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INSTRUMENTATION FOR STRUCTURAL HEALTH MONITORING: MEASURING INTERSTORY DRIFT

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ABSTRACT :

A boom in tall building construction along with peer review of alternative performance-based designs has recently exposed fundamental issues within the field of earthquake engineering; e.g., ground motion selection and modeling guidelines. In response, the City of Los Angeles has implemented new instrumentation requirements for buildings designed using “alternative” procedures citing Chapter 16 of ASCE 7. The construction boom, as well as an updated instrumentation program, provides a rich opportunity to collect unique data in both wind and earthquake events to address critical analysis and design issues. In the medium-term, the aim is to develop and implement a network for structural monitoring and performance-based assessment using LA tall buildings as a test-bed. One particularly useful response quantity within the emerging performance-based earthquake engineering methodology is interstory drift. However, current methods for measuring interstory displacements (e.g., double integration of acceleration) are problematic; as illustrated from forced vibration testing of a full-scale building. A framework for near real-time monitoring for seismic events and preliminary results of ongoing efforts to develop alternative methods for measuring drift are presented.

KEYWORDS: SHM, Instrumentation, Interstory Drift, Sensor Development

1. INTRODUCTION

Tall building construction in urban centers along the US west coast has recently surged. For example, within the City of Los Angeles, 61 buildings over 20 stories (23 over 40 stories) are under development, Figure 1 – note, currently there are only 20 buildings over 40 stories in downtown Los Angeles. A significant number of the proposed buildings are being designed using “alternative” procedures citing Chapter 16 of ASCE 7. These designs typically involve nonlinear dynamic analyses of 3D finite element models and require peer-review. A process which has led to debate within the profession over appropriate ground motion selection, as well as modeling and acceptance criteria. Systematic instrumentation of these structures could help address these fundamental questions as well as other related issues facing the earthquake engineering community.

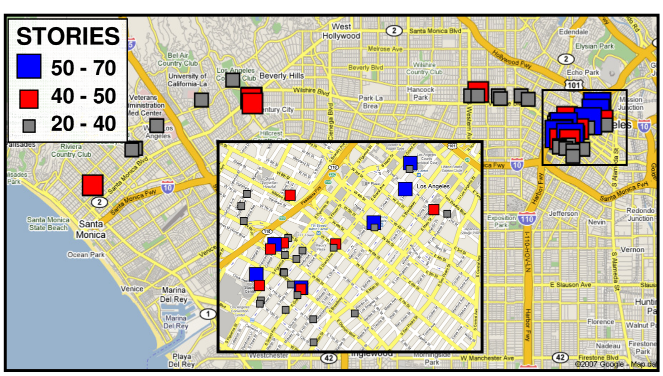

Figure 1. Tall building construction boom in Los Angeles

Table 1. Instrumentation requirements for tall buildings in Los Angeles designed with alternative procedures, LA-TBSDC 2008

Number of stories above ground	Minimum Number of channels
10 – 20	15
20 – 30	21
30 – 50	24
> 50	30

The City of Los Angeles requires building instrumentation (accelerographs) to be installed at the base, mid-level, and roof to obtain a building permit for all conventionally-designed buildings over ten stories (2002 LA Building Code §1635). Building owners, who are required to maintain the instrumentation in working order, often enroll in a program offered by California Strong Motion Instrumentation Program (CSMIP). The City of LA, partnered with CSMIP manages the extensive program for monitoring the equipment currently installed in approximately 400 buildings. Recently, UCLA researchers, along with the LA Department of Building Safety (LA-DBS) and CSMIP have drafted new requirements to increase the quantity and quality of instrumentation schemes. More specifically, alternatively-designed buildings will now be required to satisfy the minimum amount of channels (based on number of stories) according to Table 1. Additional language included in the updated guidelines better facilitate the use of alternative sensors (e.g., strain, displacement, interstory drift) as well as advanced data acquisition systems (Delli Quadri 2006). Finally, and probably most significantly, the instrumentation deployment plans are subject to approval by the Seismic Peer Review Panel (SPRP). This step, we hope, will encourage officials to enforce rational objective-based sensor deployments rather than casual acceptance of minimal recipe-based deployments. In summary, the tall building surge as well as an updated instrumentation program provides a rich opportunity to collect unique data to address critical analysis and design issues. This test-bed, along with emerging performance-based assessment tools, (e.g. fragility functions) enables further development and implementation of a novel network for structural health monitoring.

2. STRUCTURAL HEALTH MONITORING SYSTEM

Structural Health Monitoring (SHM) is the process of assessing the state of health (e.g., damage) of instrumented structures from measurements. The goal of SHM is to improve safety and reliability of infrastructure by detecting damage before it reaches a critical state, or to allow rapid post-event assessment. Traditionally, inspectors rely on visual inspection for damage detection. Although quite dependable, inspections impose high costs and inconvenience on building owners and occupants alike; for instance, visual inspections are expensive because they require qualified personnel and the removal of non-structural components, e.g. partition walls and fire proofing. In addition, such resources may not be immediately available after a damaging event, especially for dense urban areas like Los Angeles, which has plenty of tall and mixed-use buildings. Due to the obvious societal and economic benefits and recent advances in technology, SHM has emerged as an exciting field within civil engineering.

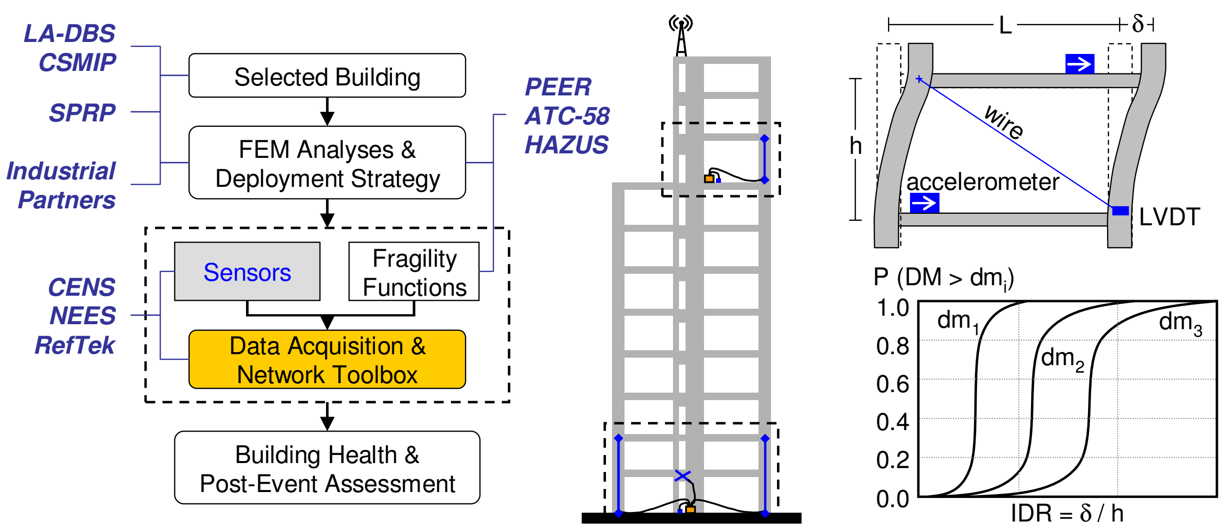

Figure 2. Proposed SHM system with example deployment and accompanying fragility curve example

The proposed SHM system is illustrated in Figure 2. Selection of buildings will coincide with currently engaged projects within the Los Angeles region with cooperation from LA-DBS and CSMIP. For a given selected building, the details of the embedded network design will be model-driven, i.e., sensor types and locations will be determined based on response quantities obtained from 3D dynamic finite element models (FEM) subjected to a suite of site-specific ground motions. For example, in moment frames, response quantities of interest might be interstory displacements (δ in Figure 2) at several floors (where maximum values are expected) along with base and roof accelerations. In a concrete core wall system, response quantities of interest might be average core wall concrete strains within the plastic hinge (yielding) region and the rotations imposed on coupling beams (or slab-wall connections). Emerging Performance-Based Earthquake Engineering (PBEE) tools for damage state detection (i.e., fragility functions) enables probabilistic post-event assessment. More specifically, monitoring key response quantities with associated fragility curves (which can be periodically updated as new information becomes available) offers concise, near real-time information (i.e., probability of reaching certain damage states) and leads to loss estimation (Porter 2006, Celebi 2004). Fragility curves are typically derived from engineering demand parameters such as interstory drift and roof displacement for structural and non-structural components and peak floor accelerations for non-structural components (Naeim 2005). Unfortunately, results from full-scale forced-vibration experiments (detailed in following section) indicate that there is a need to develop new methods for directly measuring interstory drift.

3. MEASURING INTERSTORY DRIFT

Two current methods for obtaining full-scale interstory displacements include double integration of measured acceleration on consecutive floors and from measuring the lengthening/shorting of a diagonal bay-spanning wire, Figure 2. This section illustrates some of the issues associated with these methods utilizing data from forced vibration testing of the Four Seasons Building (FSB) by the nees@UCLA equipment site, (Yu 2008). A brief literature review presents several alternative methods followed by preliminary results of ongoing efforts.

The first approach, herein referred to as acceleration-based (acc-based), involves double integration, typically via a numerical cumulative trapezoidal rule, of measured acceleration on two consecutive floors. Real data records are often plagued with small transient baseline offsets which translate into large unrealistic drifts in displacement histories (Iwan 1985, Worden 1990, Smyth 2000, Boore 2003). Although no clear consensus exists on optimal signal processing techniques, most researchers employ a high-pass digital filter (e.g., Butterworth). Exacerbating the problem, member yielding impacts (limits) floor acceleration and the ensuing inelastic deformations (i.e., baseline shifts in displacement) are lost during necessary high-pass filtering. Finally, current instrumentation schemes include accelerometers at relatively few floor levels. Sparse instrumentation requires the use of interpolation to determine accelerations at floors without instrumentation, producing inaccurate results for any given story. The second approach, herein referred to as displacement-based (disp-based), employs a displacement sensor, typically a Linear Variable Differential Transducer (LVDT) with a wire diagonally strung across a bay as in Figure 2. Assuming rigid center-line motions, which is reasonable if the wire is free to rotate, then Eqn. 3.1 can be used to estimate drift directly from measurements of shortening/lengthening (*ΔD)* of the original diagonal wire of length *D*;

$$\delta = \left(\Delta D \cdot D\right) / \left(h \cdot L\right) \qquad (3.1)$$

where *L* refers to the bay length and *h* is the floor-floor height. This approach works reasonably well in laboratory set-ups at moderate scales, where results can be verified with external reference displacements. However, it is less effective for actual buildings where the wire spans long distances (Yu 2008). In addition, this technique only offers displacement in the plane of the sensor. Finally, this approach is impractical and cumbersome for deployment in buildings with occupants and typically numerous partition walls.

During the summer months of 2004, the nees@UCLA research team performed extensive forced vibration studies on a four-story RC building damaged in the 1994 Northridge earthquake. Among hundreds of sensors, several accelerometers and LVDTs were deployed to monitor floor accelerations and interstory displacements,

Figure 3. Two eccentric mass shakers (each with a harmonic force capacity of 100kips) were mounted on the roof. Three forced vibrations tests were performed with the shaker mass oriented to induce EW, NS, and torsional vibrations. Four tri-axial accelerometers were fixed, typically at slab corners, to floor slabs. Finally, the top two stories were instrumented with three LVDT setups for measuring interstory drift. Readers interested in learning more about the overall FSB experiment, including experimental testing procedures, results and analyses, are referred to Yu et al (2008).

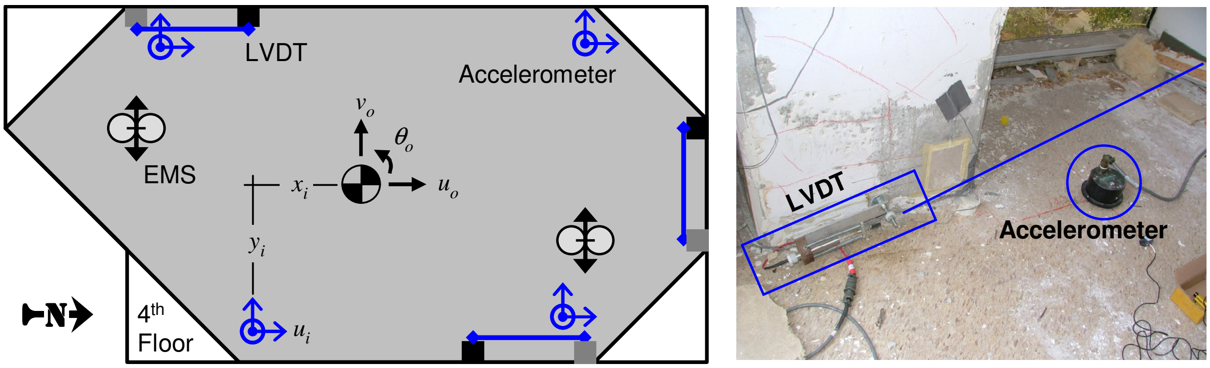

Figure 3. Four Seasons building deployment

Digitized (dynamical) data often contain inherent and unavoidable offsets which are nominally constant (sometimes linear) but easily removed with simple post-processing tools. Such is the case for most FSB acceleration data; however, the LVDT data were plagued with seemingly random piecewise-constant offsets, Figure 4a. One possible explanation could be small temporary mechanical slips somewhere within the sensing apparatus. For example, a small rotation of the entire set-up might produce a significant superfluous shortening/lengthening of the wire. Removal of these dynamic baseline shifts presents an interesting problem. One possible solution to these offsets could involve fitting (and subtracting) staircase functions using a moving average scheme. This procedure, however, does not lend to automation. Arbitrary responses, such as those induced during ground motions, make it difficult to distinguish reasonable data from offsets. Luckily, this effect is obscured during large (in this case sinusoidal) responses such as those induced between in the 3rd and 4th stories during EMS shaking. Hence a simple one-time mean removal in the window of interest (e.g., one forcing-frequency step) is sufficient. Another issue with the LVDT set-up stems from the long distance (some 30ft [9.1m]) that the spring-tensioned wire is required to span. Despite the use of heavy springs, thin piano wire, and industrial strength glue, it was impossible to completely eliminate wire slack and dynamic interaction. Presumably, any slack in the wire causes a delay and/or clipping of the peak values. This effect was indeed observed and is displayed in Figure 4b. Again, this effect becomes increasingly negligible with larger amplitudes. Figure 4c displays local drift envelopes from both disp- and acc-based methods. Data reported are from sensors located in the southwest corner during NS shaking. Note that only peak response amplitudes are reported here, investigation into phase errors and filter delays are ongoing. Thus, despite the aforementioned mechanical issues, it appears that for localized drift, both methods produce comparable responses.

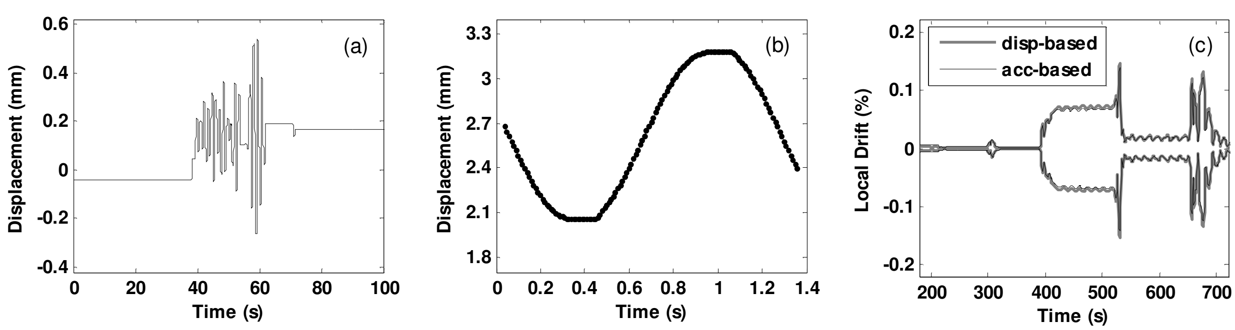

Figure 4. Random baseline shifts (a) and peak capping (b) in LVDT data, and example local drift (c)

Assuming rigid diaphragms, a minimum of three translational components (one orthogonal and two non-coincident parallel) are required to derive three independent planar story motions; EW, NS and rotation at the given reference node (u_o v_o & θ_o in Figure 3). The FSB deployment included 3 channels of displacement (two NS and one EW) and 8 channels of acceleration (four NS and four EW denoted by u_i and v_i respectively). The relationship between the local motion measured with at the i^{th} sensor and the story motions at the reference node is expressed in Eqn. 3.2.

$$u_i = u_0 - y_i\theta_0 \qquad v_i = v_0 + x_i\theta_0 \tag{3.2}$$

where x_i and y_i are the coordinates of the i^{th} sensor. Utilizing more than three channels, as is the case for FSB acceleration data, results in an over-determined system of equations, and a linear least squares approach is used to solve for the three unknown reference motions, or equivalently the inverse of Eqn. 3.2. Ideally, any combination of three appropriate channels should lead to nearly identical results. Realistically, reference motions tend to be quite sensitive to several sources of error such as channel noise, sensor misalignment, and synchronization errors. To make things worse, some of these issues are not perceivable by visual inspection of the data alone. In order to evaluate individual channel quality, local measurements are compared to expected signals derived from story motions using Eqn. 3.2 and corresponding sensor coordinates. Discrepancies are quantified with the relative root mean square (RMS) error value as in Eqn. 3.3;

$$RMS = \left\| u_0 - y_i\theta_0 - u_i \right\|_2 / \left\| u_i \right\|_2 \tag{3.3}$$

and shown in Figure 5a for the 3rd floor during NS, EW, and torsional shaking; represented by the left, middle and right vertical bars for each channel. The disproportionate error in channel u_3 is unmistakable (gray bars), whereas once removed from calculations (black bars), no discernable outliers are evident. Also, there is a substantial reduction in RMS error for the remaining channels once u_3 is removed from story motion calculations. For example, from Figure 5a the relative RMS error of about 0.2 for channel u_2 drops below 0.04 when story motions are computed without channel u_3. This dramatic improvement, and its consistency over the remaining channels, provides further evidence that distortion due solely to the allegedly *faulty* channel u_3 is indeed significant. Again, it is worth emphasizing that this distortion is not obvious when viewing channel data or even the derived story motions. It is peculiar that a single component of a tri-axial accelerometer would be *faulty* while the other component (v_3 in this case) is not, but this was observed in several cases with no discernable pattern even during shaking with comparable response amplitudes in both EW and NS directions. This procedure was repeated for the remaining floors, detailed results are available in Skolnik (2008).

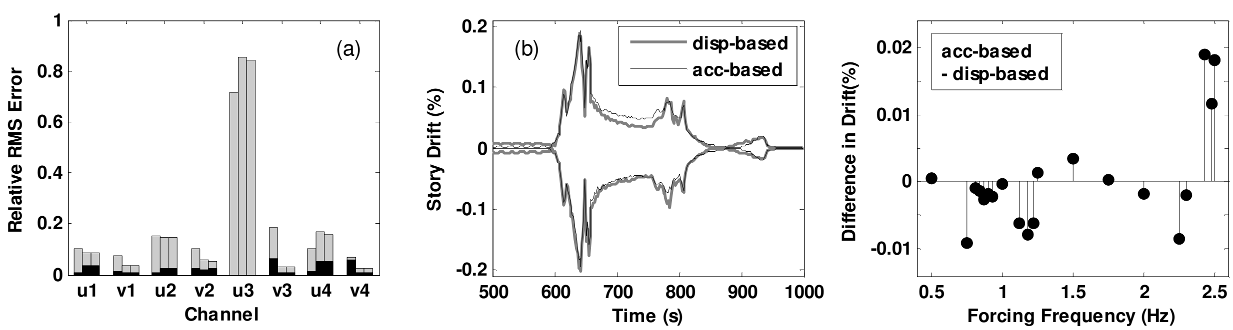

Figure 5. Relative RMS error between local measured acceleration and expected signals from story motions derived from all available channels with and without u_3 (a) and example story drifts (b) for current methods and absolute error (c)

Current methods exhibit slightly more discrepancy when comparing reference drifts as illustrated in Figure 5b for the EW direction (v_0) during torsional shaking. A likely cause is channel noise (from errors such as phase lag, channel-channel synchronization, etc.) accumulating when deriving story motions. Although not readily apparent here, evidentiary data for a bias was observed. To further investigate, the absolute error or difference (acc-based minus disp-based) in drift amplitude for several forcing frequency steps is shown figure 5c. Data reported are from NS story motions during NS shaking and EW story motions during EW and torsional shaking. There does appear to be some bias in the error; disp-based amplitudes tend to be larger than acc-based at lower forcing frequencies (less than 1.5Hz), but no clear trend is observed for higher forcing frequencies. However, this is only true over a rather small domain; zero to 0.2% drift. Unfortunately, data for larger drifts are currently not available. The error bias is not surprising since, due to the nature of EMS testing, lower forcing frequencies are synonymous with lower amplitudes from which problems associated with LVDT data are more prominent. In the end, it is difficult to say which method is more or less erroneous since we have no other means of estimating drift; a four story reference frame alongside the building was not practical.

3.2. Alternative Methods

Given the drawbacks associated with current approaches, several researchers have proposed alternative methods. This section provides a comprehensive review several innovative past efforts followed by preliminary results of ongoing work.

Current GPS technology can sample at 20Hz within a translational accuracy of ±1cm. Celebi (2002) proposes the use of GPS technology to monitor roof displacements in real-time of tall buildings or other long-period structures. Despite limited deployment capabilities – i.e., only available for roof installations – this system offers several advantages. One immediately obvious advantage is in the ease and unobtrusiveness of deployment. GPS sensors could also be used to verify displacements obtained by nearby accelerometers. Certainly, a near-real time map of roof drifts in a similar form to ShakeMaps (successfully implemented by the USGS Earthquake Hazard Program) would nicely compliment post-event assessment strategies such as the SHM system described earlier. Following the lead from motion-tracking technology emerging from Hollywood studios, Wahbeh (2003) employed high-fidelity video cameras to track LED targets. The system deployed on the Vincent Thomas Bridge was able to track displacements over 450m down the length of the span. The bridge was already instrumented with several accelerometers (by CSMIP) which provided the researchers with comparable displacements via double integration and high-pass filtering. Issues such as flexible/rigid camera mounts susceptible to low/high frequency motion plagued the test. Yet a third approach that has generated a lot of interest is embedding strain-sensitive fibers into concrete elements. Typical examples employ optical interferometers (Ansari 2007 and Casas 2003) and time domain reflectometry using coaxial cables (Su 1998). Indeed many instrumented bridges and other structures are currently being monitored with fiber optics, and have been for 10 or more years. Unfortunately, there appears to be a void in the literature when it comes to successful application inside buildings with the intention of measuring interstory drifts. Additionally, monitoring systems that depend on embedded cables (e.g., inside concrete walls) suffer from shortcomings associated with temperature gradients and debonding, not to mention installation and maintenance. Bennett (1997) published work on bench top studies where displacements and rotations were measured with a cross-hair laser and four 1D position sensitive photodiodes (PSD). Chen and Bennett (1998) advanced the system capabilities to include chord drift, generally caused by non-uniform distribution of axial deformation among columns. This was achieved by cleverly mounting the PSDs on two different vertical levels. Unfortunately, PSD technology remains fruitful within rather small-scale applications, and hence; only relatively small PSD are produced. For example, the displacement range of the system developed by Chen and Bennett was limited to ±15mm.

Building upon the pioneering work of Bennett and Chen, a novel system for non-contact measurement of interstory displacements using an adjustable dot laser and a 2D PSD is currently being developed. Because current photodiode technology has relatively small sensing area, a plano-convex lens is used to increase measuring range (from ±5mm to ±50mm). Two stages of development are shown in Figure 6. Phase I is based on simply mounting the laser to the floor/ceiling pointed up/down at a unit comprising of the lens and PSD attached to the ceiling/floor. This setup has the advantage of measuring story displacements in both lateral directions and can be easily hidden and protected within partition walls. Bench top studies of this set-up proved promising, with a high degree of linearity in both dimensions, Figure 6. However, two shortcomings are clearly evident. First, the use of laser and optics require high precision fabrication, not typically available in civil engineering laboratory environments. Employing multiple linear and rotational gages partially alleviates alignment issues by providing redundant degrees of freedom. However, high precision machining (and thus quite expensive) are ultimately required for prototype development; the next step following successful proof-of-concept testing. The second difficulty is in distinguishing translational displacements from rotations, as shown in Figure 6. Bench-top and even laboratory-scale studies may not capture the seriousness of this problem. For example, a rotation of 1 degree (relative, with respect to upper and lower joints) over a column height of 3m produces a displacement over 50mm at the sensor unit. A possible solution involves the use of a retrorflector (aka corner cube) which reflects light waves parallel to, but in the opposite direction from the incoming source. Corner cubes have three orthogonal surfaces allowing for the setup to retain 2D utility. For illustrative purposes, it is easier to draw (and imagine) the 1D case which has only two flat surfaces, or equivalently two perpendicular mirrors. Figure 6 shows the phase II setup at a small arbitrary displacement with and without rotation. If the sensing unit rotates with respect to the mirrors (or vice versa), the skewed laser will still be perpendicular to the lens. Theoretically, only the angle of travel between the mirrors is altered. Note that the laser is now included in the sensing unit, a fortuitous benefit. Unfortunately, the range of the entire setup is now reduced by half, given appropriate sized mirrors. Bench top studies of the phase II setup are currently underway. Initially, it still appears rather sensitive to rotation, even at small distances. It is believed that small misalignments are the culprit and hence, expensive fabrication might be required earlier than originally thought.

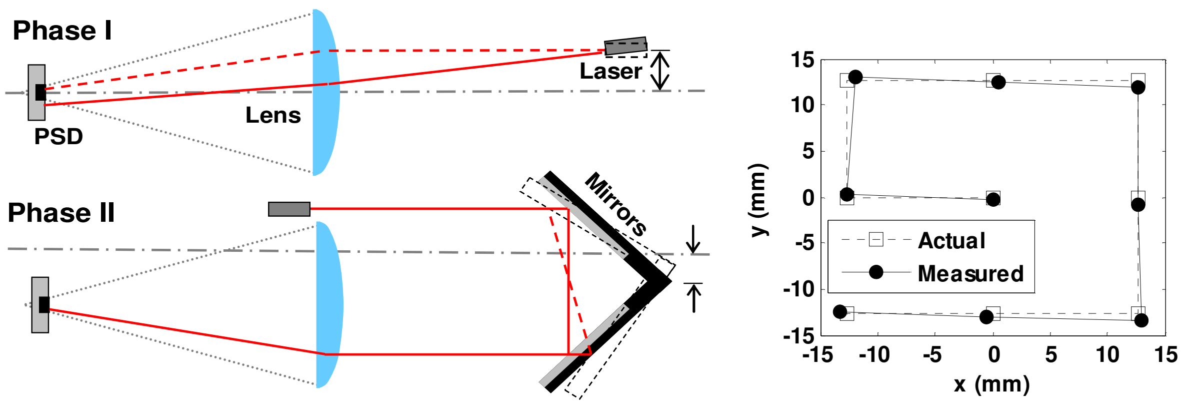

Figure 6. Phase I & II set-up of prototype non-contact sensor and preliminary (phase I) actual versus measured data

4. ONGOING AND FUTURE WORK

Continuing bench-top studies of multiple sensor configurations are underway. A small scale structure instrumented with current and alternative methods for measuring drift is also being investigated with shake table tests. Although the FSB experiment offered full-scale data, shake table testing gives the ability to input ground motions and record absolute measurements via an external reference frame. Preliminary results show disp-based drifts closely match those recorded with reference displacement sensors, while the acc-based drifts displayed poorer performance. Further testing will hopefully shed light on the circumstances leading to poorer performance. After thorough investigations into the two current methods for measuring drift, the laboratory structure will be instrumented with novel sensors including the aforementioned laser/2D-PSD prototype. Results from these tests will then be extrapolated to provide recommendations for full-scale deployments.

As an aside, shortcomings in current data acquisition and wireless networking have lead to substantial research in developing new technologies. A toolbox for wireless data acquisition is concurrently under development based on a low-power LEAP2 platform (McIntire 2006) with integrated 24bit ADC (in conjunction with Reftek, Inc.), field-tested software/hardware for robust wireless network access (Lukac 2006), and reliable RBS time synchronization (typically GPS is not readily available inside buildings). Prototype boxes (expected delivery in 08/2008) will also undergo bench top and shake-table testing, with the modest scale structure. Side-by-side comparisons these novel systems with robust wired equipment (e.g., nees@UCLA) will provide confidence in full-scale deployments; the next step.

In summary, the tall building surge as well as an updated instrumentation program provides a unique test-bed to intelligently deploy instrumentation, together with performance-based assessment tools, enabling a robust network for SHM. A key component of the proposed SHM system is the ability to accurately measure interstory drift. Current methods are investigated with data from a full-scale test, and in the future, with novel methods, in laboratory shake table studies.

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