Title

A Laser-Based Optical Sensor for Broad-Band Measurements of Building Earthquake Drift

Journal

Earthquake Spectra, 33(4)

ISSN

8755-2930

Authors

McCallen, David
Petrone, Floriana
Coates, Jason
et al.

Publication Date

2017-11-01

DOI

10.1193/041417eqs071m

Peer reviewed

A Laser-Based Optical Sensor for Broad-Band Measurements of Building Earthquake Drift

David McCallen,[a] Floriana Petrone,[b] Jason Coates,[c] and Nicholas Repanich[c]

[a] Lawrence Berkeley National Laboratory and University of California Office of the President, 1111 Broadway, Oakland CA, 94720 [b] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley CA, 94607 [c] Mechatronics Center, California State University, Chico, 400 West First Street, Chico, CA, 95929

Abstract

Accurate measurements of the time-dependent deformations of a building during earthquake excitation are essential for interpretation of the dynamic response of the as-built system and for quantifying the seismic demands. Traditional approaches for monitoring building systems are based on strong motion accelerometers mounted at selected elevations. However, accelerometer-based systems do not directly measure the deformations of the structure, and can have significant limitations that make it challenging to correctly measure deformations, particularly permanent deformations from inelastic response. In the study described herein, computational simulations and experiments were combined to evaluate the potential of a new optically based sensor to directly measure time-dependent deformations of a building, including inelastic deformations. The sensor methodology includes corrections for localized structural member rotations and can provide estimates of the absolute accelerations at each floor. A laser-based system utilizing a recently developed discrete diode position sensor (DDPS) is evaluated, and the ability of such a system to measure earthquake induced transient deformations characterized by building interstory drift is demonstrated.

INTRODUCTION

The spatially and temporally dependent deformation of a vibrating building or industrial facility can be characterized in terms of the interstory drift, which quantifies the relative building displacement between adjacent floor levels. For earthquake excitation, interstory drift has been widely adopted as a key parameter characterizing the demand on building systems and is used to quantify system demands and limit states (typically inelastic limits) in a number of seismic design codes and standards. For example, the U.S. Department of Energy (DOE) standard for DOE facilities (DOE-STD-1020-212, 2012) and the American Society of Civil Engineers standard for nuclear facilities (ASCE/SEI 43-05) have established interstory drift limits that quantify facility performance with drift-defined limit states as indicated in Table 1. Other examples of codes and guidelines that adopt maximum and residual interstory drift as structural performance parameters are ASCE-7-10, NZS-1170-04, EC-8-04 as well as PEER TBI-17 and LATBSDC-17.

Table 1. Example limit states for nuclear facilities defined in terms of maximum drift (excerpt from ASCE 43-05)

Structural system	Limit State A (Large permanent distortion)	Limit State B (Moderate permanent distortion)	Limit State C (Limited permanent distortion)	Limit State D (Essentially elastic behavior)
Concrete moment frame	0.025	0.015	0.010	0.005
Steel moment frame	0.035	0.025	0.010	0.005

Within the context of traditional strong motion accelerometer instrumentation, inters-tory drift is computed by double integration of acceleration time histories to obtain floor absolute displacements, with subsequent differencing of the displacements from adjacent floors to obtain the relative displacement associated with interstory drift. The quantitative determination of interstory drift through this approach requires significant data processing and is subject to a number of technical challenges, as described in the paper by Skolnik and Wallace (2010). Issues identified include the “delicate and sometimes subjective” signal processing steps for baseline correction, bandpass filtering, padding signal ends, and the frequency bandwidth limitations of a particular accelerometer. As noted by the authors, optimal filtering can be record-dependent and high-pass filtering applied to remove displacement record drifts can impact the ability to measure permanent displacements of the building system.

Trifunac and Todorovska (2001) and Trifunic et al. (2001) have also identified issues associated with determining permanent displacements of the ground and permanent displacements in structures with accelerometer-based systems. The authors conclude that the dynamic rotations of the accelerometer instrument, which in practice are not typically measured or known, are necessary if there is any intent to accurately and reliably compute displacements from acceleration records.

In addition to the identified technical challenges, there are often practical limitations to building instrumentation systems. Typical building accelerometer-based instrumentation, whose design is in many cases cost constrained, tends to be very sparse with accelerometers on relatively few floors. This necessitates some form of interpolation scheme to provide an estimation of story drift at all elevations. The accuracy of such interpolation schemes has not been thoroughly evaluated for a wide range of building types and earthquake ground motions, particularly when localized floor inelastic behavior occurs. Ideally, it would be desirable to achieve an instrumentation cost function that allows instrumentation at every floor.

For owners and operators of mission critical facilities, who after a major earthquake can be faced with time-critical decisions related to structure occupancy, continuity of operations, or the potential for release of hazardous materials, there is motivation for enhanced instrumentation to support decision making. For structural systems where limit states are defined in terms of drift, it would be very advantageous to have reliable drift measurements immediately after an earthquake event to compare to known limit states.

A promising alternative approach to measuring interstory drift, which has received some attention in the past few years, utilizes optically based techniques to directly estimate story relative displacement. In one optically based approach, interstory drift can be measured by projecting an intense, coherent light source across a story height and sensing the position of incidence on a light-sensitive detector on the adjacent floor to measure structural deformation, as indicated in Figure 1.

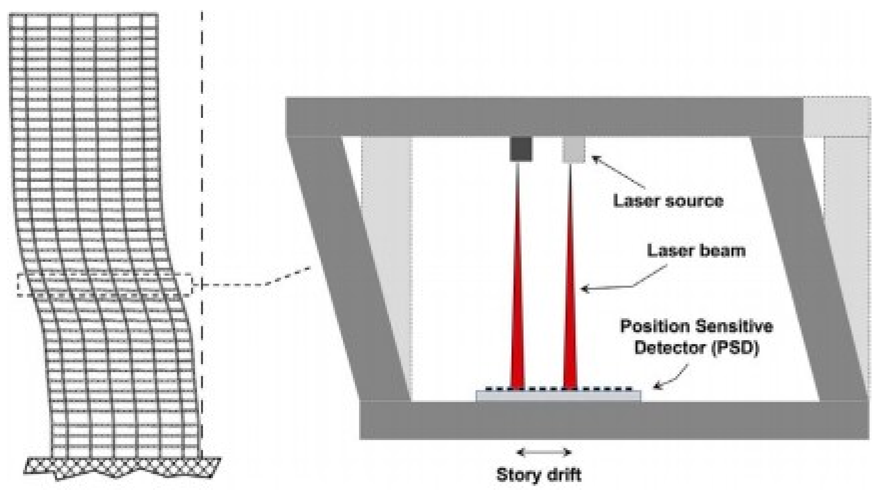

Figure 1. Optical measurement of interstory drift using a laser and position sensitive detector (PSD).

Commercially available position sensors based on optical (light) phenomenon, known broadly as position sensitive detectors (PSD), have seen significant use in recent years in many optical research facilities and industrial applications. An important class of PSD sensors are based on a photoelectric effect, whereby a laser beam incident on the semiconductor material of the PSD results in electron flow that is measured on electrodes at the PSD boundaries as described by Andersson (2008). By measuring resulting currents, and considering their proportionality to resistance and thus to path length in the substrate materials, the location of the incident laser beam can be very precisely determined. This type of PSD has been used extensively in many industrial and research applications for the measurement of small amplitude displacements and vibrations. For example, the utilization of a PSD to determine the vibrational stability of a major research facility consisting of a large structure and massive optical bench at the U.S. Department of Energy's National Ignition Facility is described by Zacharias et al. (2004). In such applications, commercially available PSDs are utilized to precisely determine the point at which the incident laser beam strikes a PSD surface during small amplitude vibrations.

A PSD sensor provides a very effective means for measuring any relative motion between an incident laser beam and the PSD sensor, and the extremely short time latency of the underlying physics allows for a very broad frequency bandwidth of dynamic vibration measurement. Such a system is also very well suited to measuring permanent relative displacement.

A number of early research studies have investigated the potential application of lasers and optical sensors for measuring dynamic building response. Chen et al. (1998) and Yun et al. (1999) performed early investigations into utilizing lasers and PSDs for measuring the dynamic response of building systems. Skolnik et al. (2008) and Slolnik and Wallace (2010) performed comprehensive studies of the measurement of interstory drift, which pointed out some of the remaining technical challenges for implementation of optical systems, including the fact that commercially available PSDs are dimensionally too small to allow measurement of earthquake induced interstory drift. Each of these studies have also highlighted the fact that in a building system, structural rotations associated with local deformations of structural elements, e.g., horizontal beams and other laser mounting locations, can have a significant impact on the laser propagation and must be appropriately accounted for in any drift determination.

Islam et al. (2016) recently explored an alternative approach to optically based measurement of interstory drift, which relies on a sensor to compute the change in distance between the laser source and the receiving sensor, which is then geometrically translated into lateral drift. However, their study does not address local rotations of the laser source, which can be a significant issue.

The work described herein focuses on a new type of PSD that has been developed specifically for building monitoring applications. This sensor, termed a discrete diode position sensor (DDPS), makes use of a rectangular array of inexpensive discrete light sensitive diodes to measure the incident laser location. This sensor can accommodate the large displacements associated with interstory drift, and can readily measure permanent displacements resulting from inelastic system behavior. Additionally, a methodology for addressing local rotation of the laser source has been developed. This type of measurement system has the potential for appropriately measuring, and reporting immediately after an earthquake, dynamic and permanent inelastic interstory drifts. This data can provide building response observables that can be directly compared with established structure limit states in existing codes and standards (e.g., Table 1), to inform rapid post-earthquake actions and decisions for mission critical facilities.

In the remaining body of this article, the design of the new DDPS is described and the sensor performance is evaluated through experimental data from two testbeds constructed specifically for sensor evaluations. Computational simulations are employed to define representative building inelastic interstory drifts, which are adopted as testbed target motions to evaluate sensor performance. A computational model is also used to simulate the deployed sensor system and provide full insight into sensor system performance, as well as to lay the foundation for a validated, predictive sensor system simulation tool that can be used to design sensor systems on real and more complicated structural systems.

A DISCRETE DIODE POSITION SENSOR

A DDPS has been designed with a two-dimensional (2-D) array of light sensitive photodiodes, as shown in Figure 2. Each individual diode has an output consisting of an analog voltage proportional to the amount of laser light impinging on the diode. In this application, each diode is essentially being utilized as an “on” (laser hitting the diode) – “off” (laser not hitting the diode) switch. The sensor design employs a simple op-amp comparator circuit, which compares each diode voltage to a user defined voltage threshold to determine which diodes are detecting incident laser light (i.e., “on”) at any instant of time, as indicated in Figure 3. A bank of comparators indicates which diodes are activated and a Field Programmable Gate Array (FPGA) latches the output values of the entire circuit of n diodes simultaneously to develop a map of “on” and “off” diodes, thus determining the spatial location of the incident laser beam at each instant of time as the building deforms.

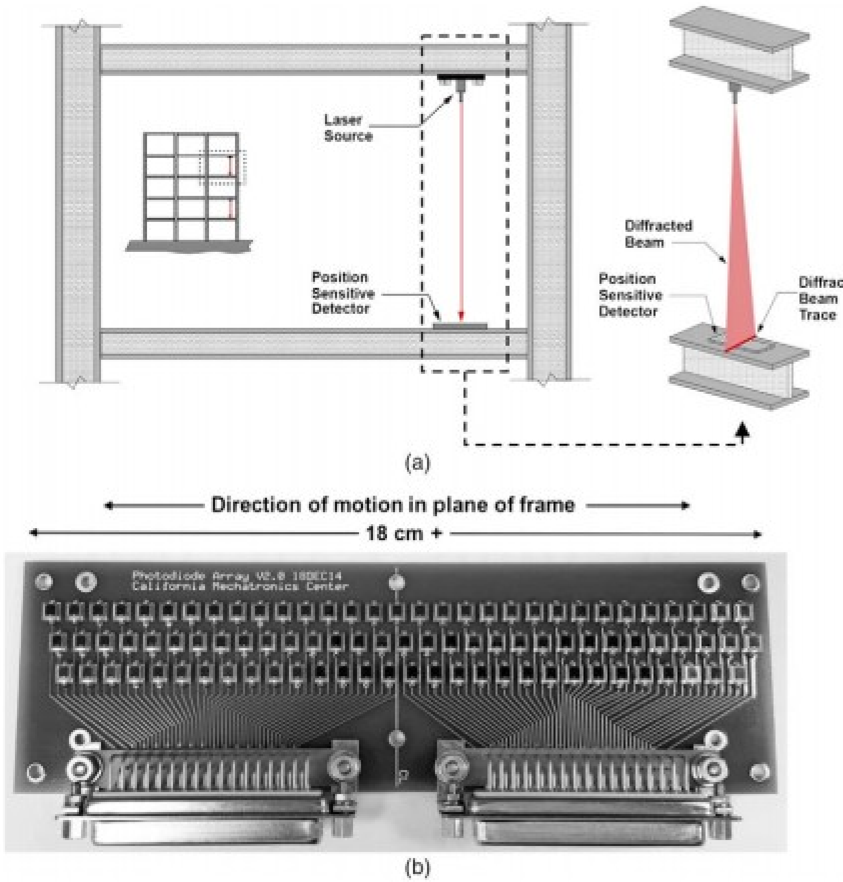

Figure 2. A discrete diode position sensor (DDPS). a) Mounting configuration in a structural frame; b) Prototype staggered 92 diode DDPS sensor array.

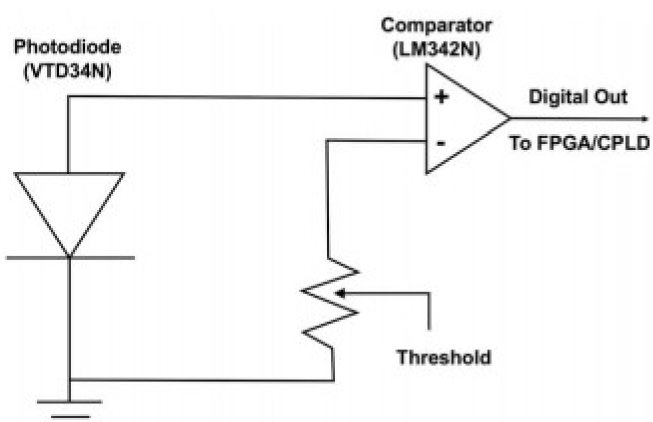

Figure 3. Photodiode conversion circuit to establish "on" and "off" status of sensor diodes.

The prototype DDPS which has been developed utilizes 92 diodes arranged in a staggered rectangular array, as shown in Figure 2b. Each DDPS is intended to measure drift in the plane of the corresponding structural frame, and the incident laser beam is passed through a diffraction optic to create a linear laser trace on the sensor, see Figure 2a. The line trace is generated with sufficient width orthogonal to the frame so that under three-dimensional (3-D) earthquake motions, the laser trace does not translate off the diode grid of the DDPS as a result of out-of-plane deformations, i.e., orthogonal to the plane of the frame being measured. The staggered grid of discrete diodes is configured such that the laser beam is always incident on one or more diodes and the position of the laser trace is established at all times. In practical application, 3-D structural response under bi-axial earthquake motions could be measured either by implementing a square array of diodes, with two orthogonal line laser beams, which measure motion in orthogonal directions simultaneously, or by placing DDPSs orthogonal to each other.

To ensure that the moving laser beam is precisely tracked on the sensor face and full dynamic waveforms of interstory drift are measured, a high sampling rate is employed. For the prototype sensor designed and utilized in this study, a sampling rate of 384 times per second was used, whereby the entire array of diodes was simultaneously sampled 384 times per second to assess "on" and "off" status of the entire array, corresponding to a Nyquist frequency of 192 Hz. Interstory drift response history data from the DDPS is stored in a micro-processing unit for immediate display and data exfiltration.

A detail of the staggered diode array configuration used for the prototype sensor adopted in this study is shown in Figure 4, where examples of laser position are shown at three instants of time. To increase the position localization accuracy, the three linear arrays of diodes are staggered so that the active areas of the diodes overlap by $D/3$, where D is the nominal width of the active area of the diode. As the laser trace moves back and forth with in-plane motion of the building frame, the position of the laser is theoretically determined to within $D/6$ of the diode active area width. The readout of the sensor is a quantized set of displacements that increment by $D/3$, as indicated graphically in Figure 4.

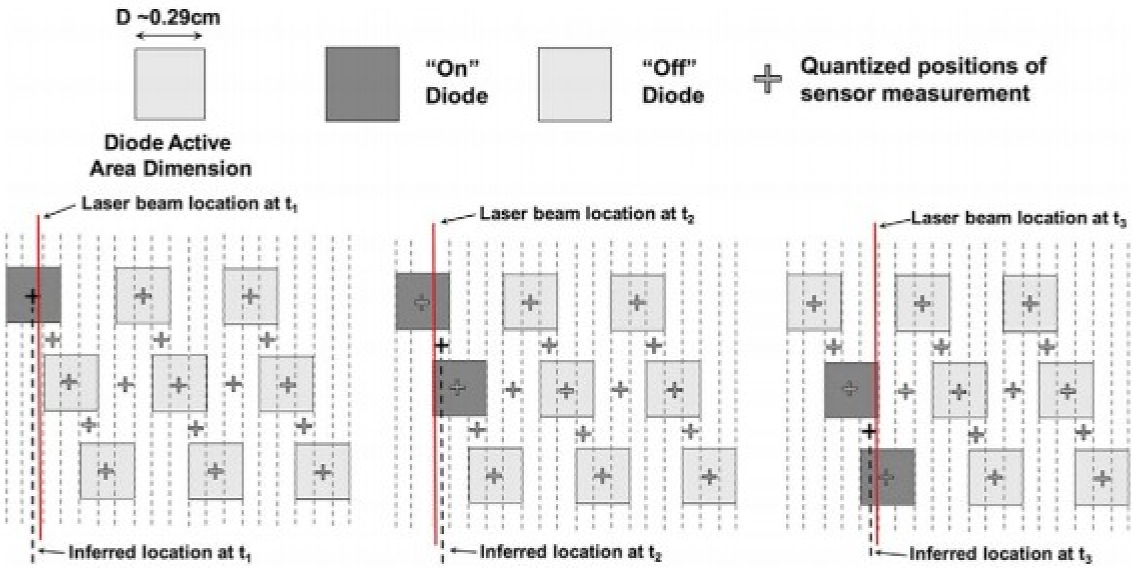

Figure 4. Sensor diode array and inferred displacement at three instants of time.

For the commercial diodes employed in this study, the width of the active area of each diode is approximately *D* = 0.29 cm, which would yield a theoretical sensor position measurement error of approximately 0.05 cm. However, in practice carefully controlled and measured static sweeps of a laser line over the DDPS indicated that the realized position error was closer to 0.10 cm due to slight positioning errors of the individual diodes, effective diode areas affected by some dimensional variability, and the fact that the diffracted laser trace had a finite dimension and was not a perfect infinitesimal line as assumed in the ideal *D*/6 error. As illustrated in the sensor transient measurement data presented below, the sensor position error of 0.10 cm proved to be a good estimate for DDPS position measurement error.

The diode layout described here is not unique and other configurations are possible depending on the objective of the drift measurements. For the work described herein, the goal was to measure full drift response history waveforms as accurately as possible, but a far more sparse array of diodes could be employed if the principal objective was to measure the maximum interstory drift and determine if specific drift limits were exceeded.

DDPS MEASUREMENT OF INTERSTORY DRIFTS

To evaluate the performance of the DDPS, two dedicated experimental testbeds were designed and constructed. The first testbed, hereafter indicated as Testbed #1, consisted of an automatically controlled precision motion table that was designed to generate realistic interstory drift motions, including permanent drifts representative of inelastic structural response. This testbed was utilized to evaluate the ability of the DDPS to accurately measure dynamic interstory drift time histories across a range of drift amplitudes and with a range of dynamic frequency content. The second testbed, Testbed #2, which consisted of a laboratory scale two-story metal frame structure, was utilized to assess the ability of the sensor to correctly measure interstory drifts in an actual structure subjected to earthquake motions, including the complicating features of local structural member rotations.

The automatically controlled motion table, Testbed #1 shown in Figure 5, was used to generate representative interstory drift motions for sensor evaluations. The table employs a closed-loop control system with a digital motion controller providing commands to a linear stepping motor to precisely produce a target displacement response history on the top of the motion table. A magnetic linear encoder is employed in the table to measure the position of the motion table platen. Through careful verification, the table was demonstrated capable of replicating target earthquake displacement time histories within a maximum displacement error of 0.008 cm.

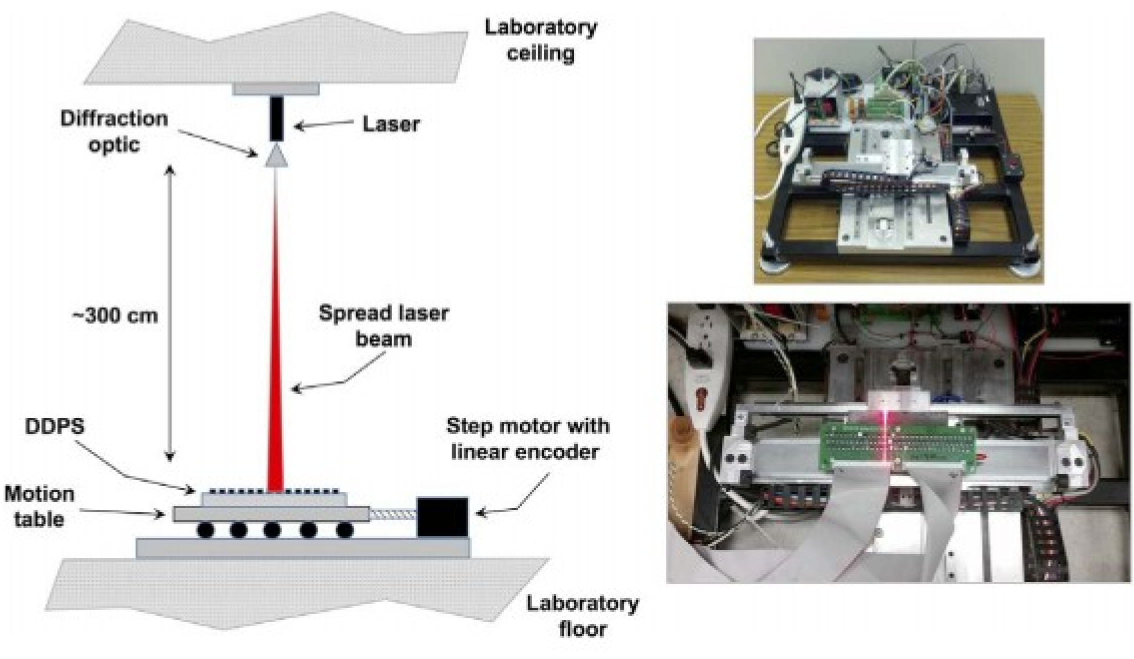

Figure 5. Sensor Testbed #1 - an automatically controlled motion table for imposing target interstory drift time histories in the laboratory.

To provide realistic synthetic interstory drifts for evaluating sensor performance, including the effects of inelastic action, detailed nonlinear finite element models of steel moment frame buildings were employed. NEVADA (McCallen and Larsen 2001), a finite deformation, inelastic finite element program for the nonlinear analysis of frame structures was used to develop interstory drift time histories for representative steel building structures subjected to actual measured strong near-field ground motions. The NEVADA models consisted of a co-rotational, finite displacement fiber beam element with steel inelasticity represented through a classical elasto-plastic material with kinematic hardening. The NEVADA nonlinear models have been extensively verified through comparison with other finite element code implementations by McCallen and Larsen (2001), Petrone et al. (2016) and Wong et al. (2016). The details of the NEVADA code formulation and the representative steel building designs are summarized in McCallen and Larsen (2001).

To exercise the DDPS and evaluate sensor performance, synthetic interstory drift time histories were generated for a number of multi-story steel frame buildings. The results from a 40-story and a 3-story steel moment frame buildings are described here. The 40-story frame was subjected to the measured near-field ground motion from the 1992 Landers California Earthquake Lucerne Station, component LUCEW with instrument correction for long period waveforms as described by Chen (1995). This Landers motion results in significant inelastic response occurring at approximately one-third of the height of the building. The resulting interstory drift response history at the ninth story is shown in Figure 6a, which exhibits significant permanent drift as a result of the strong near-field pulse. Similarly, a nonlinear model of a representative three-story steel building was subjected to a measured near-field ground motion from the 1999, Kocaeli (Izmit) Turkey Earthquake Yarimca Station, component YPTEW (Strong-motion Virtual Data Center). For this earthquake ground motion, the three-story building also exhibits inelastic response as shown in Figure 6b, with the maximum permanent drift recorded at the first floor. These two drift response history records span a range of drift amplitude and frequency content, and provide representative drift motions for assessing DDPS performance and accuracy.

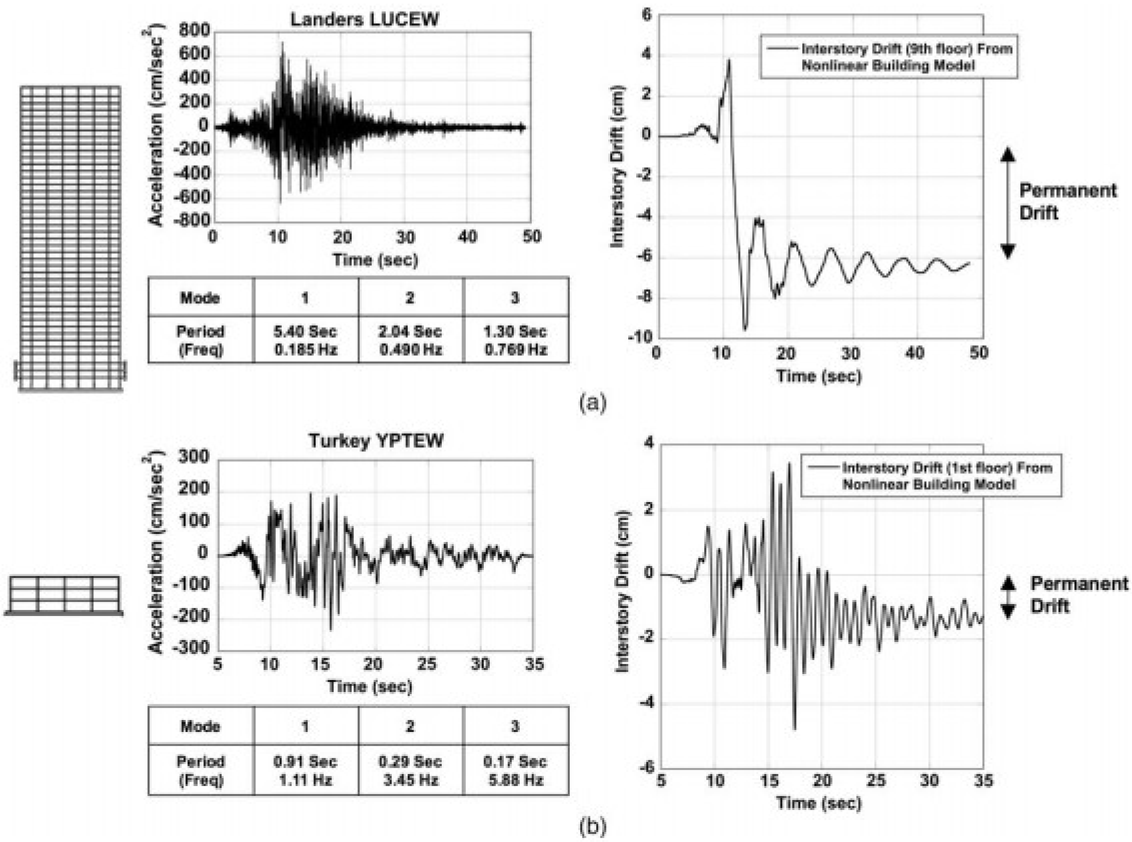

Figure 6. Representative synthetic interstory drifts from detailed nonlinear building Finite Element Models. (a) Forty-story steel frame subjected to Landers ground motion (Chen 1995); (b) three-story steel frame subjected to Turkey ground motion (VDC).

The synthetic drift response history waveforms were precisely replicated by the automatic control system on the motion table Testbed #1 and the drift was measured with the DDPS system, as shown in Figure 7. The DDPS measurements of drift were compared to the actual drift imparted by the motion table and Figure 8 provides the comparison between imposed drift and the DDPS measurement of drift for both the flexible low frequency 40-story building and the stiffer, high-frequency three-story building. In both cases, the DDPS exhibited excellent agreement with the imposed drifts and the maximum sensor error was within approximately 0.10 cm. To maintain this error level, it is only necessary to ensure that the laser line source does not become divergent, which could result in an increase of the laser line trace width. For story heights of practical relevance, it was found that the strong coherency of laser light can easily maintain the laser line source dimension and thus the sensor accuracy is essentially invariant with respect to story height.

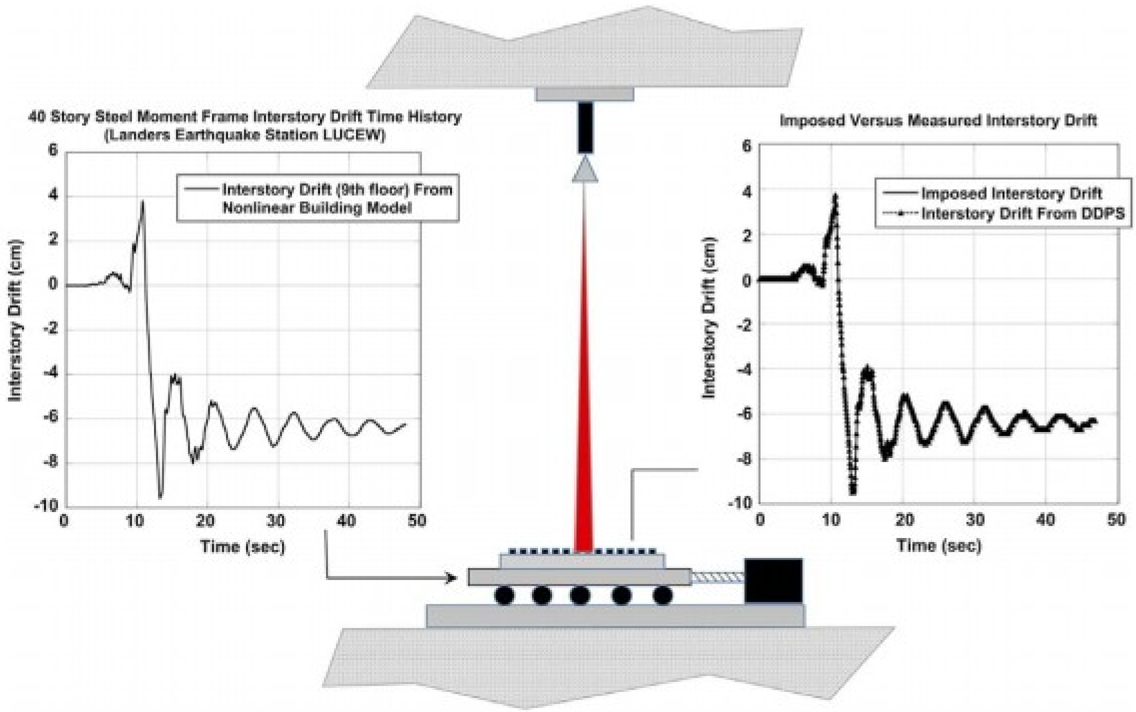

Figure 7. Generation of synthetic interstory drift time histories on the precision motion table; target and replicated interstory drift for a 40-story frame undergoing inelastic deformation.

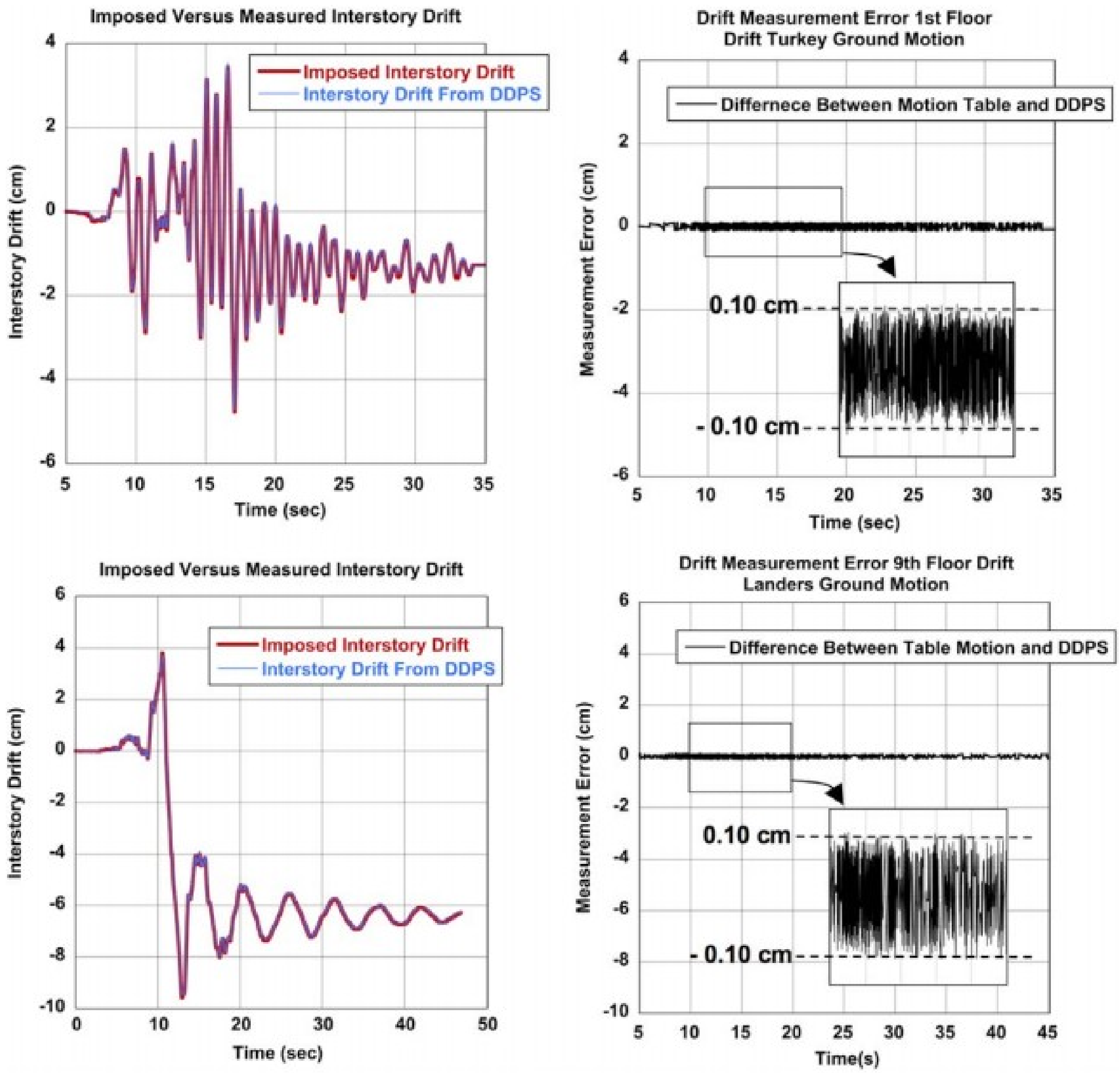

Figure 8. Drift response history comparison between DDPS sensor and imposed (ground truth) drift for 3- and 40-story steel frame buildings subjected to near-field ground motion.

The DDPS demonstrated an ability to measure both the full dynamic drift waveforms as well as the permanent story displacements resulting from inelastic frame response. It is noted that no data post-processing is required, as the laser position is determined and written directly to memory at each sampling instant. The DDPS provides a direct measurement, and immediate logging, of the interstory drift values.

As noted, and identified in previous studies (Skolnik et al. 2008, Skolnik and Wallace 2010, Bennett and Batroney 1997), the local rotation of the structural members at the location at which the laser is mounted can potentially have a significant effect on the observed measurement of interstory drift. The mounted laser can rotate with the local rotation of the individual structural elements to which it is attached, thereby effecting the trajectory of the laser beam propagating across the story height. This is illustrated in Figure 9, where the deformation of a single bay of the 40-story frame during earthquake motion is extracted from the finite element model of the building and shown at exaggerated scale. This demonstrates that the potential for significant local rotation must be addressed in the DDPS measurement of drift.

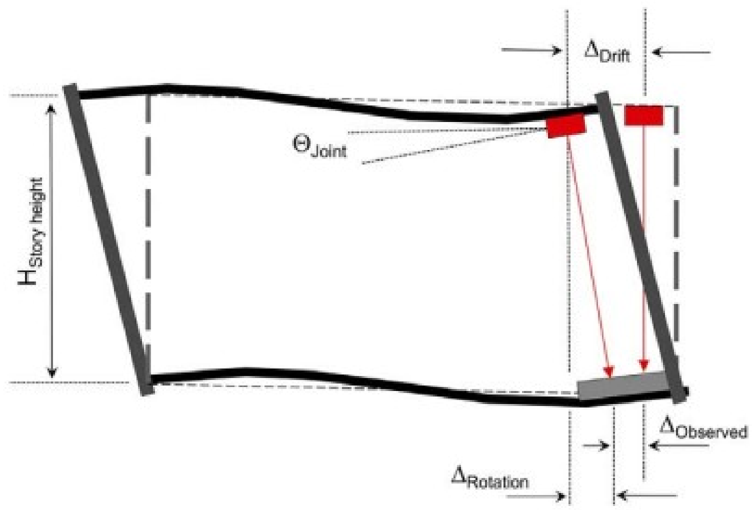

Figure 9. Exaggerated building frame displacement from a finite element model illustrating the local rotation of a laser mounted on a horizontal beam.

If the local rotation at each time step, $\Theta_{Joint}(t)$, is known, the effect of this rotation on the lateral drift can be included in the drift computation. If the drift is denoted $\Delta_{Drift}(t)$, see Figure 9, the drift is given by:

$$\Delta_{Drift}(t) = \Delta_{Observed}(t) + \Delta_{Rotation}(t) \qquad (1)$$

where $\Delta_{Observed}(t)$ is the translation of the laser beam directly measured on the DDPS and $\Delta_{Rotation}(t)$ is the laser translation due to local rotation of the laser. The translation due to local rotation is then calculated as

$$\Delta_{Rotation}(t) = \Theta_{Joint}(t) \cdot H_{StoryHeight} \qquad (2)$$

where $\Theta_{Joint}(t)$ is the rotation at the laser mount location and $H_{StoryHeight}$ is the story height. Equation 2 effectively provides a correction term to the translation measured directly on the DDPS.

The local rotation correction requires the dynamic response history of the rotation at the laser mount location, $\Theta_{Joint}(t)$, which is a challenging quantity to measure in a structure undergoing earthquake excitation. While many technologies and associated MEMS sensors can measure static rotations at a point, imposing earthquake accelerations and dynamic rotations significantly complicates the rotation measurement. Typical static rotation sensors rely on a static gravity field for measurement of rotation and are adversely impacted by time dependent accelerations.

The methodology that was adopted for measuring the rotation response history in this study consisted of utilizing a second DDPS mounted in a vertical plane (for example on a column face) so that rotation of the laser mounting point could be directly determined from the motion of a propagating laser impinging on the vertically mounted diode array, as shown in Figure 10. This approach uses the amplification of the rotation observable by the optical path length across the width of the frame bay. While this requires both vertical and horizontal clear lines of sight, it proved to be a very effective and reliable way of measuring local rotations. Based on an assumption of small displacements and small rotations, the floor rotation can be calculated simply from the laser motion on the vertical sensor, as

$$\Theta_{Joint}(t) = \Delta_{Vertical}(t)/BayWidth \qquad (3)$$

where $\Delta_{Vertical}(t)$ is the vertical translation of the horizontally propagating laser beam as measured on the vertical DDPS sensor. In practical application, a single laser beam source can be split and diffracted in both vertical and horizontal directions for the two sensors.

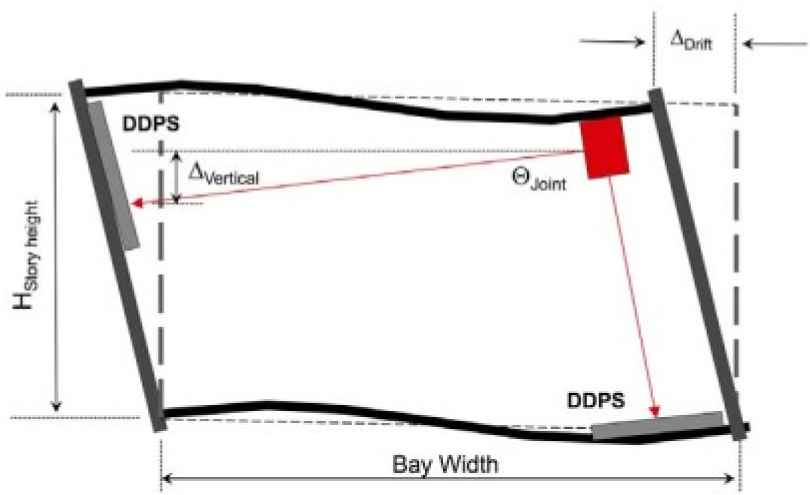

Figure 10. Utilizing a vertically mounted DDPS to obtain local laser rotation.

It is noted that during deformation there generally is also a component of rotation at the DDPS sensor mount location, however through analysis and experimental testing, this rotation component was confirmed to be a higher order component and does not impact the sensor reading. The rotation at the laser mount location, on the other hand, is critical because the rotation influence is effectively amplified by the laser beam propagation across the story height and must be corrected for. The rotation correction defined above is valid for both elastic and inelastic deformations of the building system.

To obtain additional data on the performance of the DDPS on an actual structure, including the effects of local member rotation, Testbed #2 consisting of a laboratory scale frame was developed, as shown in Figure 11. This system was a purposely flexible scale model two-story aluminum moment frame mounted on a low friction bearing system with an automatically controlled, linear motion motor at the base to apply specified horizontal earthquake motions in the plane of the frame.

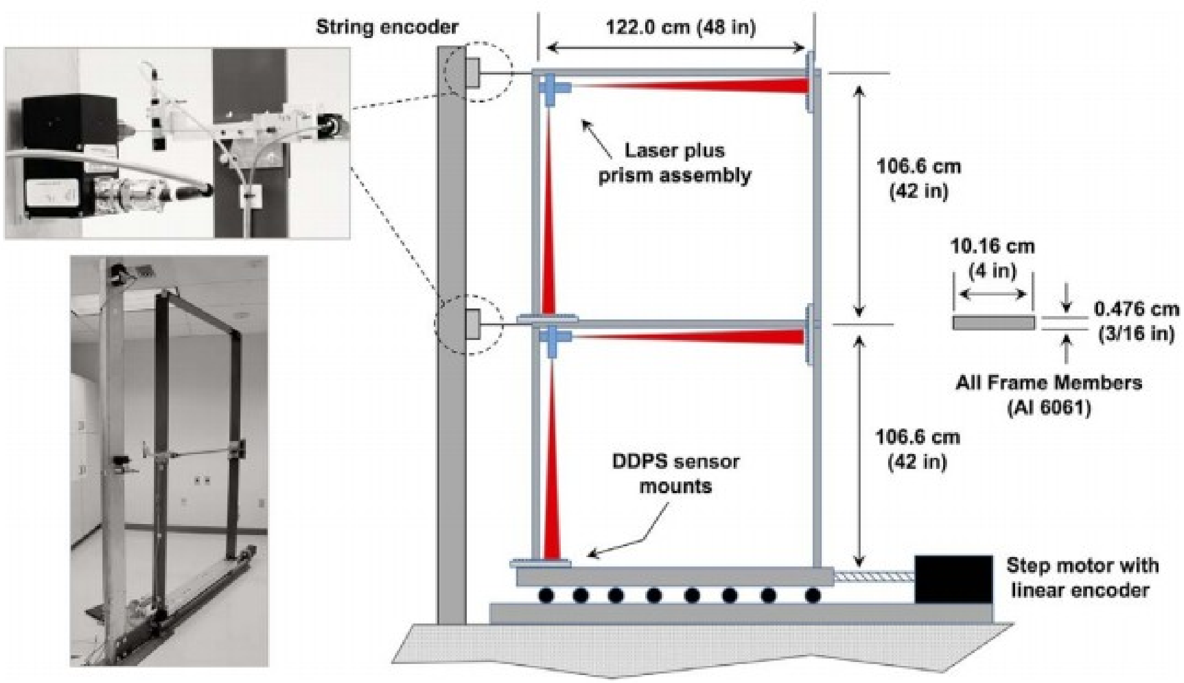

Figure 11. Sensor Testbed #2, an automatically controlled laboratory scale two-story frame system with string encoders connected to an adjacent tower for floor displacement measurements.

As shown in Figure 11, two string encoders consisting of a tensioned string on a ratcheted rotational spool were used to directly measure the absolute displacements at each floor level, thus providing a means for calculating interstory drift ground truth.

In this experimental frame, DDPSs were mounted at the floor levels and on the face of columns so that drift and appropriate local rotation corrections could be measured. Similar to the motion table in Testbed #1, a stepper motor was employed to subject the base of the frame to prescribed earthquake ground displacement motions. This experimental setup was used to evaluate the ability of the DDPSs to measure interstory drift as well as to assess the significance and ability to appropriately determine the rotation correction at the laser mounting location.

Two representative earthquake time histories were employed for the sensor assessment. The first ground motion record consisted of the well-known El Centro California ground motion (PEER), scaled by a factor of 0.7 to ensure that the driving motor would remain within its maximum displacement stroke. Whereas the second record consisted of the band-limited ground motions from the Landers California earthquake Lucerne station (PEER), scaled by a factor of 0.5.

The DDPS interstory drift measurements obtained for the applied El Centro ground motion are shown in Figures 12 and 13 for the first and second story, respectively. From these plots two observations can be made. First, the local rotation correction is significant, particularly for the first-floor level as evidenced by comparing the DDPS drift measurements with and without the local rotation correction, see Figure 12a. Secondly, the total corrected drift obtained from the DDPS exhibits excellent agreement with the ground truth drift obtained by differencing the absolute displacements obtained from the stepper motor encoder and string encoders at each floor level, as shown in Figure 12b. This structure remains linear elastic during the earthquake excitation so there is no permanent displacement, but the DDPS provides an excellent measurement of the full dynamic waveforms of the interstory drift. Both the amplitude and frequency content are accurately represented by the DDPS measurements.

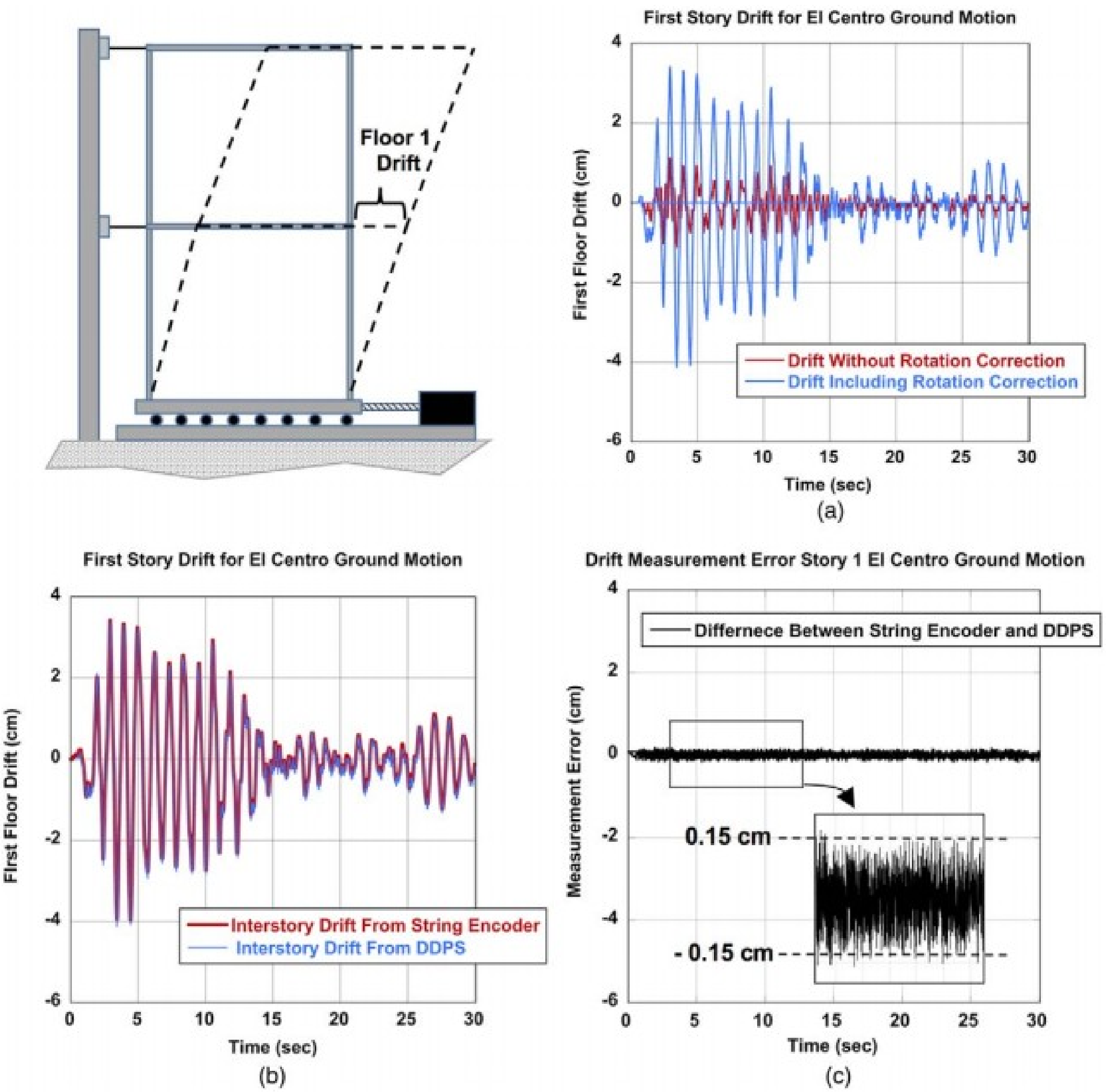

Figure 12. El Centro motion: first floor interstory drift. (a) DDPS drift measurement with and without local rotation correction; (b) comparison of actual interstory drift from string encoders with DDPS measured drift; (c) measurement error.

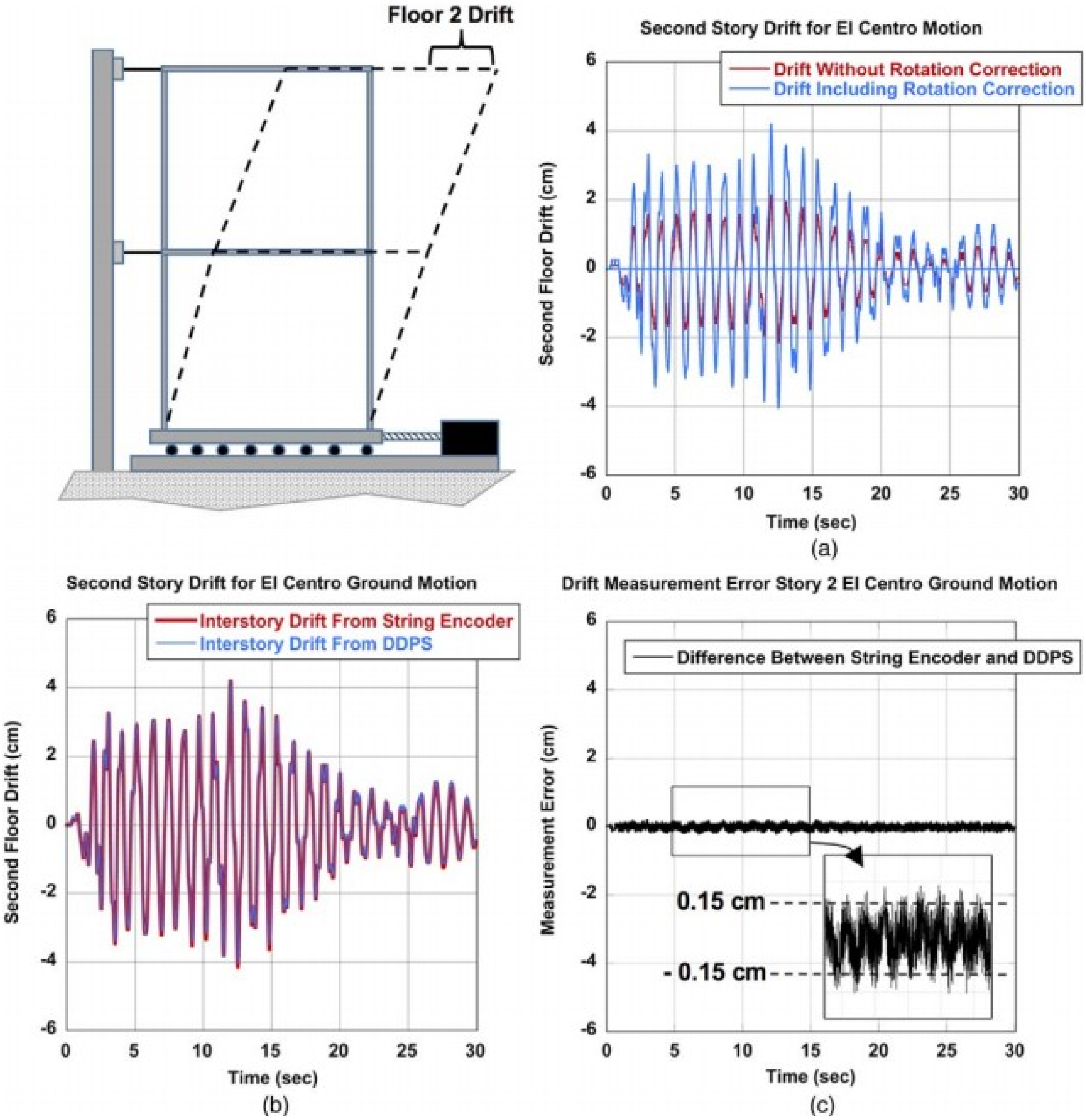

Figure 13. El Centro motion: second floor interstory drift. (a) DDPS drift measurement with and without local rotation correction; (b) comparison of actual interstory drift from string encoders with DDPS measured drift; (c) measurement error.

The experimental results for the Landers ground motions are shown in Figure 14 and Figure 15. Similarly to the El Centro motions, it is clear that the rotation correction is essential and the DDPS provides an excellent measure of the interstory drift. The DDPS provided accurate measurements of the drift at both floor levels. In all cases the maximum difference between sensor measurement and ground truth drifts was on the order of 0.15 to 0.20 cm. This difference reflects the error contributions from the measurements on both the horizontal and vertical sensors. A simple error analysis that includes both the direct drift measurement on the horizontal sensor and the rotation error due to the vertical sensor error indicates that maximum error should be on the order of twice the error from a single sensor measurement or 2 × 0.10 cm, which is in accordance with the observed sensor errors.

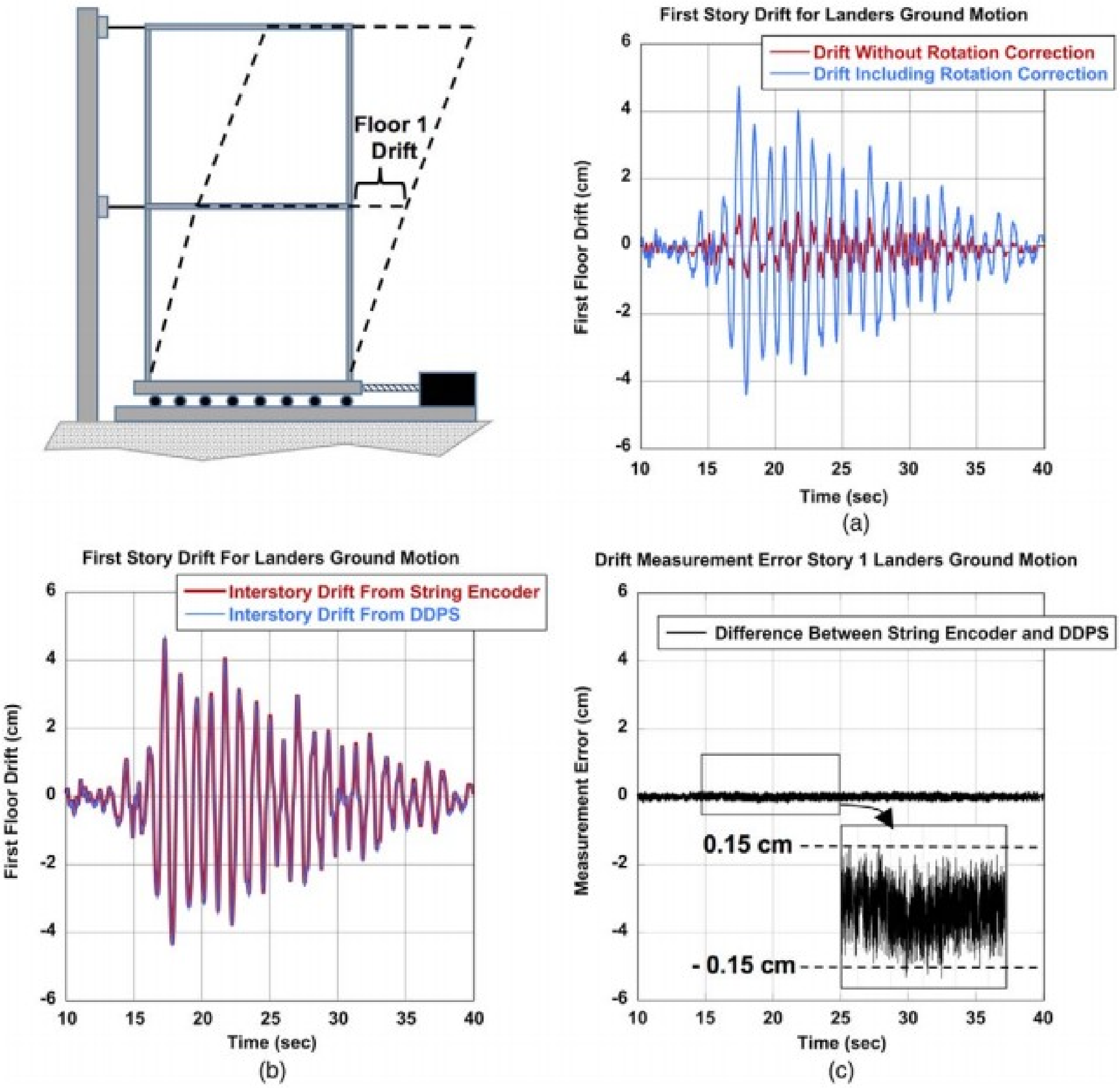

Figure 14. Landers motion: first floor interstory drift. (a) DDPS drift measurement with and without local rotation correction; (b) comparison of actual interstory drift from string encoders with DDPS measured drift; (c) measurement error.

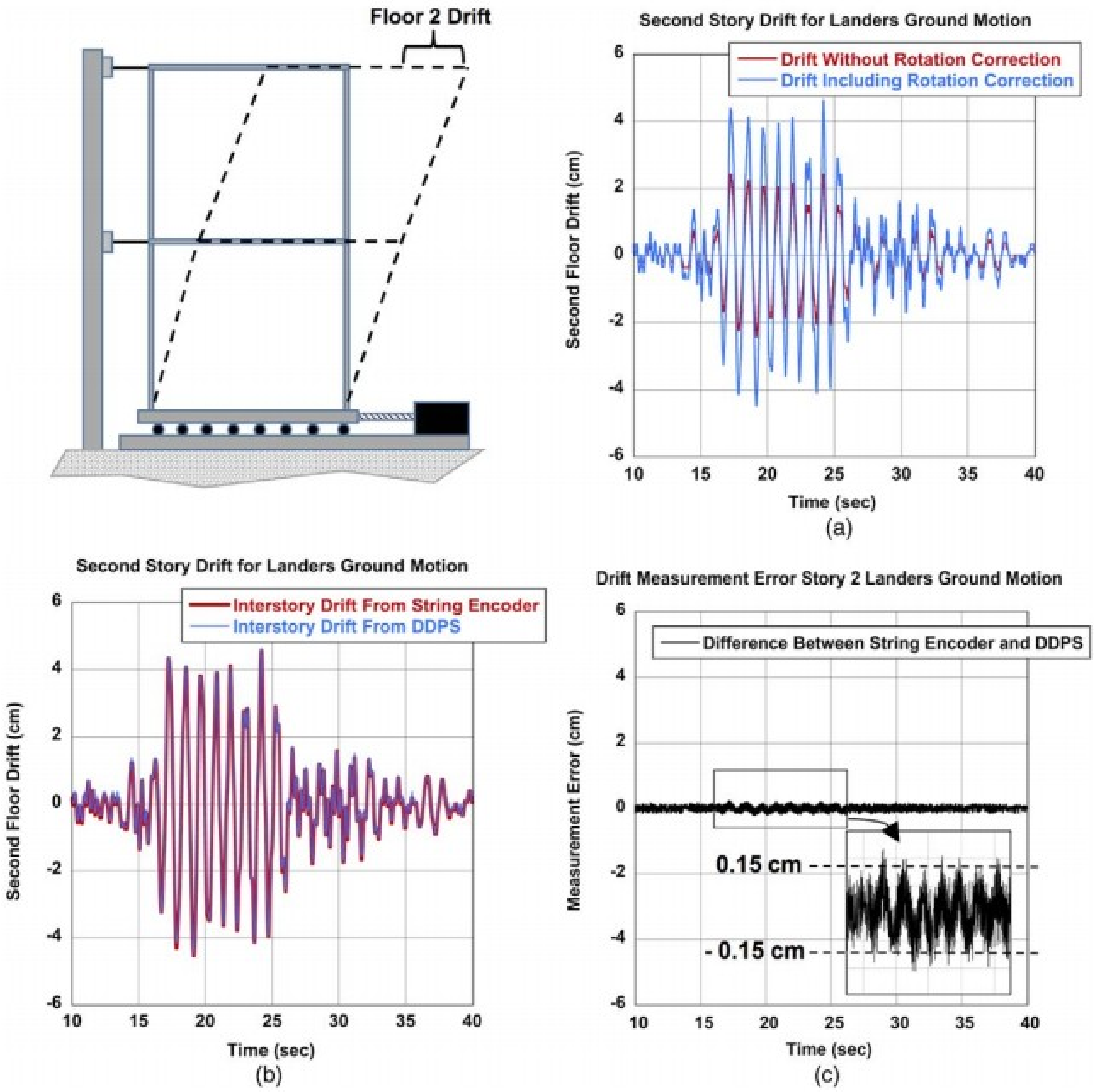

Figure 15. Landers motion: second floor interstory drift. (a) DDPS drift measurement with and without local rotation correction; (b) comparison of actual interstory drift from string encoders with DDPS measured drift; (c) measurement error.

The scale model two-story test frame proved to be very flexible with significant member deformations under lateral excitation as a consequence of the slenderness of the members. This resulted in significant lateral displacements as well as significant local member rotations, which may be larger than would occur in an actual building system. However, these features of Testbed #2 allowed for a demanding exercise of the DDPS system and particularly demonstrated the ability to correct for local member rotations at the laser mounting point.

COMPUTATIONAL SIMULATION OF SENSOR SYSTEM PERFORMANCE

To comprehensively understand sensor system performance, including the accuracy of the methodology used to compute rotations and associated corrections (Figures 9 and 10), it would be desirable to have a validated, predictive model of the sensor system.

A sensor system simulation capability would also be an important tool for designing and assessing sensor system performance for multiple types of structural systems and configurations. To begin the development and build confidence in a simulation-based sensor performance prediction tool, finite element modeling of the frame structure in Testbed #2 was undertaken.

A beam element based finite element model (FEM) was constructed to represent the Testbed #2 frame structure, as shown in Figure 16. The simulation model included a 4-beam element discretization of each column and beam in the frame, and lumped masses to account for the experimental hardware (lasers, DDPSs and associate electronics). The frame model included finite displacement geometry change through an updated co-rotational coordinate system for each element, and was statically initialized under gravity load before performing a dynamic earthquake simulation. The damping of the computational system model was determined experimentally through a push-over and release of the experimental frame, with a computation of the logarithmic decrement of the resulting frame ring-down (Chopra 2012). The model employed Rayleigh damping with the damping anchored to the first and third modes. The FEM characteristics and a comparison between experimental and model predicted ring-down of the frame are shown in Figure 16.

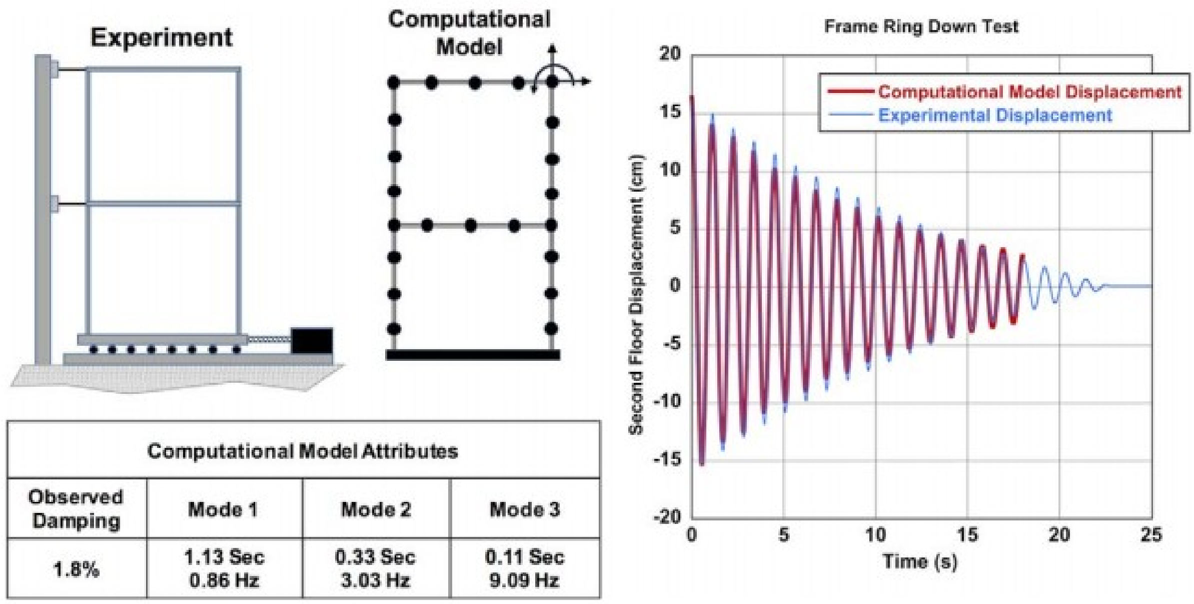

Figure 16. Computational model of the Testbed #2 frame; ring down for damping, calibration, and model frequencies.

The computational model of the frame system was used to simulate the structural response and predict the experimental performance of the sensor system. The approach was to perform a response simulation for the model using the specified earthquake motions from Testbed #2, and subsequently utilize the model predicted displacements and rotations at both the laser mount and sensor mount locations to compute the expected measurements of the sensor system. It is noted that this approach is evaluating two major aspects; first the accuracy of the model to replicate the response of the as-built frame, and second the assumptions and geometric approximations implicit in developing the sensor rotation corrections, that is, Equation 1 through Equation 3.

The computational model prediction of the story drift measured by the DDPS system under El Centro base motion is shown in Figure 17 along with the actual sensor measured drift. The model exhibits good agreement with the measured sensor data for both the case in which the local rotation is not included and the case in which the local rotation correction is included. The simulation model predictions agree well with the experimental data both in terms of frequency content and amplitude of drift. The corresponding simulation data for the Landers motion is shown in Figure 18, where a good correlation between FEM prediction and DDPS results is observed. Building confidence in the ability to appropriately simulate sensor performance is important to the evaluation of expected sensor performance on more complex structural systems such as shear walls or coupled shear wall–frame systems.

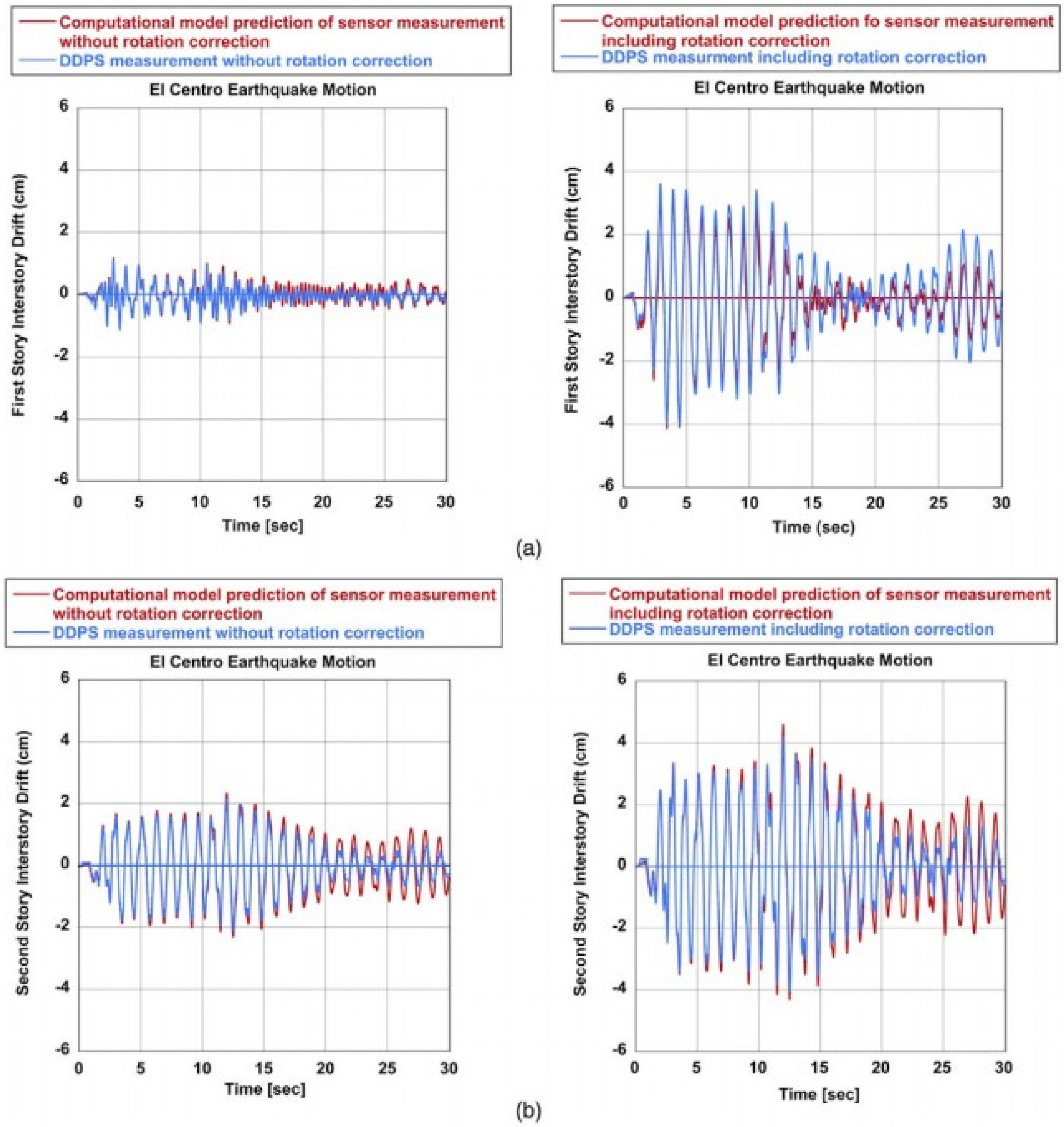

Figure 17. Model-based prediction of sensor performance under El Centro motion. (a) First-story drift: model prediction vs. DDPS data without and with rotation correction; (b) second-story drift: model prediction vs. DDPS data without and with rotation correction.

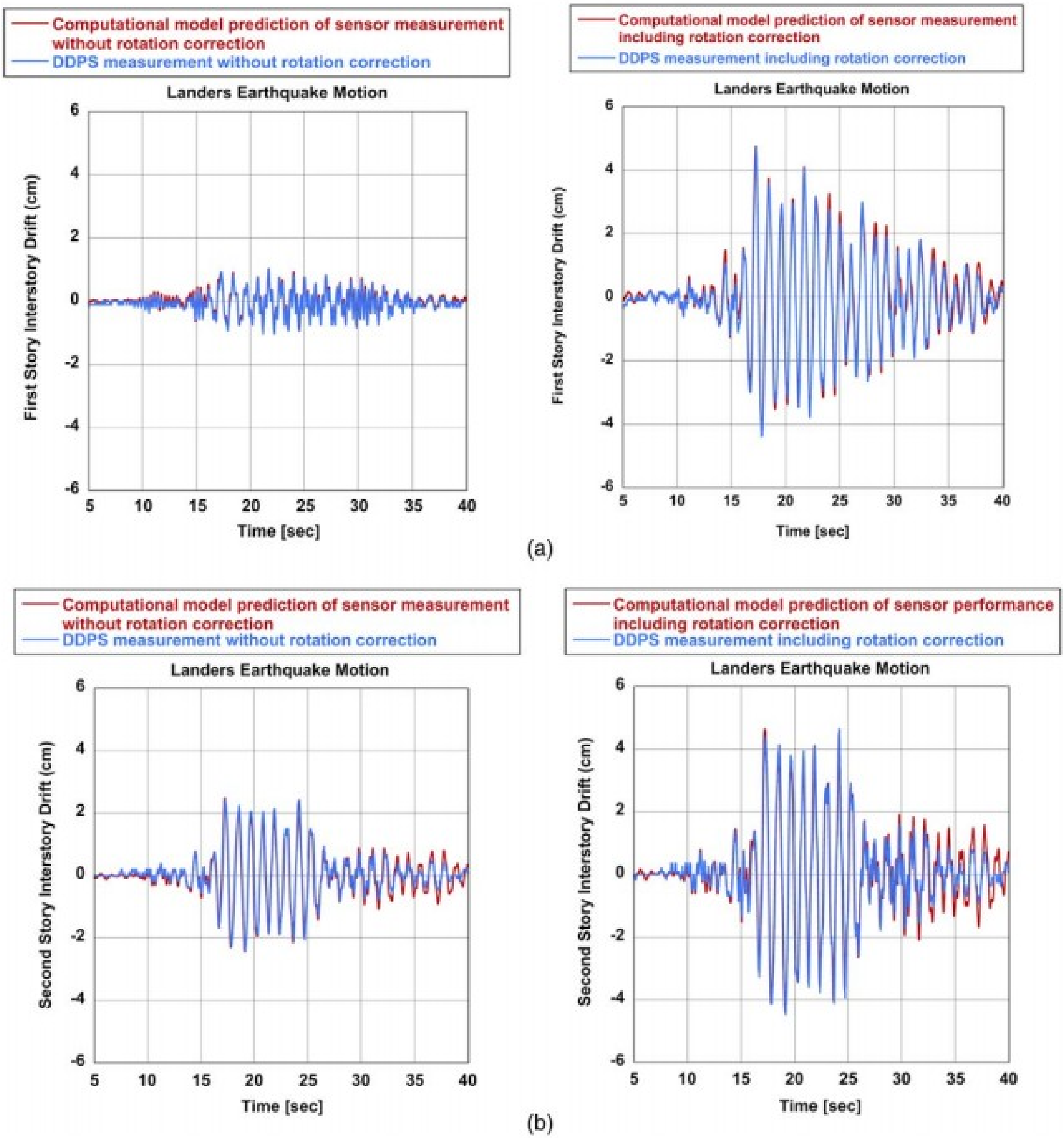

Figure 18. Model-based prediction of sensor performance under Landers motion. (a) First-story drift: model prediction vs. DDPS data without and with rotation correction; (b) second story-drift: model prediction vs. DDPS data without and with rotation correction.

ESTIMATING IN-STRUCTURE ACCELERATIONS FROM DDPS DATA

The principal function of the DDPS is the direct measurement of building story drift. However, it would be useful if the sensor could also provide an accurate estimate of in-structure absolute accelerations for the interpretation of inertial loads and the evaluation of facility secondary equipment loads. If a DDPS is placed at every floor of a building, interstory drift time histories defining the relative displacements across each floor will be obtained. Starting at the base of the building, the drifts can be summed to provide the floor displacement relative to the base of the building at each floor level, as follows:

$$D_i(t) = \sum_{k=1}^{i} d_k(t) \cdot h_k \tag{4}$$

where $D_i(t)$ is the displacement of floor i at time t relative to the base of the building, $d_k(t)$ is the drift ratio of story k at time t, h_k is the height of story k and the summation occurs from the base of the building to story i(k = 1, 2… i). If the ground motion excitation at the base of the building is known in terms of ground displacement or acceleration, for example through a free field strong motion accelerometer, Equation 4 provides a basis for estimating in-structure accelerations through appropriate numerical differentiation of the displacement response history at each floor level.

The drift time histories measured by the DDPS are quantized as a result of the discrete nature of the diode array measurements indicated in Figure 4. This is expressed in the drift response history measurement as a series of step functions, as shown in expanded DDPS sensor data of interstory drift in Figure 19. The step function character of the drift introduces fictitious high frequency content that must be removed from the signal prior to numerical differentiation to obtain in-structure acceleration estimates.

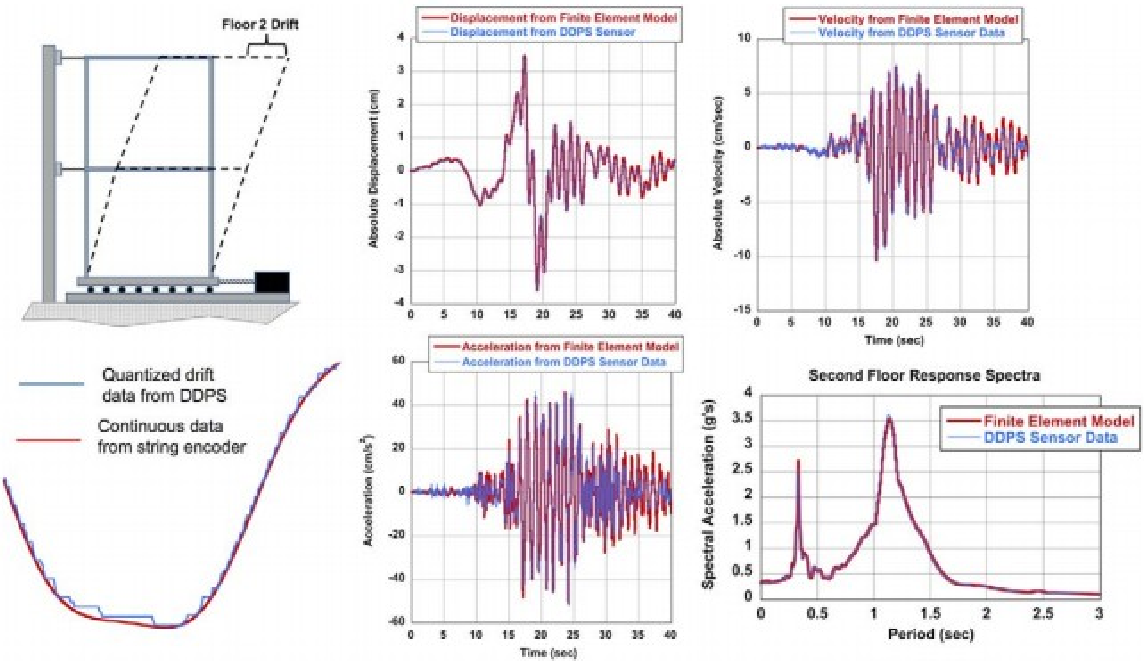

Figure 19. Quantized character of DDPS drift data and estimations of absolute displacement, velocity and acceleration from low-pass filtering of DDPS data (Landers ground motion, PEER).

The ability to estimate in-structure accelerations from DDPS drift data was examined with respect to Testbed #2 shown in Figure 11. For this experimental arrangement, the earthquake excitation was applied by the automatic control system as a known base displacement history. The absolute displacement response history at each floor level was obtained by determining the relative displacement at each floor level, see Equation 4, and adding the time varying frame base motion to develop an absolute displacement response history for each floor level. The resulting quantized absolute displacement floor time histories were low-pass filtered to remove the fictitious high frequency components, and then differentiated to obtain estimates of absolute floor accelerations. In the experimental evaluation of the frame in Figure 11, the floor accelerations were not measured, however, the finite element model of the frame was shown to provide very good estimates of the frame response (Figures 17 and 18). Consequently, the accelerations estimated from the DDPS data were compared with the in-structure accelerations from the computational model. The second-floor displacements, velocities and accelerations processed from the DDPS data by the procedure described above are shown in Figure 19. The floor displacement time histories were processed with a low-pass Butterworth filter, for this particular structure the filter employed consisted of a 5 Hz low-pass filter. The agreement between processed DDPS data and the in-structure quantities computed with the FEM of the frame was excellent both in terms of response history and in-structure acceleration spectra.

In practice, the filtering bandwidth would need to be carefully considered so as not to filter out response generated by the structural system. However, the results shown here indicate that DDPS data offers significant promise in not only being able to measure interstory drift, but also yield good estimates of in-structure accelerations.

DISCUSSION AND SUMMARY

As the earthquake engineering community trends more toward performance-based design, earthquake performance objectives beyond life safety will be desired for many structural systems. For critical industrial and safety-related facilities, the establishment of specific limit states and corresponding post-event performance expectations will be crucial to continuity of operations and appropriate economic and safety functions. An ability to rapidly measure and display key system response observables will be essential to validating performance, determining if design limit states were surpassed, and informing appropriate and timely post-event actions.

The optical sensor described herein provides a tool for accurately and rapidly measuring building interstory drifts. The introduction of discrete diodes as a motion measurement mechanism allows for measurement of the large displacements associated with flexible building earthquake drift (i.e., large relative to commercial position sensitive detector dimensions) at a very low cost. The ability to measure interstory drift and absolute in-structure accelerations for 2-D building systems, including permanent displacements associated with inelastic action, was demonstrated through the utilization of both numerical simulations and experimental data. Experiments planned for the near future will extend this work and validate the ability of the DDPS to measure interstory drifts and absolute in-structure accelerations in a larger scale 3-D structure under bi-directional earthquake excitations.

As this technology matures and becomes fully validated through simulations and experiments of realistic earthquake conditions, value engineering to optimize cost and functionality will be necessary to advance this technology to application-ready status. The functionality of the original piece-component sensor used in the frame experiments has recently been integrated into a single board suitable for practical applications on real buildings, see Figure 20 (McCallen et al. 2017). Additional value engineering options, such as using an intense LED light instead of the more-costly laser light, are under consideration. It would be desirable to reach a design cost point that would allow placing optical sensors at every floor of a multistory building.

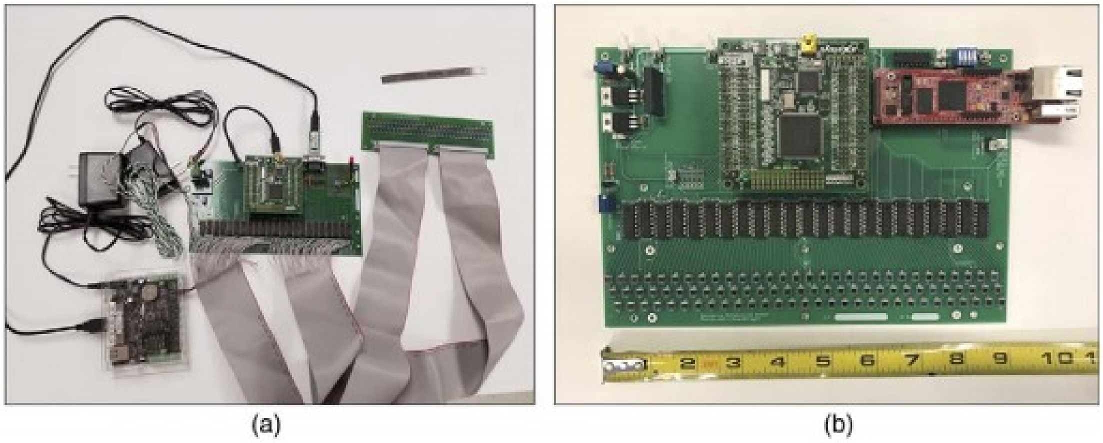

Figure 20. DDPS sensor packages. (a) Component based sensor system used in experimental data acquisition; (b) prototype integrated, single board sensor package for field deployment.

In addition to value engineering of the sensor, there will be a number of practical considerations related to developing an application-ready system including the provision of back-up power and meeting eye safety requirements for an active laser, ideally through limiting laser power levels. There will also be considerations for laser and sensor system mounting with the provision of clear lines-of-sight for the two laser beam paths, which could require on the order of +/− 4 to 5 inches of laser beam motion under large earthquake events. For many industrial facilities, structural systems are exposed and can be readily accessed. However, for commercial buildings, access to main structural components, and the ability to provide access to the sensor system for maintenance, may require more innovative approaches. For new buildings and facilities, it would be desirable to design-in the monitoring system to accommodate the necessary mounting and lines-of-sight.

Finally, the sensor system performance under extreme events, where localized member buckling might occur (e.g., beam flange buckling near a joint) needs to be carefully assessed. The mounting hardware through which the lasers and sensors are attached to the structural elements should be performed with careful consideration to mitigate any effects of localized inelastic behavior. Work is ongoing with application to larger steel frame structures and recommendations for mounting will be developed.

ACKNOWLEDGMENTS

A portion of this work was supported by the U.S. Department of Energy Office of Nuclear Safety at the Lawrence Berkeley National Laboratory and testbed development was completed by students and faculty at California State University, Chico with support from the Lawrence Livermore National Laboratory Educational Program.

REFERENCES

American Society of Civil Engineers (ASCE), 2005. *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*, ASCE/SEI 43-05, Reston, VA.

American Society of Civil Engineers (ASCE), 2010. *Minimum Design Loads for Buildings And Other Structures*, ASCE-7, 2010. Reston, VA.

Andersson, H., 2008. Position Sensitive Detectors – Device Technology and Applications in Spectroscopy, Doctor Thesis, Electronics Design Division, Mid Sweden University, Sundsvall, Sweden.

Bennett, K. D., and Batroney, C. B., 1997. Interstory drift monitoring in smart buildings using laser crosshair projection, *Opt. Eng.* 36, 1889– 1892.

Chen, W. M., Bennett, K. D., Feng, J., Wang, Y. P., and Huang, S. L., 1998. Laser technique for measuring three dimensional interstory drift, *Proceedings of the Society for Photonics and Optics* 3555, 305– 310.

Chen, X., 1995. *Near-Field Ground Motion from the Landers Earthquake*, California Institute of Technology, Earthquake Engineering Research Laboratory, Report No. EERL 95-02, Pasadena, CA.

Chopra, A. K., 2012. *Dynamics of Structures: Theory and Application to Earthquake Engineering*, 4th Edition, Prentice Hall, Upper Saddle River, NJ.

European Committee for Standardization (CEN), 2004. Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, EN 1998–1.

Islam, M. N., Zareie, S., Shahria Alam, M., and Seethaler, R. J., 2016. Novel method for interstory drift measurement of building frames using laser-displacement sensors, *Journal of Structural Engineering* 142, 06016001.

Los Angeles Tall Buildings Structural Design Council, 2017. *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Regions*, LATBSDC, Los Angeles, CA.

McCallen, D. B., Coates, J., Repanich, N., and Wattenburg, W. H., 2017. An Optically Based Interstory Drift Meter System for Rapid Assessment of the Earthquake Response of Building Structures, International Patent WO 2017/011056 A1.

McCallen, D. B., and Larsen, S. C., 2001. Nevada – *A simulation environment for regional scale estimation of ground motion and structural response*, Tech. Rep. UCRL-ID-152115, Lawrence Livermore National Laboratory.

Pacific Earthquake Engineering Research Center Ground Motion Database (PEER), http://ngawest2.berkeley.edu/.

Pacific Earthquake Engineering Center (PEER), 2017. *Tall Buildings Initiative (TBI) - Guidelines for Performance-Based Seismic Design of Tall Buildings*, PEER Report 2017/06, University of California, Berkeley.

Petrone, F., Wong, J., McCallen, D. B., and McKenna, F., 2016, Development of advanced numerical tools for the nonlinear seismic analysis of nuclear systems, in *Transactions of the American Nuclear Society*, 115, 765– 768.

Skolnik, D. A., Kaiser, W. J., and Wallace, J. W., 2008. Instrumentation for structural health monitoring: measuring interstory drift, in *Proceedings of the 14th World Conference on Earthquake Engineering*, 12–17 October, Beijing China.

Skolnik, D. A., and Wallace, J. W., 2010. Critical assessment of interstory drift measurements, *Journal of Structural Engineering* 136, 1574– 1584.

Strong-Motion Virtual Data Center (VDC), n.d. Available at http://www.strongmotioncenter.org.

Technical Committee BD-006-04-11, 2004. *Structural Design Actions. Part 5: Earthquake Actions*, NZS 1170.5 Supp 1:2004, Standards New Zealand, Wellington, New Zealand.

Trifunac, M. D., Ivanovic, S. S., and Todorovska, M. I., 2001. Apparent periods of a building II: Time-frequency analysis, *Journal of Structural Engineering* 127, 527– 537.

Trifunac, M. D., and Todorovska, M. I., 2001. A note on the usable dynamic range of acceler-ographs recording translation, *Journal of Soil Dynamics and Earthquake Engineering* 21, 275– 286.

U.S. Department of Energy (DOE), 2012. *Natural Phenomenon Hazards Analysis and Design Criteria for DOE Facilities, DOE-STD-1020-212*, Washington, D.C.

Wong, J., Petrone, F., McCallen, D. B., and McKenna, F., 2016. Nonlinear computational simulations for the earthquake response of nuclear systems, in *Proceedings of the 10th Nuclear Plants Current Issues Symposium*, VII, 3/1-3/11, Charlotte, NC, 11–14 December 2016.

Yun, F., Yong, Z., Weimin, C., Rong, S., Shanglian, H., and Bennett, K. D., 1999. Five dimensional interstory drift measurement with cross hair laser, *Acta Photonica Sinica* 28, 1006– 1009.

Zacharias, R. A., Beer, N. R., Bliss, E. S., Burkhart, S. C., Cohen, S. J., Sutton, S. B., Van Atta, R. L., Winters, S. E., Salmon, J. T., Latta, M. R., Stolz, C. J., Pigg, D. C., and Arnold, T. J., 2004. Alignment and wavefront control systems at the National Ignition Facility, *Optical Engineering* 43, 2873– 2884.