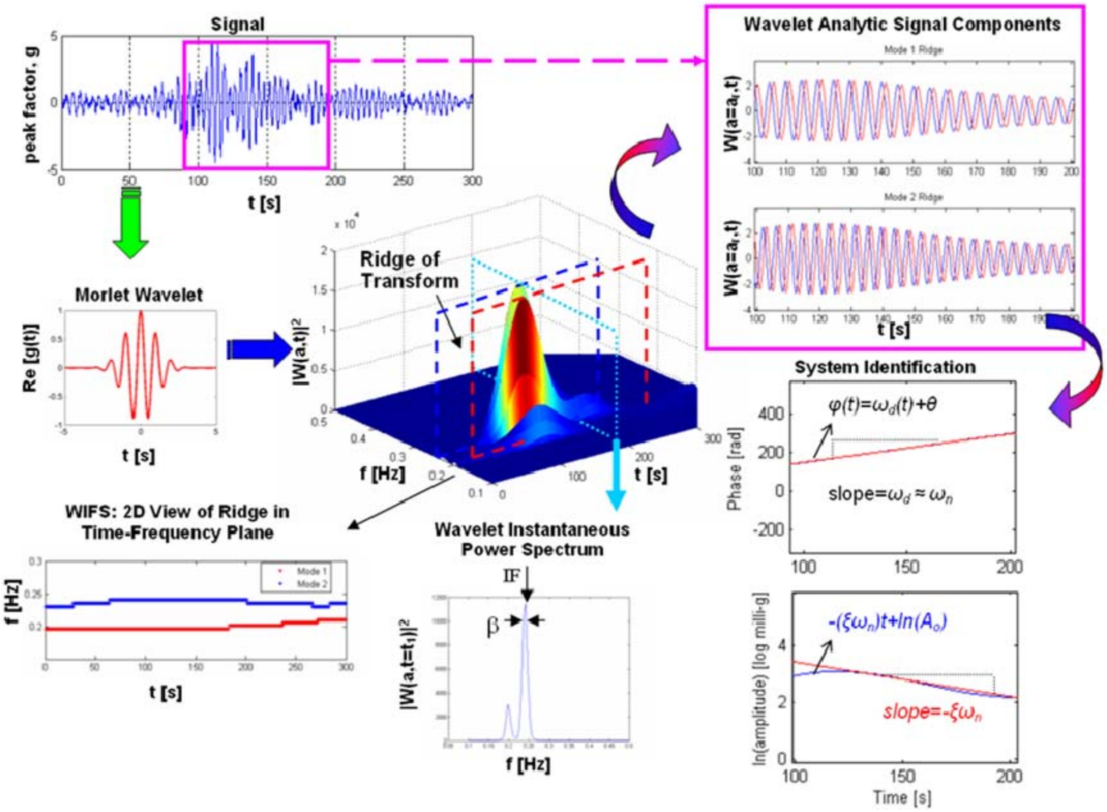

Figure 14: Schematic of Wavelet-Based Analysis Framework

TSVD) even permits nonstationary response data to be processed using conventional time and frequency domain approaches(Bashor and Kareem 2007). Not only have these transforms proven useful for studying the response of tall buildings, but they are also valuable for characterizing multipath effects in pre-processing of data(Kijewski-Correa and Kochly 2007). Further, since they are well equipped for handling transient data, these transforms could similarly be applied to the analysis of seismic response data.

Applications to Seismic Responses

Unfortunately there is limited information on system identification approaches specifically geared toward tall buildings under earthquakes, generally due to the limited occurrences of instrumented tall buildings experiencing significant ground motion. In general, if there is no recording of the base excitation, the system identification methods commonly used for analyzing seismic response are not valid and must be abandoned in favor of output-only approaches, though their performance will be somewhat challenged by the lack of sufficient amounts of data for averaging and the issue of nonstationarity. Even in cases where the base excitation is recorded (system input is known), many of the system identification methods used for seismic responses of buildings, as overviewed in two recent papers(Kijewski-Correa and Cycon 2007)(Kijewski-Correa, Taciroglu, Beck 2008), would not be readily extendable to tall buildings since they were intended for structures where sensors are applied at every floor.

Table 2: Inventory of Instrumented Tall Buildings(Kijewski-Correa and Cycon 2007)

Building	**Location**	**Ht. [m]**	**Type**	**No. of Sensors/ Recorded Events**
A-Chicago [3 Buildings]	Chicago	--	S, RC	4/AV since 2002
A-30	Hong Kong	120	S/RC	2/AV since 1995
A-47	San Francisco	172	S	18/Loma Prieta EQ (1989)
A-54	Los Angeles	221	S	20/Northridge EQ (1994)
A-57	Boston	245	S	8/AV 1973-1978
A-73	Seoul	264	RC	6/AV since 2005
Bank of China (BPRC)	Hong Kong	370	S/RC	2/T. Sally (1996)
Building C	Hong Kong	218	RC	2/T. Imbudo (2003), T. Dujuan (2003)
Building E	Hong Kong	206	RC	2/T. Imbudo (2003), T. Dujuan (2003)
Central Plaza Tower (CPT)	Hong Kong	374	RC	2/T. Sally (1996)
Di Wang Tower (DWT)	Shenzen, PRC	384	S/RC	2/T. Sally (1996)
Guangdong Intl. Bldg. (GIB)	Guangzhou, PRC	200	RC	2/AV
Jin Mao Tower (JMT)	Shanghai	365	S/RC	2/T. Rananim (2004)
Republic Plaza (RP)	Singapore	280	S/RC	4/21 Minor EQ
Transamerica Bldg. (TRA)	San Francisco	257	S	22/Loma Prieta EQ (1989)
Union Bank Bldg. (UBB)	Los Angeles	42-ST	S	2/San Fernando EQ (1971)
Notes: RC: Reinforced Concrete, S: Steel, AV: Ambient Vibrations, EQ: Earthquake, T: Typhoon				

ENVIRONMENTAL SCAN

Kijewski-Correa and Cycon(Kijewski-Correa and Cycon 2007) summarized the applications of full-scale monitoring on buildings using a review of the current literature. This review encompassed buildings of all height; excerpts of that study are reproduced in Table 2 retaining only "tall buildings," which will be defined as those having at least 30 stories or being 100 m in height. A number of the buildings are anonymously cited in the literature and are given an internal designation of A-## where ## is the number of floors. Admittedly, there are certainly are more full-scale monitoring efforts underway for tall buildings that are performed confidentially by private companies with results unpublished; however, the present environmental scan does provide some indication of the prevalence of full-scale monitoring for tall buildings. In addition to those projects listed in the table, a number of structures were instrumented, at times temporarily, to generate databases of viscous damping ratios, as led by Canadian researchers (165 Buildings), and followed by

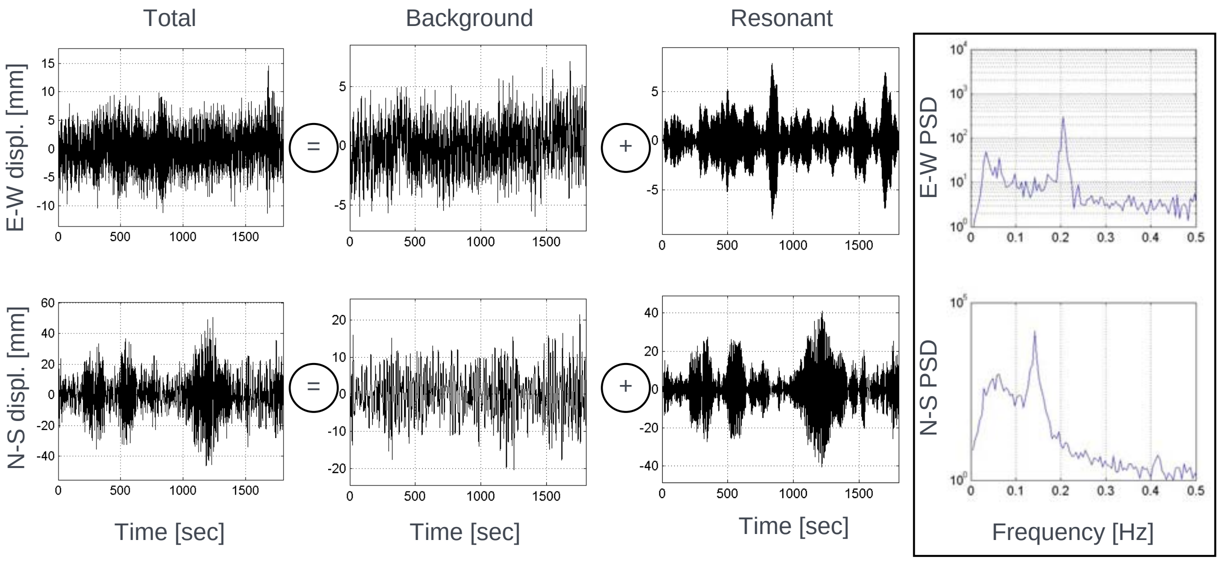

Figure 15: Full-scale Observations of Wind-Induced Displacements, Including the Background Component (Kijewski-Correa et al. 2006b)

those assembled by Italian (185 Buildings), Japanese (205 Buildings), and Korean researchers (67 Buildings)(Davenport and Hill-Carroll 1986, Lagomarsino and Pagnini 1995, Satake and others 2003, Yoon and Ju 2004). While most of these buildings are of the low- to mid-rise variety, these databases do include some isolated measurements on tall buildings.

Some of the more noteworthy efforts in Asia (Brownjohn, Pan, Cheong 1998; Fang and others 1999; Li and others 2003; Li and others 2004; Li and others 2004; Li, Xiao, Wong 2005a; Li and others 2006; Campbell, Kwok, Hitchcock 2005) include the Di Wang Building, Bank of China, Central Plaza, Jin Mao and Republic Plaza. These efforts have included the quantification of amplitude-dependent dynamic properties by RDT for the DiWang, Central Plaza and the Bank of China (Li, Xiao, Wong 2003; Li, Xiao, Wong 2005a). Meanwhile the Chicago Full-Scale Monitoring Program has compared wind tunnel predicted responses with full-scale measurements in an effort to systematically validate the procedures used in the design of several tall buildings in Chicago, with recent expansion other sites overseas. The researchers at the University of Notre Dame affiliated with this effort have also applied spectral, time and time-frequency domain techniques to isolate frequency and damping estimates not only from the buildings affiliated with this project (Kijewski-Correa and others 2006b; Pirnia and others 2007) but also from the John Hancock Tower in Boston (Kijewski, Brown, Kareem 2003) and over 60 buildings that comprise the South Korean Full-Scale Database (Erwin, Kijewski-Correa, Yoon 2007).

Recognizing the importance of capturing the total response of tall buildings under wind, a number of researchers have also explored the use of GPS. Following the earlier work of Celebi and Sanli (2002) on mid-rise buildings in San Francisco and Los Angeles. This was followed by a temporary deployment on the Di Wang Building (384 m) in China by Chen et al. (2001) and a 66-story multi-purpose building in Korea (Park and others 2004). These temporary deployments of GPS technology were followed by long-term deployments on Singapore's Republic Plaza (280 m) (Brownjohn 2003) and in Chicago (Kijewski-Correa, Kareem, Kochly 2006). The system in Chicago has been operating since 2002 enabling the quantification of quasi-static (background) response of a tall building in full-scale (Fig. 15).

LESSONS LEARNED

Stakeholder Confidence

In order to facilitate a paradigm-shift in the application and advancement of full-scale monitoring to tall buildings, it is important to consider the stakeholders involved(Kijewski-Correa and Kareem 2007). This understanding must consider their needs, risks and constraints, whether they be practical and/or economic. These vary with region, as some stakeholders have a vastly different incentive base (quantifying the behavior of a new or complex structural system) than others (monitoring health over structure's life cycle). As a result, there can be no "one size fits all" approach to monitoring, particularly across hazards (earthquakes vs. wind). Unfortunately, stakeholder appreciation of the value of full-scale monitoring has not advanced in some countries at a rate commensurate with the advances in sensor and information technologies.

In California, where earthquakes have raised concerns about survivability and rapid reoccupation, monitoring has been widely embraced. This in part is due to code incentives that have motivated and even required developers and owners to incorporate such technologies, e.g., Building Occupation Resumption Program (BORP), as well as high-level, coordinated initiatives such as the California Strong Motion Instrumentation Program (CSMIP). In fact, strong motion programs have generated 150 instrumented sites in the United States (Huang and Shakal 2001), 100 sites in Japan, and 40 sites in Taiwan (Huang 2006). This is in stark contrast to the situation outside of seismic zones in the United States, where an instrumented building is still regarded as a "troubled building" and publicly disclosed monitoring efforts may generate severe public misconceptions and even liability issues. Ultimately, there must be *fiscal benefits* to the ownership that motivate the investment in monitoring and the case for this has not been made successfully in regions where wind governs the design for serviceability/habitability limit states and assessment and reoccupation are non-issues.

Thus, unless a building has demonstrated suspect performance, e.g., excessive vibrations disruptive to occupants, owners will not invest in instrumentation.

In fact, even if the equipment costs could be subsidized by federal research dollars, other fiscal issues remain a major concern. Owners are often receptive to no-cost monitoring to learn more about the performance of their building and use the real-time data streams for maintenance and operation; however, they have significant concerns about fiscal losses that could result if the building is negatively perceived by the public. In contrast with the attitudes in Asia, an instrumented tall building in the United States is not an "intelligent" structure but a "suspect" one. Thus there are some issues of public education and perception that must be addressed. In the interim, one must generally guarantee confidentiality of the data and the building's identity, prohibiting dissemination data to the wider engineering community to benefit the design state-of-the-art. Furthermore, it restricts the ability of researchers to conduct full-scale assessments of occupant comfort, a critical limit state in serviceability/habitability design that unfortunately requires human feedback for meaningful interpretation of the acceptability of recorded accelerations.

In all cases, legal advisors to the ownership will be involved to protect these investments. In best case scenarios, confidentiality agreements are developed. In worst case scenarios, legal advisors often intercede and completely discourage owner cooperation. They cite the liability of inaction: if some problem should be uncovered and the owners fail to act, then they can be held liable by tenants. Sadly, the legal advisors instead prefer to have owners "in the dark," as they are not liable for problems they had no knowledge of. This attitude returns to the fiscal benefits issue: monitoring outside of seismic zones is perceived to provide no fiscal benefit and even potential loss and thus should be avoided.

How can these attitudes be changed? Without a tangible case to fiscally motivate the need for monitoring, code incentives appear to be the most viable strategy. There is precedent for mandated monitoring of "non-seismic" hazards. For example, in the Shinjuku District of Tokyo, populated by a number of tall buildings, pedestrian wind effects have been an issue and thus city ordinance requires developers to install anemometer arrays to verify the safety of the pedestrian environment. Unfortunately, changing municipal codes is a highly political, labor intensive and time consuming process and is often only propelled by public outcry in the wake of a failure or other disaster that could have been arrested by monitoring. Still, a code-based incentive will not only bring ownership to the table but it will also help to publicly legitimize monitoring as a pro-active and not re-active measure, which in turn will improve public perception and hopefully their involvement in the full-scale evaluation of perception criteria. Other options include design firms mandating monitoring as part of the construction process as feedback or validation of the design, though many firms lack the ability themselves to process and analyze the data and would likely need to team with researchers or other private consultants in this endeavor.

Predictive Models for Damping

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

Since habitability limit states are so critical for this class of structure, effective means to reduce accelerations are equally of interest. To this end, additional damping is consistently effective in reducing acceleration responses in habitability limit states, though to date it still cannot be predicted in the design stage(Bentz and Kijewski-Correa 2008). This makes accurate estimates of viscous damping from full-scale data and the subsequent development of predictive empirical models a vital need for the tall buildings community. The success of this effort depends not only on expanding full-scale monitoring efforts within the community to generate data, but then having means to analyze that data effectively. There remains a need to improve system identification methods for "output only" applications, ideally suitable for cases when limited stationary or even nonstationary data is available.

However these efforts are inevitably constrained by the availability of high quality data, from a wide range of buildings with varying usages, structural systems and foundations. In order for trends to be effectively diagnosed, multiple buildings sharing similar attributes must be monitored. These data must be collected at comparable stationary vibration levels for sufficient durations of time, and then processed and analyzed using the same techniques, by personnel with comparable training. This certainly is a tall order and suggests that issues of access to tall buildings for full-scale monitoring, open archiving and exchange of data among researchers, and standardization of data processing practices will all be necessary within the community in order to produce reliable databases of damping in tall buildings suitable to better inform the design process.

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