An Optically Based Sensor System for Rapidly Assessing the Earthquake Response of Critical Facilities

Final Summary Report to the Nuclear Safety Research and Development Program of the U.S. Department of Energy Office of Nuclear Safety

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Background

The U.S. Department of Energy (DOE) has a vast enterprise of mission-critical facilities, many of which are one of a kind, that are distributed throughout the United States. Many of the unique and most essential facilities are related to nuclear research and development, nuclear materials handling and nuclear operations and a number of the facilities reside in locations of high seismicity as shown in Figure 1.

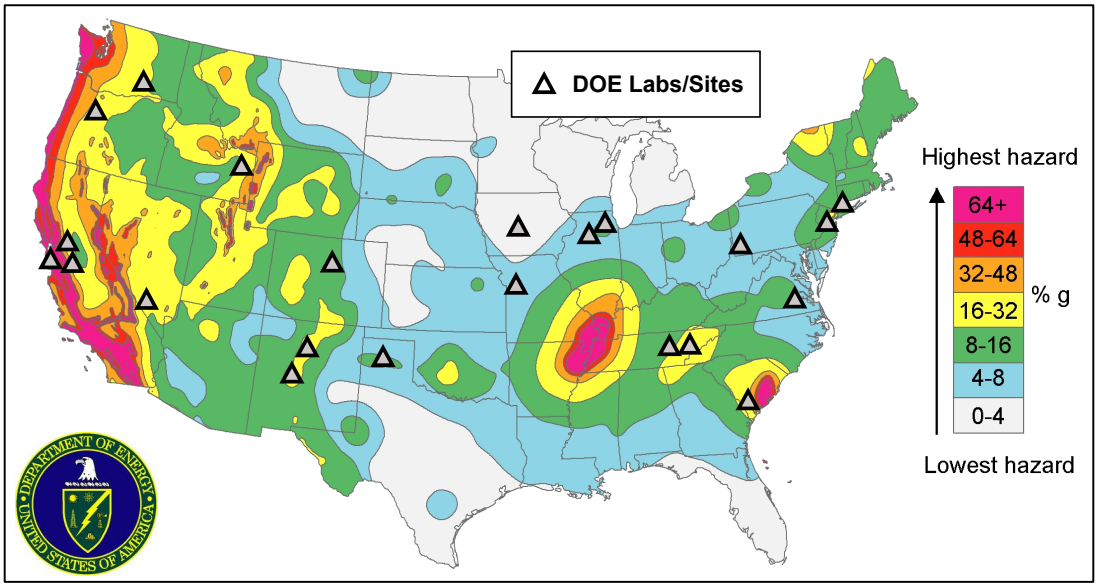

Figure 1. Major DOE facilities located on a map of U.S. earthquake hazard (Hazard map courtesy United States Geologic Survey).

Historically, the DOE has been at the leading edge of the development of natural phenomenon safety standards and safety technologies for nuclear facilities. DOE standard 1020[1], developed by a collaborative team of DOE and external experts, was a ground-breaking standard that developed a comprehensive risk-informed, performance-based approach to the analysis and design of nuclear facilities. Not only has DOE-1020 guided the analysis of DOE facilities, key elements of 1020 have influenced other standards such as the U.S. Nuclear Regulatory Commission (NRC) standards for nuclear power stations and the American Society of Civil Engineers (ASCE) standards for nuclear facilities. The chronology of seismic design standards for nuclear facilities is represented in Figure 2.

The trend in modern performance based design is to develop facility natural hazard performance goals that go beyond traditional simple life safety considerations. This includes defining performance-based limit states that correlate with different levels of infrastructure damage and risk. In DOE standard 1020 (DOE-STD-1020-212, 2012), as well as many other engineering standards (e.g. ASCE/SEI 43-05, ASCE, ASCE 7-10, NZS-1170-04) facility interstory drift, which is the relative displacement between adjacent

[1] Natural Phenomenon Hazards Design and Evaluation for Department of Energy Facilities, U.S. Department of Energy, DOE Standard 1020, 1984.

floor levels as shown in Figure 3, is used as a key measure of structural demand and a quantity for limit state definition. As an example, the drift defined limit state definitions included in ASCE 43-05 are shown in Table 1.

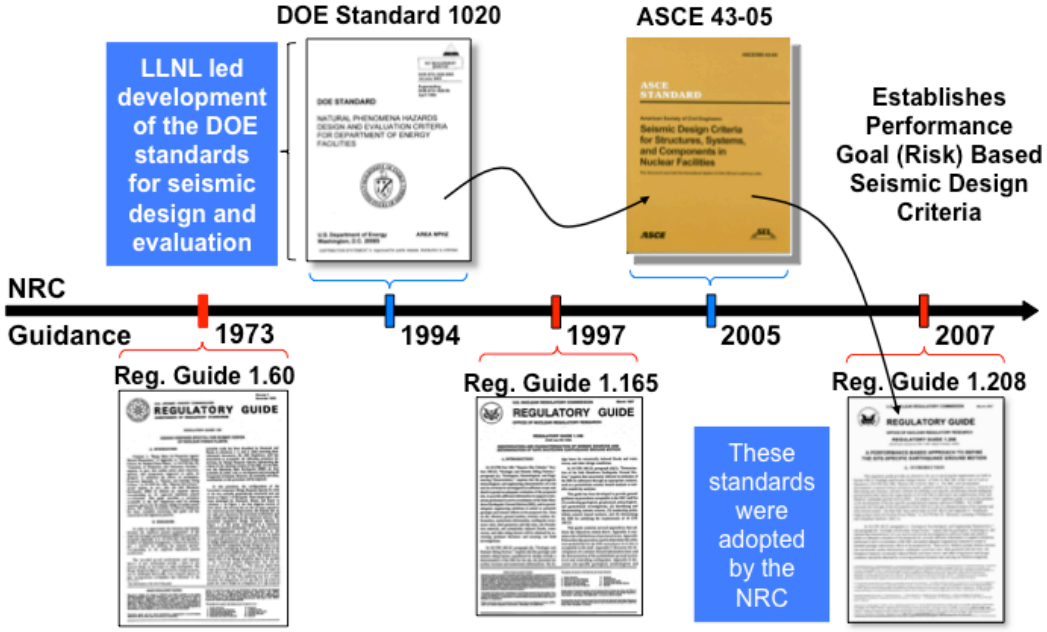

Figure 2. Chronology of DOE, ASCE and NRC developments in nuclear facility earthquake design standards.

A performance-based approach to earthquake analysis and design allows a facility owner to make rational decisions on the desired level of seismic performance of a particular facility based on appropriate considerations of functional safety, operational requirements and required continuity of operations. For example, as indicated in Table 1, a facility owner can select a facility performance that is associated with essentially little or no damage (Limit State D), small (Limit State C) or moderate damage (Limit State B), or significant damage short of collapse (Limit State A). It is noted that a performance-based approach can be especially important when evaluating existing facilities where the seismic hazard may have increased substantially over time due to new scientific knowledge of the geological setting at the site, and it may be either impossible or prohibitively expensive to achieve elastic behavior in the system. In such cases, the allowance of some limited inelastic behavior may be the most effective and appropriate approach to achieving acceptable seismic performance.

The ability to accurately measure the transient response of a vibrating facility is important for determining the actual as-built performance of the facility (validating the accuracy of facility computational models), and for determining the facility response to major upsets like earthquake events. Because interstory drift has been adopted as a principal design quantity and limit state parameter, it would be highly desirable to have a capability to rapidly measure and display the peak interstory drifts that occur during a major earthquake event. Obtaining peak interstory drift values would allow a direct comparison between facility design limit states and actual drift values during an event to determine if

the facility design limit states were exceeded, what level of damage may have occurred during the earthquake and importantly the location where damage might have occurred.

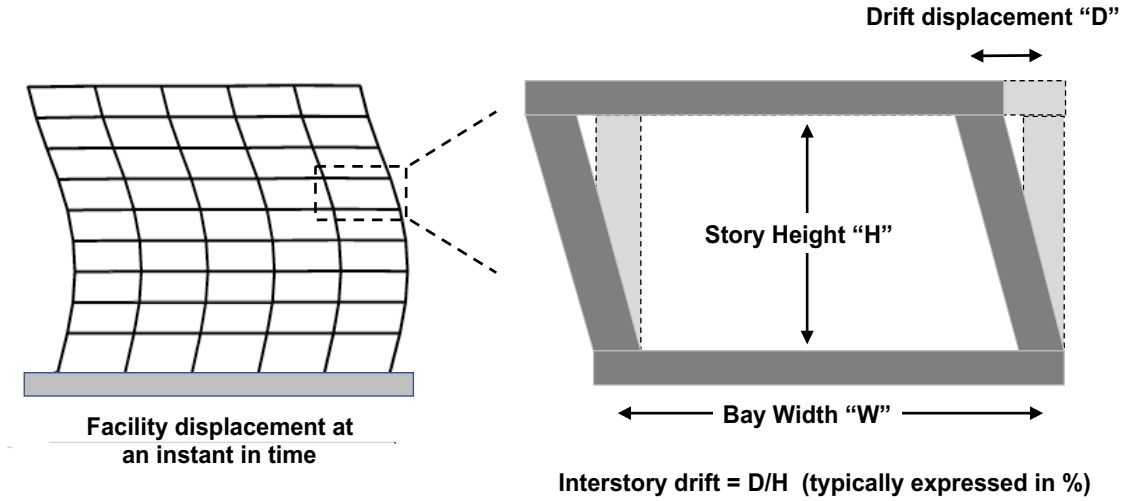

Figure 3. Interstory drift in a vibrating structure.

The historical method for estimating interstory drifts is based on accelerometers deployed in the structure. When an accelerometer-based approach is used, the acceleration time history data from strong motion accelerometers is double integrated to obtain estimates of absolute displacements at the floor levels, and the displacements are then differenced to estimate interstory drift. The estimation of interstory drift from accelerometers is a very challenging problem that is fraught with uncertainty and errors, particularly in the case when permanent drift occurs due to inelastic behavior in the structure. The major challenges associated with determining interstory drift from accelerometer data have been clearly summarized by Skolnick and Wallace in an important research journal paper[2].

An alternative method for measuring interstory drift based on an optical sensor has been proposed by McCallen[3] as well as other researchers. This approach utilizes a light sensitive sensor to measure the translation, and thus the interstory drift, of a laser propagated across the height of a building floor as indicated in Figure 4. The direct measurement of drift through optical means has many potential advantages including the fact that the physics of light-based processes are extremely fast, allowing a very broad frequency band measurement. Additional advantages include the fact that an optically based system can readily measure permanent drift associated with inelastic behavior of the structure, and a direct measurement of drift eliminates the need for extensive post-processing and enables an immediate read-out of peak drifts after an earthquake.

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[2] Skolnick, D.A. and Wallace, J.W., 2010, Critical Assessment of Interstory Drift Measurements, *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 136.

[3] McCallen, D.B., 2013, A Laser Based System for Expedient Measurement of Vibratory Motions and Permanent Deformation in Civil Infrastructure Systems. Lawrence Livermore National Laboratory white paper.

Table 1. Limit states for nuclear facilities defined by maximum interstory drift.

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
Concrete shear wall (bending controlled)	0.008 - 0.010*	0.006 – 0.008	0.004 – 0.005	0.004 – 0.005
Concrete shear wall (shear controlled)	0.0075	0.006	0.004	0.004
Steel moment frame	0.035	0.025	0.010	0.005
Steel concentrically braced frame	0.020	0.013	0.005	0.005
Steel eccentrically braced frame	0.030	0.017	0.005	0.005

- Range dependent on wall reinforcement pattern

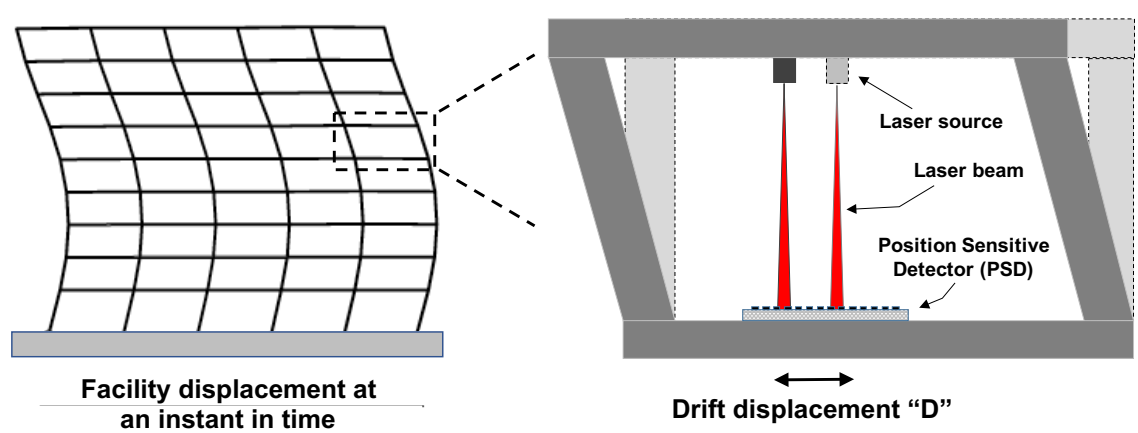

Figure 4. Concept for measurement of interstory drift with an optical sensor.

An optical sensor concept that relies on discrete diodes to detect the position of an incident laser beam has been undergoing basic development by the University of California, California State University Chico and Lawrence Livermore Lab over the past three years. This discrete diode position sensor (DDPS) design is the result of a comparative study of different sensor concepts and has been tested in the laboratory for representative earthquake interstory drifts on a motion table and on a simple two-story aluminum frame structure. The DDPS has exhibited excellent performance and demonstrated the ability to measure earthquake induced interstory drift under small-scale laboratory conditions[4].

The work described herein was focused on evaluating the prototype DDPS performance under conditions that are more representative of field conditions in an actual structure. The experimental data obtained provides important new information and validation of sensor performance and moves the technology measurably closer to being ready for actual application.

Optical Sensor Description

The latest version of the DDPS that was constructed for this project's experiments consists of a staggered array of discrete diodes as shown in Figure 5. Each diode serves as an on/off switch depending on whether the laser is hitting the diode (and therefore the diode is "on") or missing the diode (and therefore the diode is "off") at any instant of time. When the laser strikes a diode, a voltage is generated and monitoring all of the diode voltages provides a determination whether the diode is off or on. By determining which diodes are "on", the location of the incident laser is determined at each instant of motion.

In application, a laser beam is diffracted through an optic to generate a laser line trace on the sensor, and as the floors are subjected to relative motion during an earthquake, the laser line source moves back-and-forth across the diode array (Figure 5 and Figure 6). By tracking this motion, through detection of "off" and "on" diodes at each instant of time, the time variation of interstory drift is directly measured. It is noted that in general, earthquakes create bi-directional motions. The current DDPS design is intended to measure in-plane drift in a building frame, the width of the incident beam is adjusted so that the out-of-plane deformations associated with earthquake motions orthogonal to the frame do not result in the laser trace moving off the diode array.

For this study the components of the sensor, including diodes, comparators, field programmable gate array, microprocessor, thumb drive plug-in and ethernet connection were all mounted on a single circuit board as shown in Figure 5. The diode array has a staggered configuration to increase the measurement fidelity of the sensor. When in operation, the comparators are used to determine if the voltage for each diode has exceeded a specified threshold value selected to indicate incident laser light. The field programmable gate array latches the on/off status for all 92 diodes 384 times per second so that any high frequency drift motions are fully resolved.

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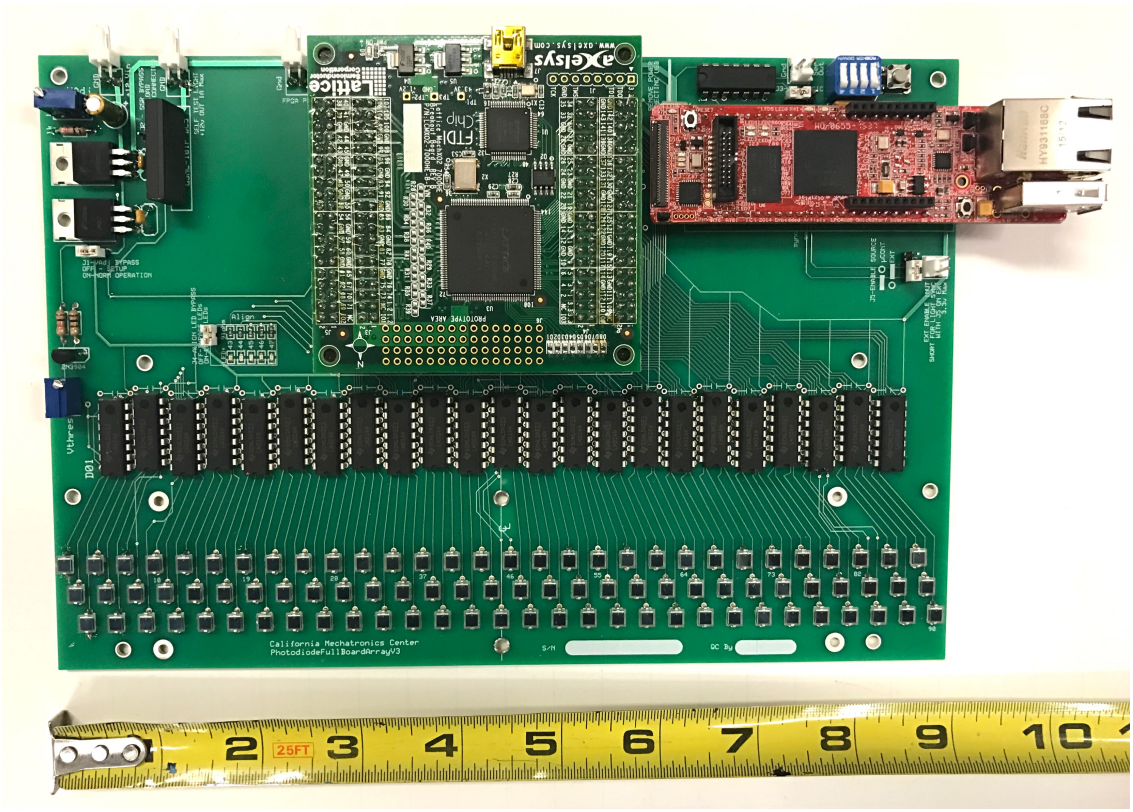
[4] McCallen, D., Petrone, F, Coates, J., Repanich, N., 2017, A Laser-Based Optical Sensor for Broad-Band Measurements of Building Earthquake Drift, *Earthquake Spectra* (in press, to appear).

The sensor saves time histories of the measured interstory drift for the duration of the earthquake event and can immediately output both drift histories and peak drifts for each story level after the earthquake. The physical dimensions of the sensor board and diode array are driven by the need to measure large drifts in a building during a major earthquake event.



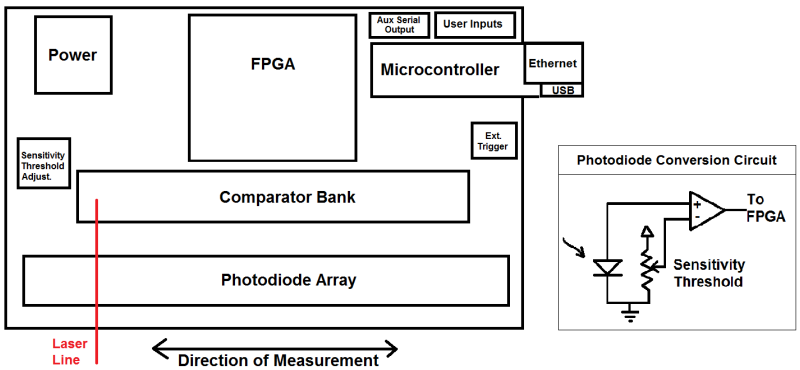


Figure 5. Discrete Diode Position Sensor (DDPS) integrated design.

Experimental Sensor Testing on a 1/3 Scale Steel Frame

The focus of the current research and development effort was the experimental testing of the DDPS sensors on a 1/3 scale steel frame structure at the University of Nevada Reno

(Figure 7). The steel frame which was utilized was developed for previous UNR experiments on seismic base isolation and was overly stiff. For the current study the frame was modified to enhance the flexibility of the frame system and added masses were placed at each floor level to represent building deadload. Existing diagonal bracing was removed and the beam-to-column connections in the first and second floor of one direction of the frame were modified from a full moment connection to pinned connections. The frame was mounted on a shake table at the University of Nevada Earthquake Engineering Laboratory as shown in Figure 8 with a suite of diagnostics.

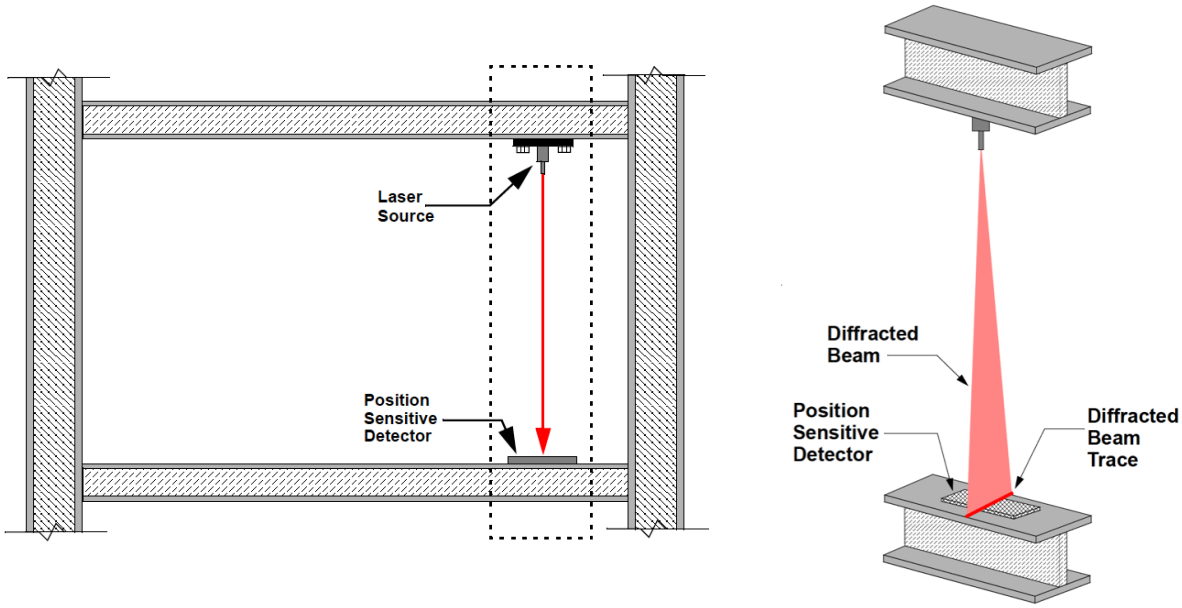


Figure 6. Laser and DDPS sensor mounted in a building frame – concept of optical measurement of interstory drift.

The DDPS's were deployed on the frame to measure lateral displacement of the frame and to measure the rotation at the mounting point of the lasers so the rotation of the laser could be corrected for in the drift measurement as shown in Figure 9. Ground truth measurements of the frame drift were measured by a set of tensioned cables with a calibrated spool to precisely measure cable extension and contraction. The ground truth diagnostic configuration is shown in Figure 10. One set of cables were extended horizontally from the diagnostics tower to the frame and the one set of cables were placed diagonally across each frame bay.

Both sets of tensioned cables were used to measure the drift of each story of the frame, the horizontal cables measured the absolute horizontal displacement at each floor level, which were differenced to get floor drift. The diagonal cables were used to measure the extension or contraction of the diagonal dimension of each frame bay, which is then geometrically translated into story drift. It was found that the drift measurements made by both measurement techniques were in excellent correlation so there was high confidence in the ground truth floor drift measurements for evaluation of the DDPS sensor measurement accuracy.

Figure 7. The 1/3 scale steel frame being mounted on the UNR shake table.

Figure 8. Test frame on the shake table and the diagnostics tower.

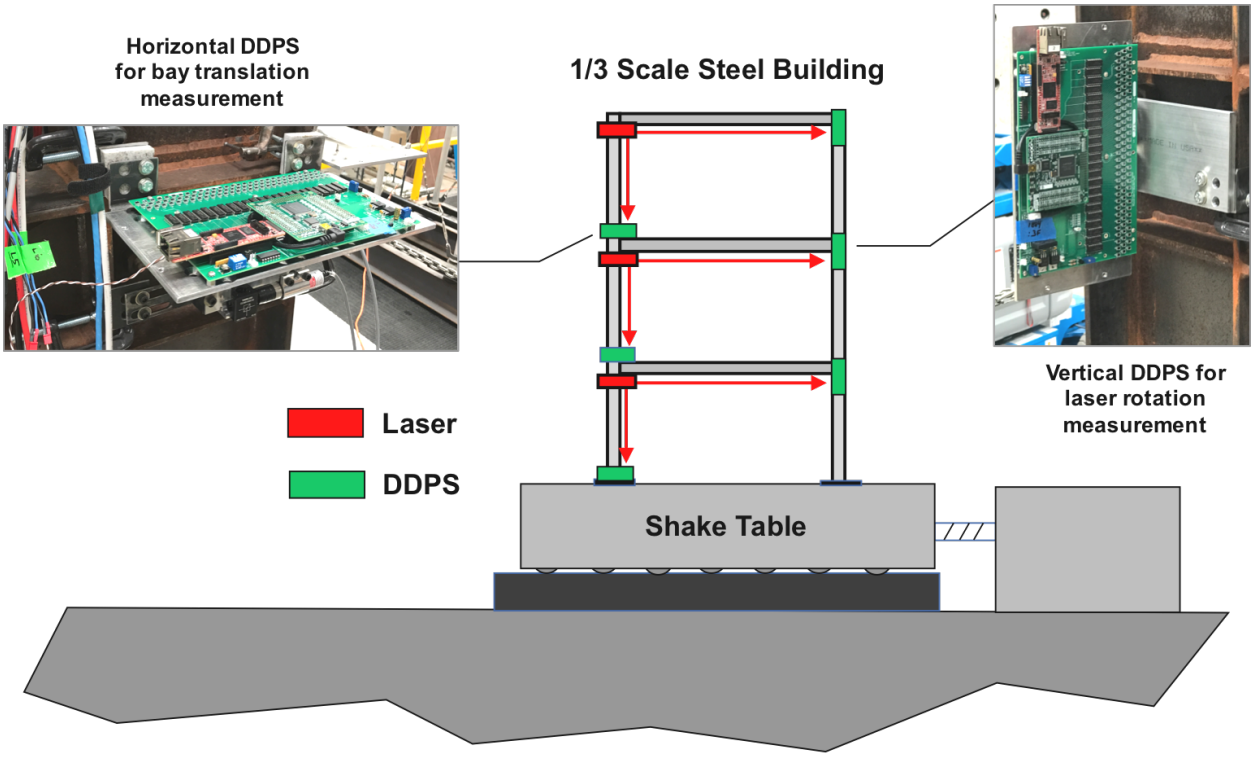


Figure 9. Layout of DDPS sensors and lasers.

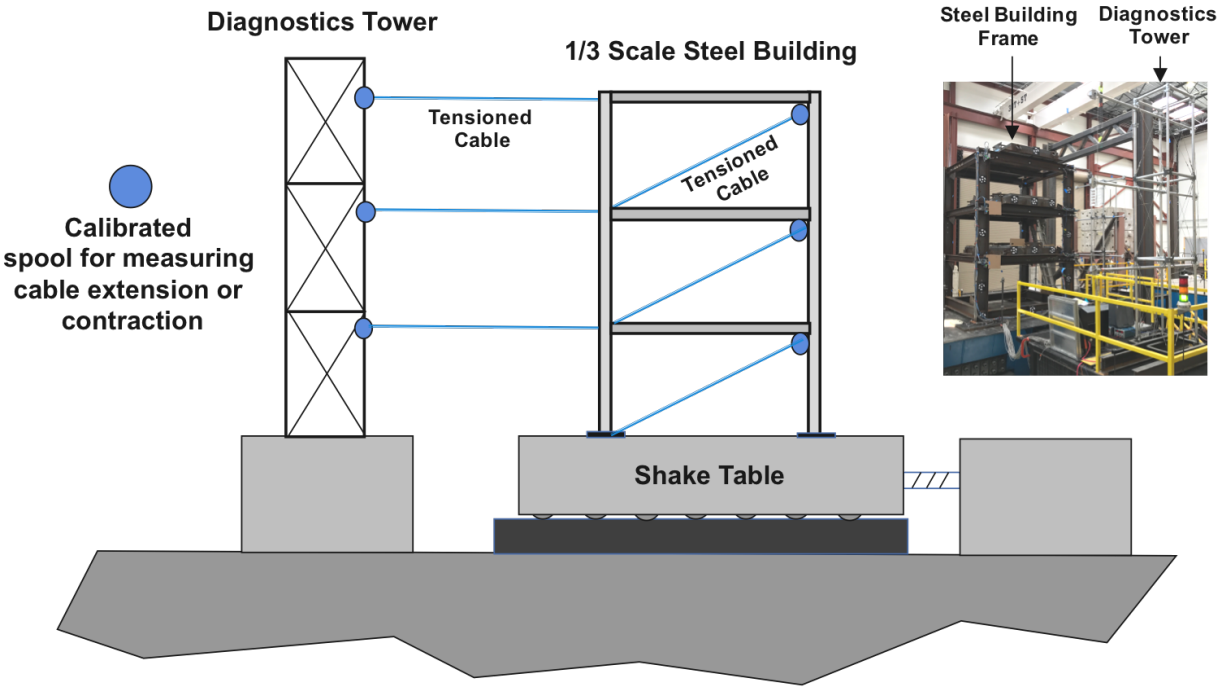


Figure 10. Layout of ground truth measurement diagnostics.

The experimental frame was subjected to measured earthquake ground motion accelerations from two representative earthquakes. The ground motions included the 1940 El Centro California earthquake El Centro station motions and the 1994 Northridge California earthquake Rinaldi station motions (Figure 11). The El Centro record is representative of a ground location distant from the causative fault and the Rinaldi motion is representative of a ground location near the causative fault where low frequency, near-fault waveforms are present. The two measured horizontal components of motion for these earthquakes were applied biaxially in orthogonal directions by the shake table to the test frame structure.

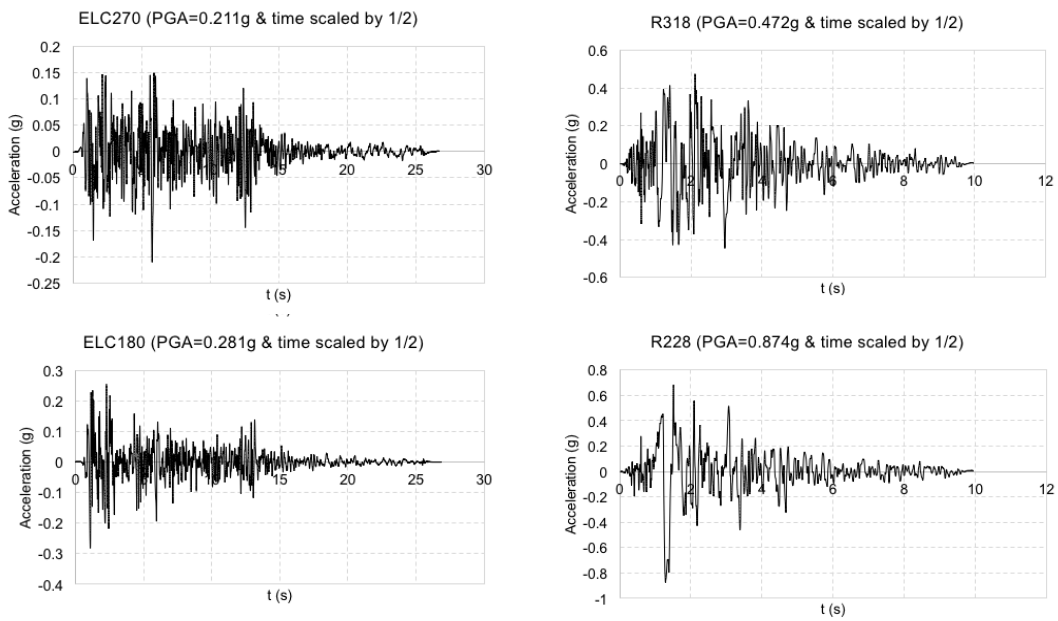


Figure 11. Earthquake ground motion accelerations for the 1940 El Centro California earthquake (M=6.9) El Centro station and the 1994 Northridge California earthquake (M=6.7) Rinaldi station.

A number of simulated earthquake experiments were performed at different scaled values of these earthquake records. The fundamental objective was to assess the performance of the DDPS at the larger, more realistic scale associated with the 1/3 scale steel frame. Additionally, important practical considerations of sensor performance under strong shaking (i.e. no detrimental impact of strong shaking on sensor accuracy and reliability), and sensor mounting integrity were explored. The ability of the sensor, and its mounting hardware, to perform under earthquake conditions is a crucial part of performance validation. The conditions of the UNR tests are expected to be very representative of the as-built conditions in an actual structure subjected to earthquake motions.

Test Frame Dynamics

The dynamic behavior of the steel test frame was evaluated through carefully controlled shake table excitation experiments and finite element modeling. To evaluate the frame dynamics, the frame transient response was measured for both small amplitude white

noise (broad band) table motions as well as from observations of frame ring-down from a snap test of the frame, i.e. a sudden displacement step of the shake table which imparted an impulse to the frame. For assessment of the experimental results, a detailed three-dimensional finite element model of the frame was constructed as shown in Figure 12.

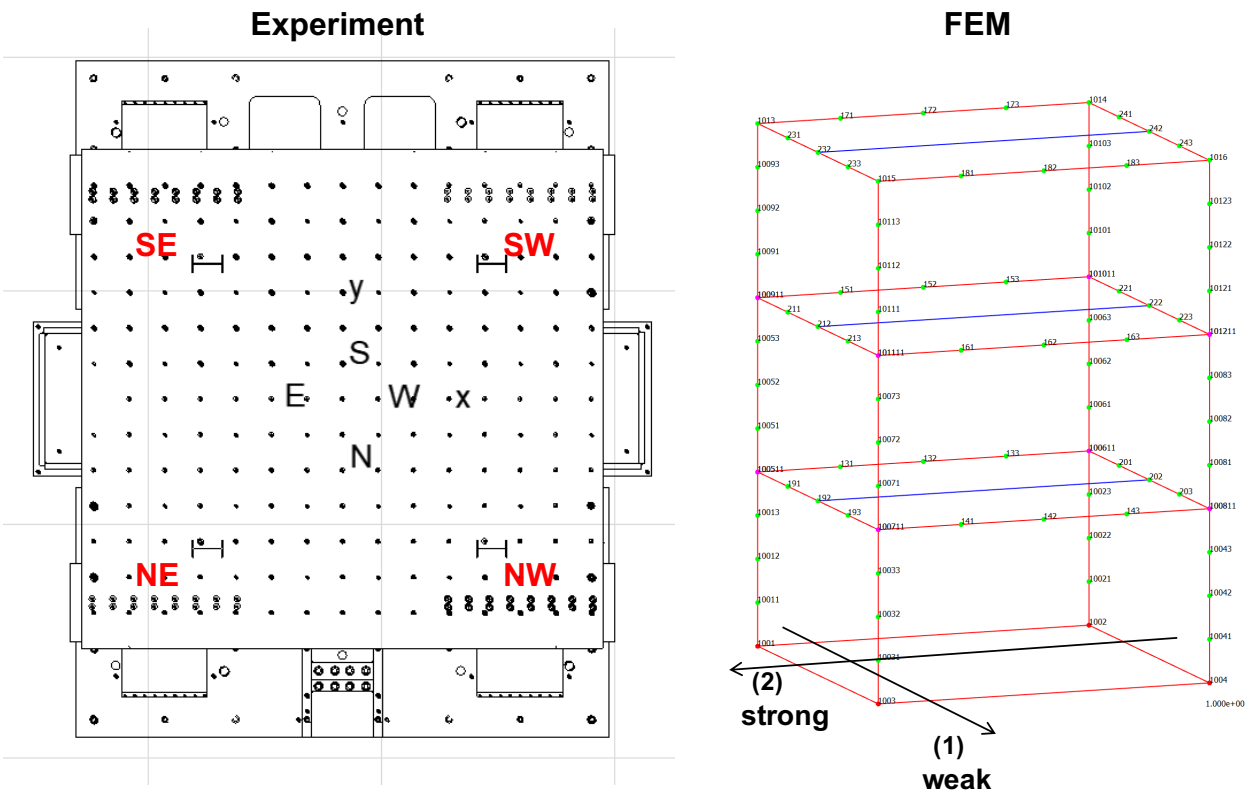


Figure 12. Table platen configuration and finite element model of the frame.

The dynamic results of a frame response to a snap test in the weak frame direction of the frame (north-south on platen) are shown in Figure 13. The shake table was subjected to sequential rapid step motions with the table top displacement indicated as the red line in Figure 13. The table top was stepped through a finite displacement and then abruptly stepped back in the opposite direction. This “snap” motion excites the frame structure and then ring down of the frame can be observed to identify both the natural frequency of vibration of the frame as well as the inherent damping in the frame structure. Also shown in Figure 13 is the finite element prediction of the frame response for the snap test motion. In the finite element model Rayleigh damping was employed with the damping value obtained empirically from the ring-down data of the frame.

In addition to the snap test, the finite element model was utilized to examine the frame response to imposed earthquake motions, for example the measured response of the frame to El Centro ground motions is compared to the finite element simulation in Figure 14. The finite element results are in reasonable agreement with the observed response.

The observed and predicted natural periods of vibration of the frame structure are shown in Table 2.

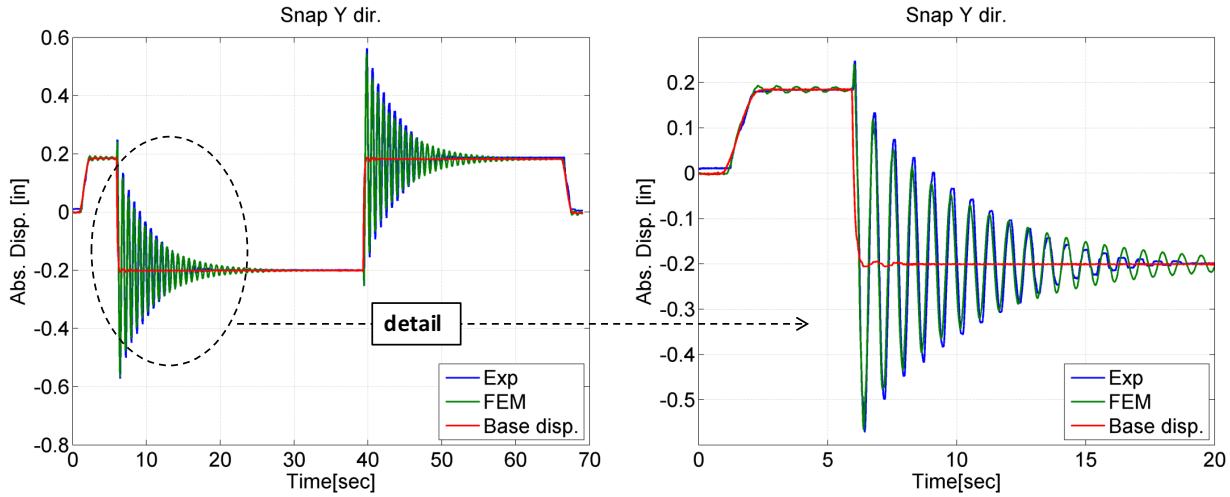


Figure 13. Results from a snap test of the frame structure; red line shows the frame base motion imparted by the shake table, blue line shows the measured frame roof response, green line shows the finite element model prediction of the frame roof response for the snap test motions.

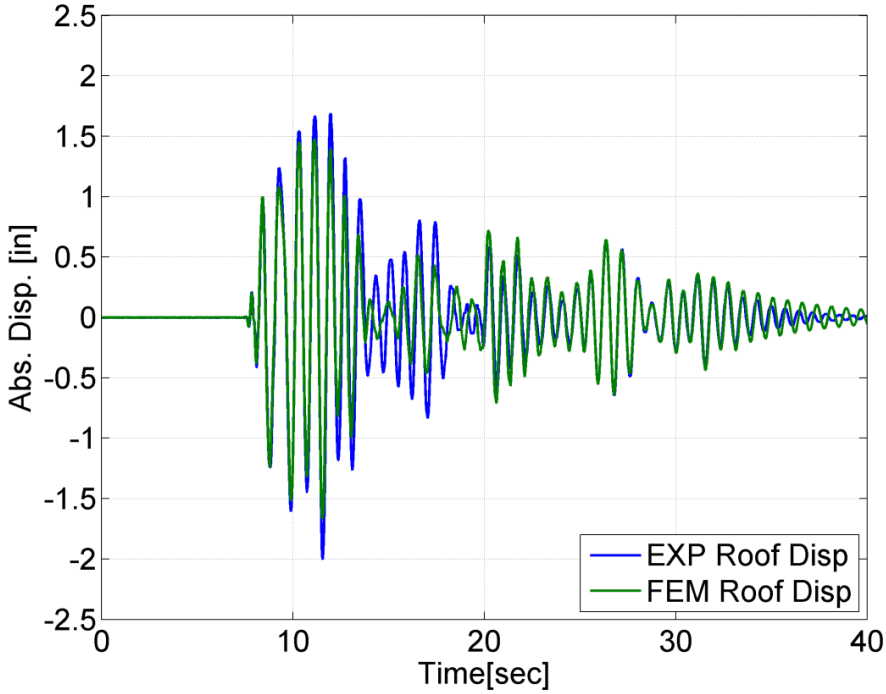


Figure 14. Comparison of roof displacement from the shake table test with the roof displacement predicted by the finite element model (El Centro 100% motions).

Table 2. Observed and computed frame natural periods of vibration.

Mode #	Observed frame periods (from snap tests)	Computed frame periods (from 3D finite element model)
1	0.777 sec	0.767 sec
2	0.190 sec	0.178 sec
3	0.154 sec	0.153 sec

The finite element model of the frame structure was slightly stiffer than the actual frame. After some quick sensitivity studies, it is judged that this is most likely due to additional flexibility at the connection between the frame base and the shake table platen, i.e. the as-built connection was not a truly a fixed connection as idealized in the finite element model (the connection shown in Figure 15). While the detailed evaluation and study of the finite element model results was outside the scope of this project, the project team will take a closer look at the influence of base plate flexibility in the future.

It is noted that this frame response data provides a good dataset for validation of finite elements models of streel frame structures and thus provides broader utility and value beyond the current research project.

Experimental Sensor Data for Earthquake Excitations

The experimental program executed a large number of shake table tests in sequence. The testing approach was to start with low amplitude motions, where the target motions shown in Figure 11 were scaled down in amplitude, and then incrementally increase the motion amplitude until the full earthquake motions, and even higher scaled motions, were achieved. This approach provided data on overall performance of the experimental set-up prior to shaking the system with very strong motions. The experimental system performed quite well and good data on sensor performance was obtained. Overall 30 earthquake tests were executed at varying amplitudes for both uniaxial and biaxial motions.

The sensors performed well during the experimental testing. No adverse effects due to strong shaking were observed in either the sensors or the mounting systems (see Appendix A for the details of the mounting system). Three representative datasets are included here to demonstrate the comparison between the DDPS and ground truth measurements.

El Centro ground motions – 100% amplitude motions applied biaxially to the frame

The interstory drift time histories for all three stories of the building for the 100% El Centro motions applied biaxially to the building frame are shown in Figure 16. The DDPS drift values account for both the lateral sway of the frame and the local rotation of the structural members at the mounting location of the laser (the rotation is measured by the horizontally

propagating lasers shown in Figure 9). The DDPS measured drift values capture both the amplitude and frequency content of the story drifts for all three stories.

Figure 15. Frame column base plate connection.

Rinaldi ground motions – 20% amplitude motions applied biaxially to the frame

The interstory drift time histories for all three stories of the building for the 20% Rinaldi motions applied biaxially to the building frame are shown in Figure 17. The Rinaldi motions contain a significant near-field ground displacement pulse which excites the frame strongly as the first ground motion waveforms are applied, so this motion was scaled down to provide margin against major frame damage and potential frame collapse. Similar to the El Centro 100% motions, the DDPS drift values are in good agreement with the ground truth drifts.

El Centro ground motions – 250% amplitude motions applied uniaxially to the frame

At the end of the overall testing campaign, the frame was shaken very strongly with the El Centro ground motions scaled to 250% of the ground motion record. The interstory drifts obtained from the ground truth diagnostics and the DDPSs are shown in Figure 18 and good agreement was observed.

The high stiffness of the steel test frame actually created significant demand on the optical sensors. The interstory displacements, and resulting drifts, in the 1/3 scale frame were small compared to the displacements that would occur in a full-scale building structure and the DDPS design is physically dimensioned to measure full-scale buildings drifts, i.e. the sensor dimensions shown in Figure 5 were driven by full-scale structure drifts. Nevertheless, even with the relatively small amplitude interstory displacements in the scaled experiment, the sensors performed very well.

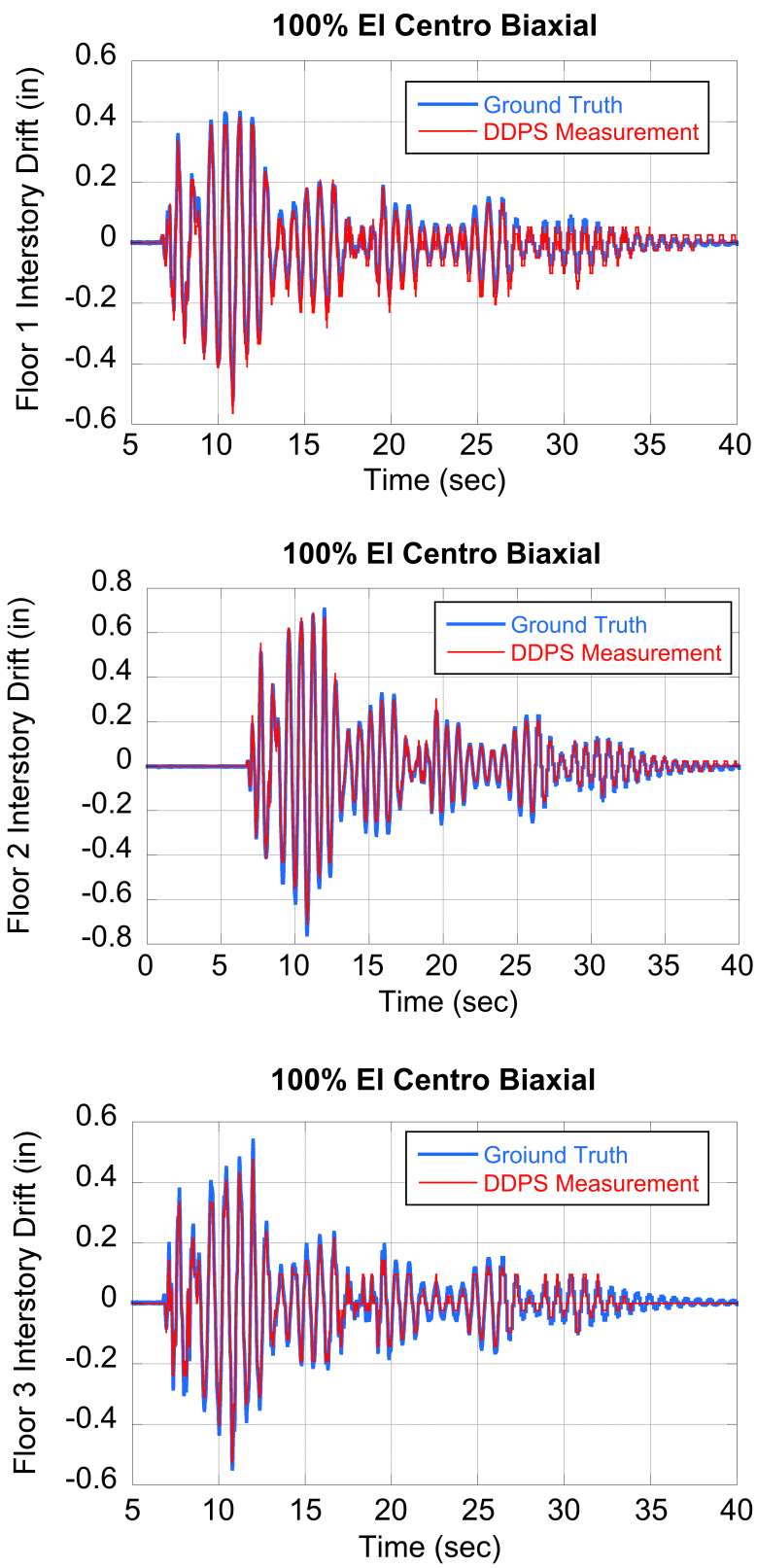


Figure 16. Ground truth and DDPS measurements of interstory drift (100% El Centro motions).

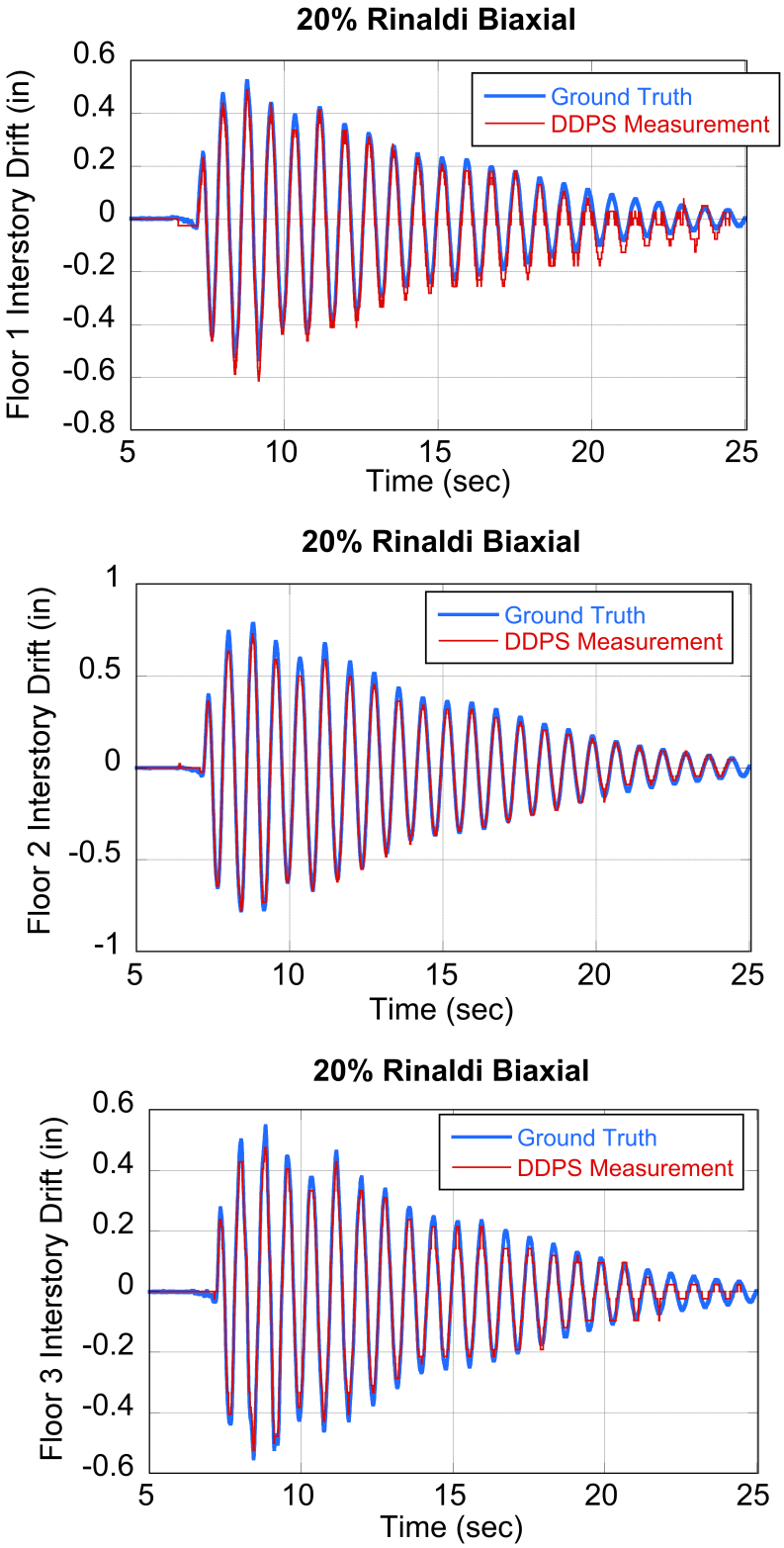


Figure 17. Ground truth and DDPS measurements of interstory drift ` (20% Rinaldi motions).

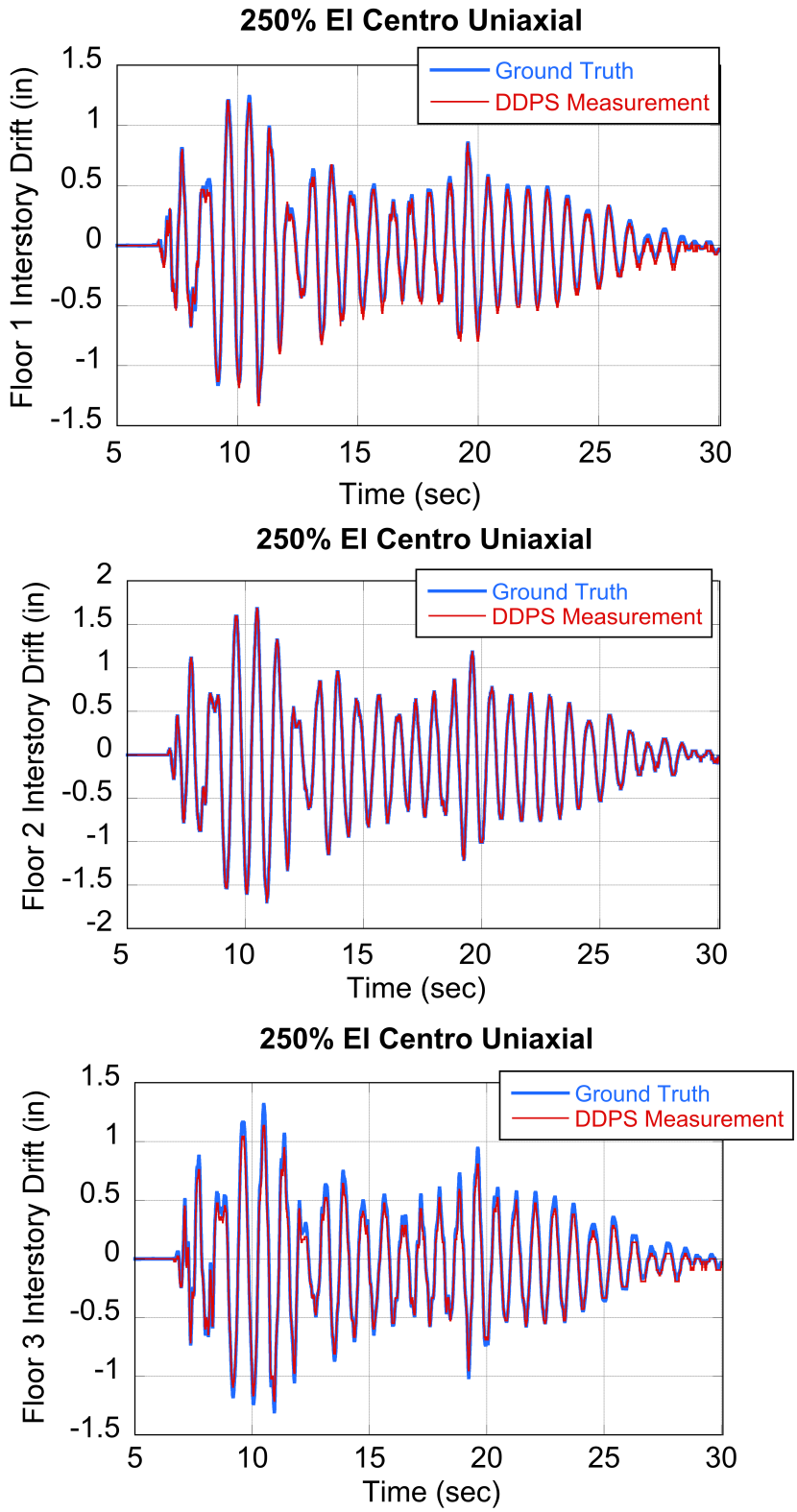


Figure 18. Ground truth and DDPS measurements of interstory drift (250% El Centro motions).

The drift displacement amplitude scaling with building size is illustrated in Figure 19 and Table 3, where the interstory drifts for ~1/3 scale and full-scale buildings are shown for the design standard limit state drifts in Table 1. At the 1/3 scale, the small displacements result in a larger relative sensor error, but as shown in Figures 16-18, the sensors have sufficient resolution even for the small drift displacements of the scaled building.

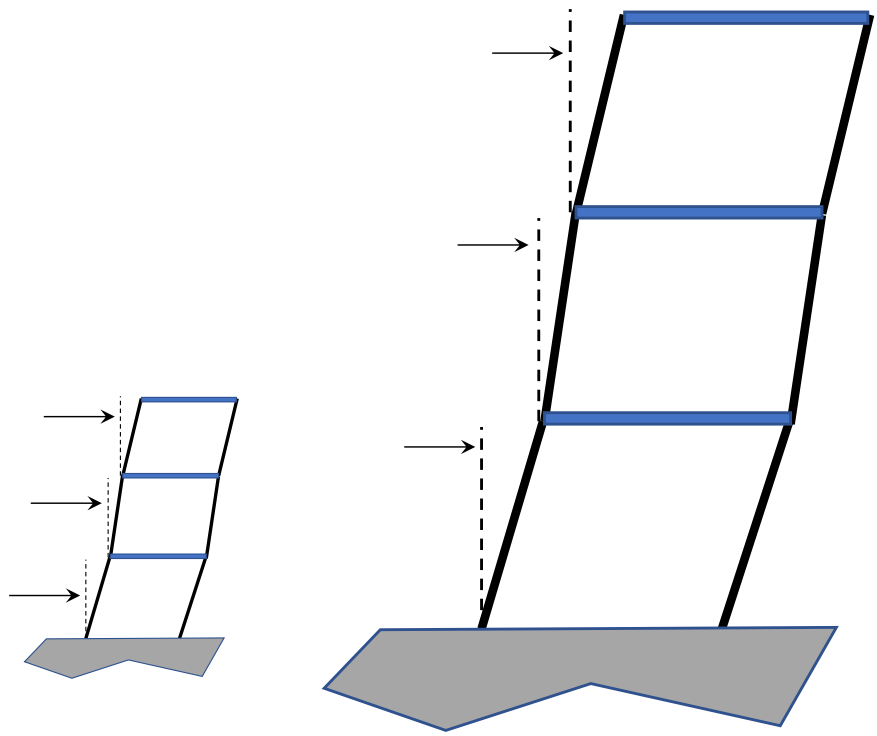


Figure 19. 1/3 scale and full-scale building structures.

Table 3. Interstory displacements at selected % drifts for 1/3 scale and full-scale buildings.

	~1/3 scale steel frame (story heights 48 in.)	**Full-scale steel frame (story heights 144 in.)**
Interstory displacement at 0.5% drift	0.24 inches	0.72 inches
Interstory displacement at 1% drift	0.48 inches	1.44 inches
Interstory displacement at 2.5% drift	1.20 inches	3.60 inches
Interstory displacement at 3.5% drift	1.68 inches	5.04 inches

In practice, the dimension of the DDPS diode array is driven by the measurement of the extreme drifts associated with Limit State A (Table 1, corresponding to “large permanent distortion”), which requires a diode array on the order of 9-10 inches (+/- 5 inches of drift measurement) for a building with twelve-foot story heights. As shown in Figure 5 the current DDPS prototype has a diode array dimension of approximately 9 inches, which is readily expandable as needed to accommodate larger drift displacements associated with taller floor heights.

Summary and Technology Readiness for Application

This research project evaluated the DDPS performance at significantly more realistic conditions than pervious small-scale laboratory tests. The sensors and mounting systems were found to perform well at high levels of earthquake shaking without any detrimental dynamic response characteristics of the vibrating integrated sensor board. In addition, the accuracy and ability of the DDPS system to accurately and reliably measure interstory drift after a set of 30 strong motion events was demonstrated. These results demonstrate the sensor accuracy and the resiliency of the sensors under strong shaking.

The DDPS technology is demonstrably close to being ready for practical application. Remaining tasks include formalizing the design and guidance for sensor mounting options in actual structures, and value engineering to reduce cost and maximize sensor reliability. It would also be very beneficial if the second line of sight and sensor used to measure local laser rotation (i.e. the horizontal laser lines of sight in Figure 9) could be replaced with an alternative means of measuring the local rotation of the laser. Obviating the need for a second line of site would significantly aid the simplicity of sensor system deployment. The current research motivated thought on an alternative methodology for measuring local rotation and that technique is under consideration.

In terms of practical application, the ultimate vision for the DDPS sensor system is to provide the data necessary for a very rapid determination of structural drifts throughout a building immediately after an earthquake. This could take the form of a simple graphical “stop-light” chart which displays whether user defined limit states were surpassed during an earthquake event (Figure 20). This data would provide critical, unprecedented, information to inform emergency response operations and continuity of operations in critical facilities. In the current study, a modest effort was focused on the feasibility of an internet based tool to transmit and display data to a smartphone through a developed Android application. The feasibility of utilization of the *Internet of Things* to display such data was successfully demonstrated through the piping of data to an Android based smart phone with a stop-light colored array of interstory drift as shown in Figure 21.

This technology can provide the DOE/NNSA as well as a myriad of other agencies and commercial entities with a new means of assessing structural damage potential immediately after an earthquake event to inform critical management decisions. The optically based system offers a number of features that provide advantages over traditional accelerometer based systems including rapid data display without extensive post-processing, the ability to directly measure interstory drifts to compare with design

standard limit states, and the ability to accurately measure permanent displacements due to inelastic response.

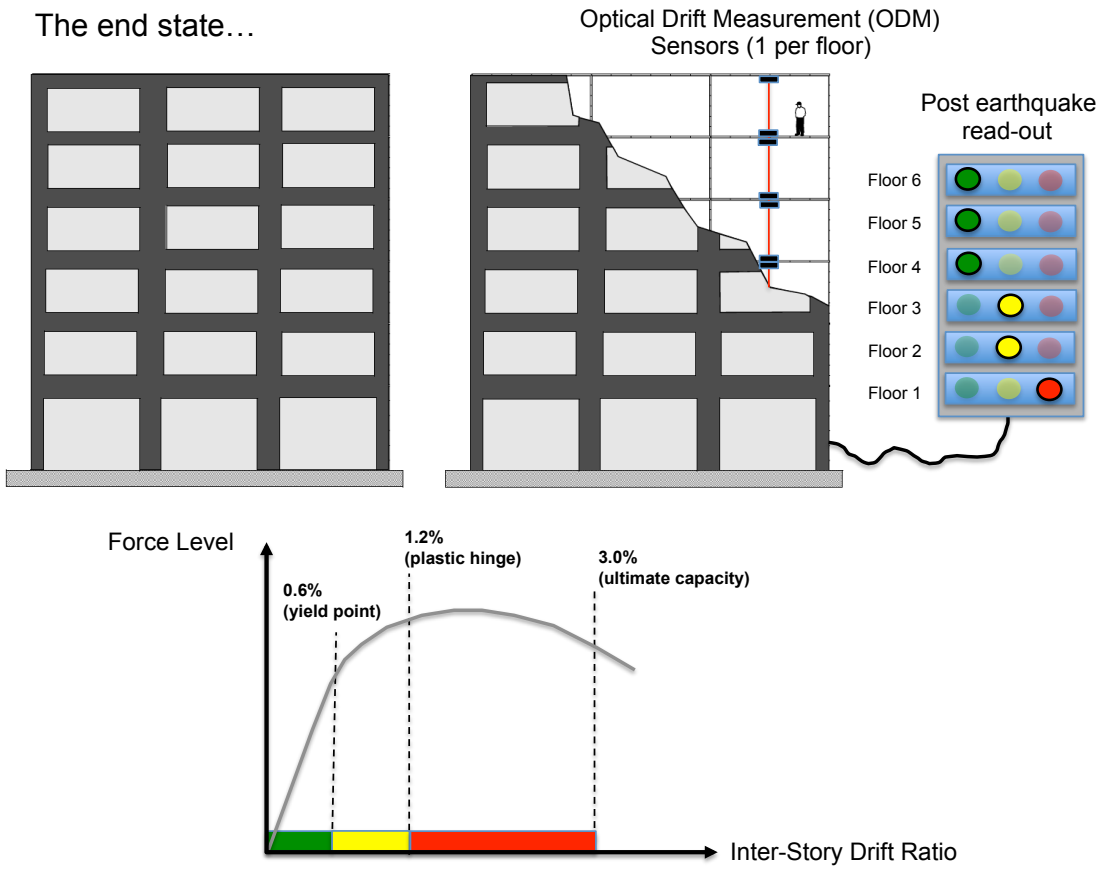


Figure 20. Real time read-out of building earthquake drift with a limit state stoplight chart.

Figure 21. Screen shot from a prototype Android phone app with peak interstory drift data from the DDPS sensors routed through the internet.

Next Steps

This research project yielded important new data and the results from this work will be translated into a research publication for a journal or professional conference to obtain peer review as well as to expose the broader community to the potential of optical sensors. To develop refined deployable sensors at scale, it will be necessary to execute technology transfer to a commercial entity capable of performing cost-effective, high-quality manufacturing and large unit production of a final sensor package. There may be opportunities to support technology transfer through the DOE SBIR programs which will be starting in the near future, and conversations with various interested commercial entities are ongoing.

Acknowledgements

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Appendix A

Test Configurations

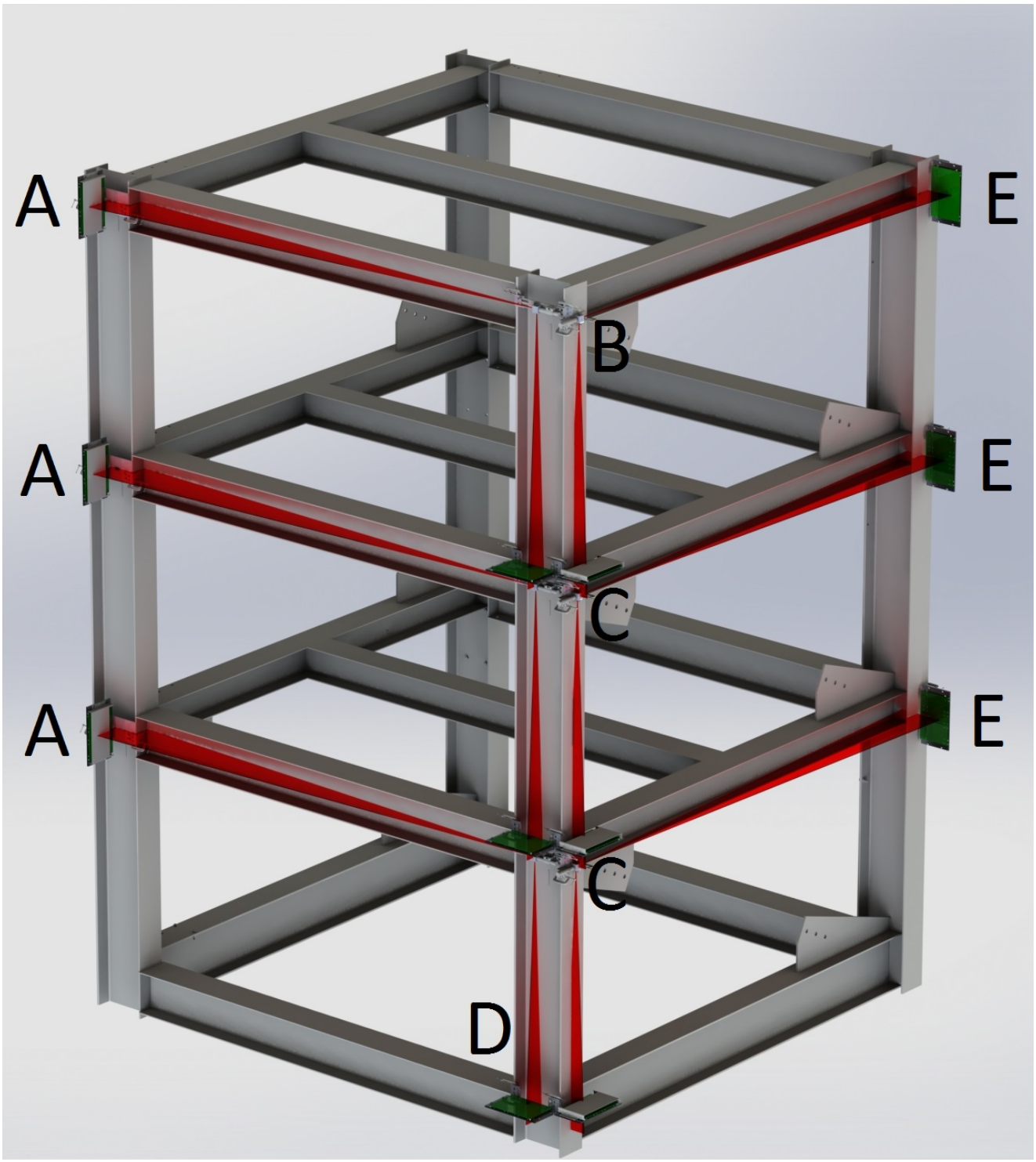
Original 1/3 scale steel building frame prior to removal of diagonals

Sensor mounting hardware fit-up on steel frame structure

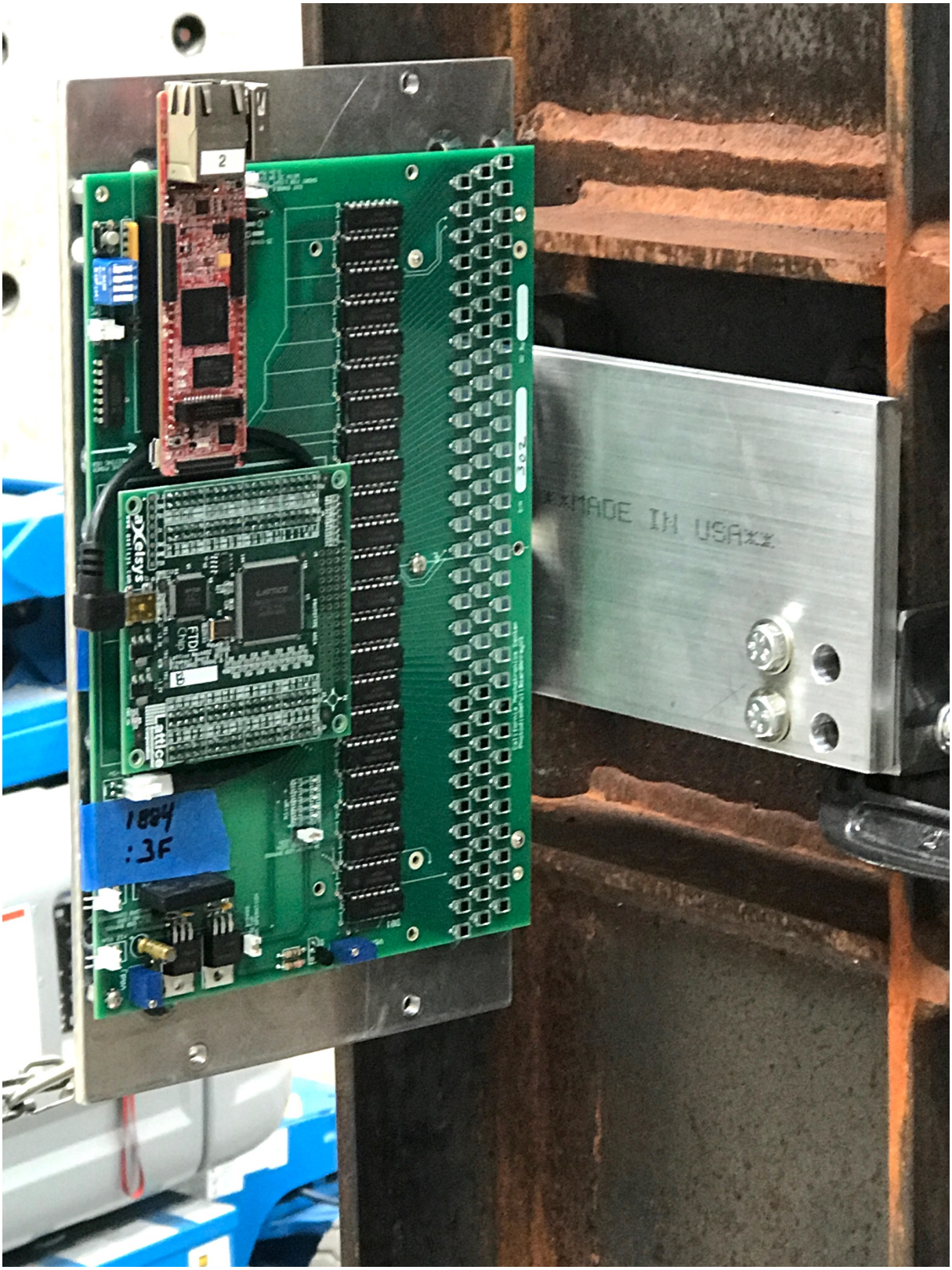
Test frame with diagonals removed and pinned beam connections in the plane of the removed diagonal elements for floors one and two (UNR shake table)

Frame on shake table with added floor mass and diagnostics tower

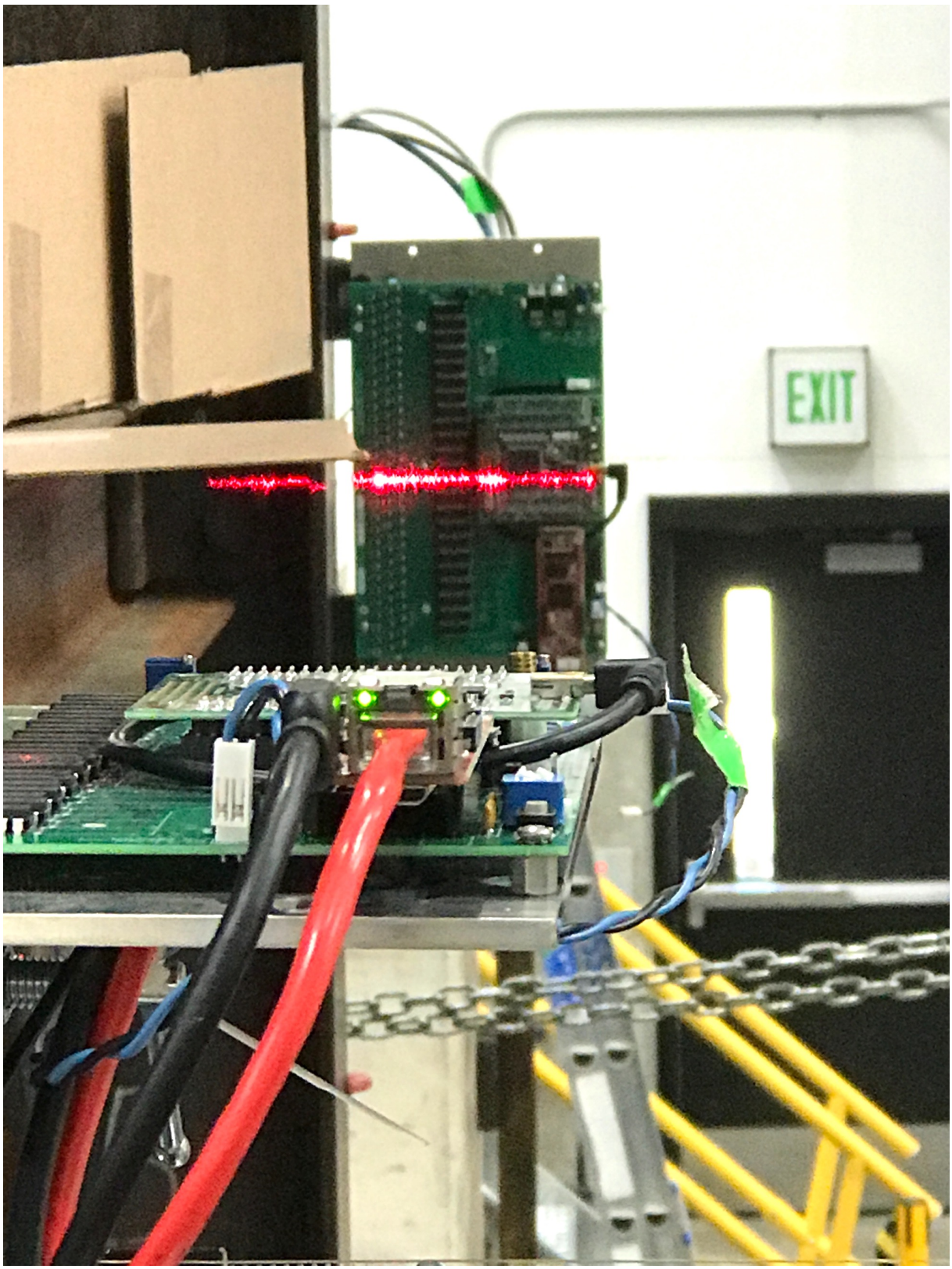
Sensors and lasers being mounted to the test frame



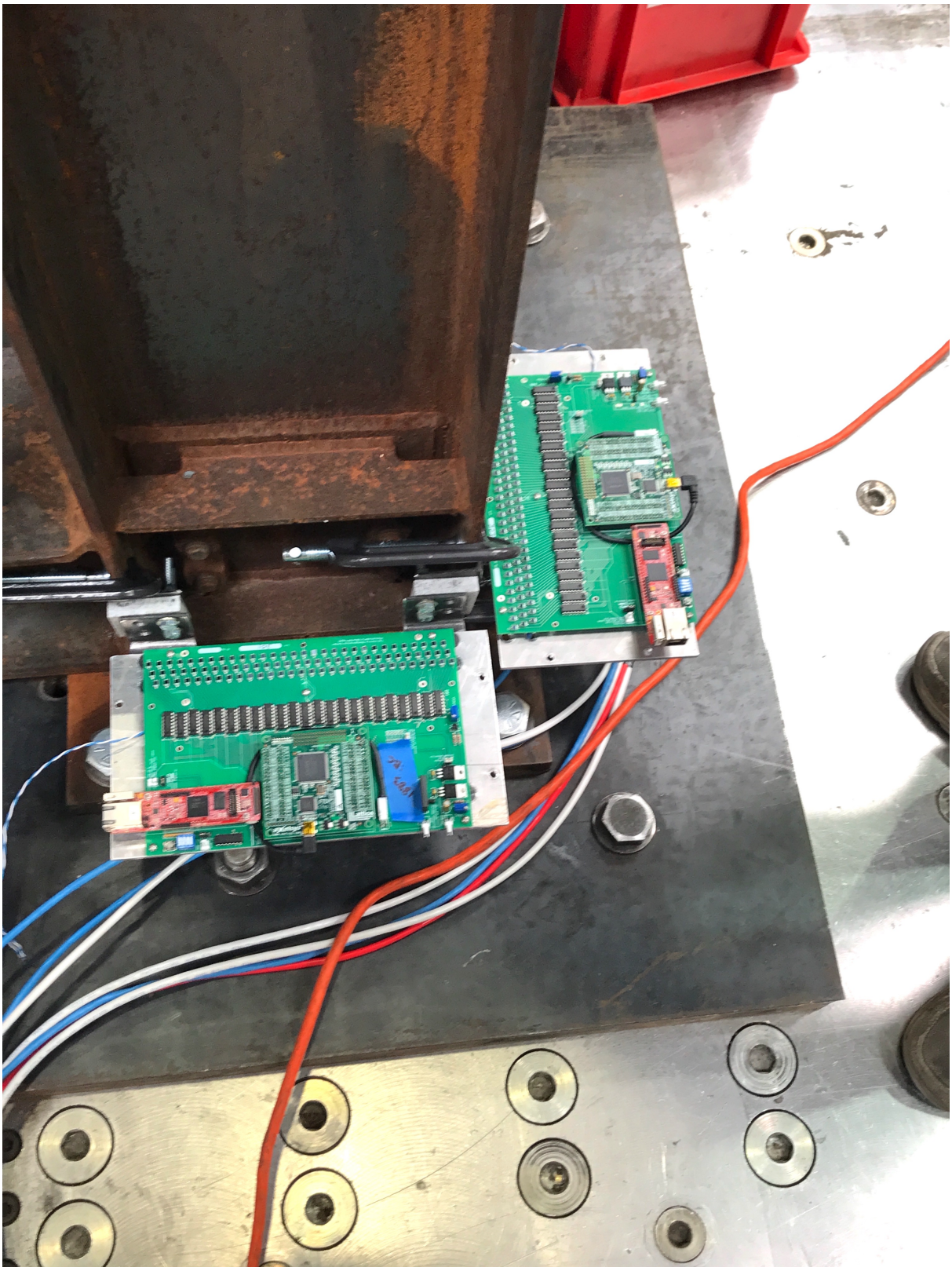
Schematic of laser – sensor system layout



Vertical DDPS mount for measuring laser rotation



Diffracted laser line source impinging on the vertical DDPS



Horizontally mounted DDPS for measuring lateral drift

Test frame and diagnostics towers viewed from the UNR shake table master control room