Seismogeodetic Monitoring of Engineered Structures Using MEMS Accelerometers

J. Saunders[1], D. Goldberg[1], J. S. Haase[1], Y. Bock[1], D. Melgar[1], J. Restrepo[2], A. Nema[2], R. Fleischman[3], Z. Zhang[3], J. Geng[1], D. Offield[1], M. Squibb[1]

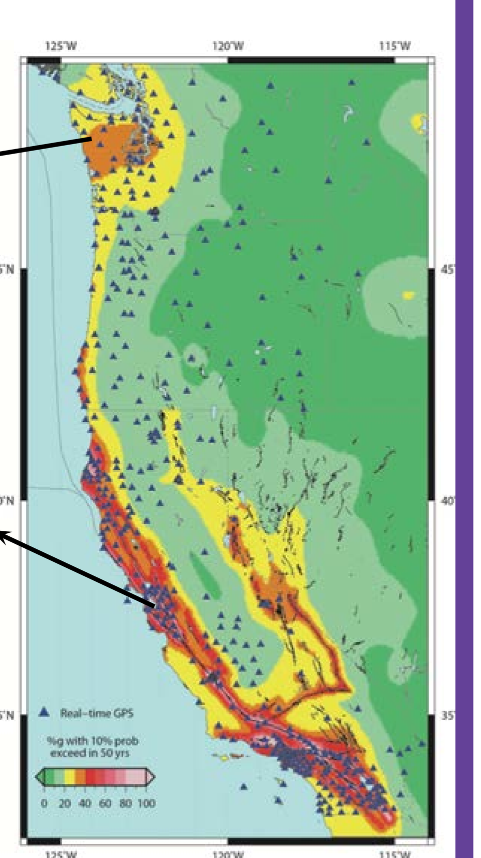
1. Scripps Institution of Oceanography, UCSD, La Jolla, CA 2. Jacobs School of Engineering, UCSD, La Jolla, CA 3. Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tuscon, AZ

ABSTRACT

Building response monitoring in seismically active areas requires accurate strong motion recordings in order to reliably assess building damage after an earthquake. The drift at the rooftop (displacement divided by the height) is the criteria specified by the Federal Emergency Management Agency (FEMA) to determine the safety for occupancy. However, accelerometer data cannot be reliably integrated to absolute displacement. We use a seismogeodetic solution, which combines the analysis of low frequency GPS with high frequency accelerometer observations through a tightly coupled Kalman filter for full bandwidth estimation of seismic displacements and velocities. We compare the seismogeodetic solutions calculated using low cost MEMS strong-motion accelerometers to solutions using observatory-grade Kinemetrics Episensor accelerometer packages built at SIO for earthquake monitoring. These instruments were run in real time on a four-story structure on the University of California San Diego Large High Performance Outdoor Shake Table during testing of an inertial force-limiting floor anchorage design system to improve the building's resistance to very strong ground motions. Testing involved three phases of building configuration: the experimental configuration with decoupled floors and walls, the traditional configuration with coupled floors and walls, and a final configuration of grouted floors and walls. Each phase involved a sequence of earthquake simulations of varying magnitudes that resemble likely events for the western United States. We compare the spectra from the MEMS and Episensor recordings to quantify the noise of the accelerometers, which we expect to be higher for the MEMS. We will show that the inexpensive MEMS alternative can be sufficient for accurately recovering the drift of large engineered structures when used in combination with the GPS solutions and by inference for deployment at field GPS stations.

EXPERIMENTAL DESIGN:

INPUT GROUND MOTIONS



SEATTLE MAXIMUM CONSIDERED EQ

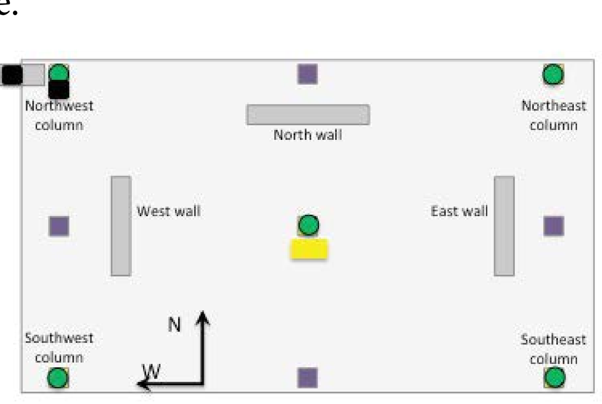
- Based on 1979 M6.6 Imperial Valley earthquake record at El Centro Array #5 Station
- 0.36 peak ground acceleration
- Distance 28km from fault
- Scaled to 0.50g
- Design Basis EQ scaled by 1/1.5

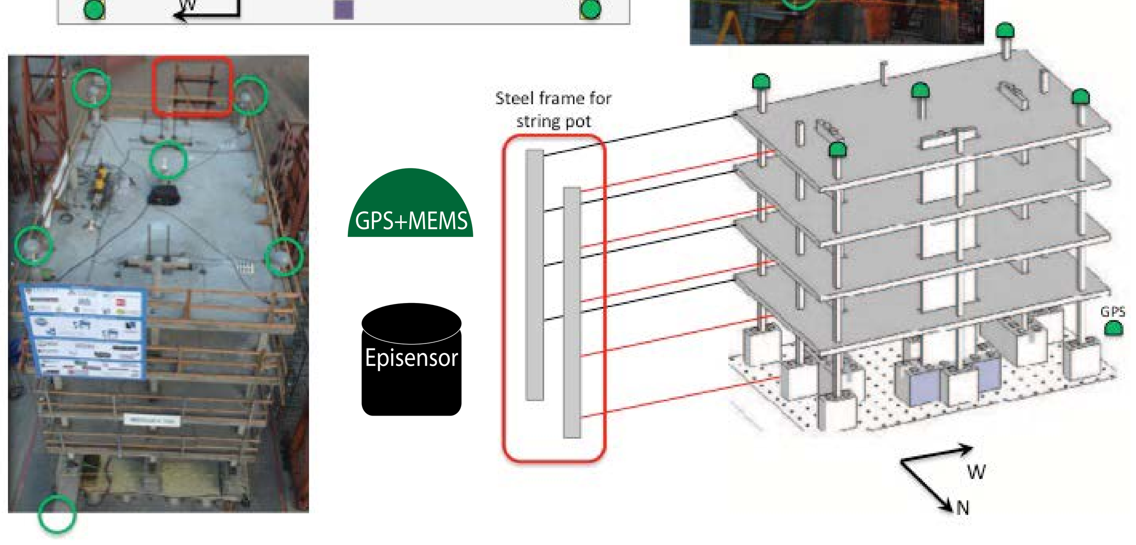
BERKELEY MAXIMUM CONSIDERED EQ

- Based on M6.9 1989 Loma Prieta earthquake recording at Los Gatos Presentation Center Station
- 0.97 peak ground acceleration
- Distance 4 km from fault
- Scaled to 0.61g
- Design Basis EQ scaled by 1/1.5

EXPERIMENTAL CONFIGURATION

Monitoring instruments included 4 collocated GPS+MEMS seismogeodetic stations on the roof of the building, and 1 collocated station on an arm extended from the NW corner of the foundation. Observatory- grade Episensors were also installed on the roof and foundation of the building. A reference GPS station was placed 48m off the shake table on the NW side.





Foundation Station GPS+MEMS and Episensor

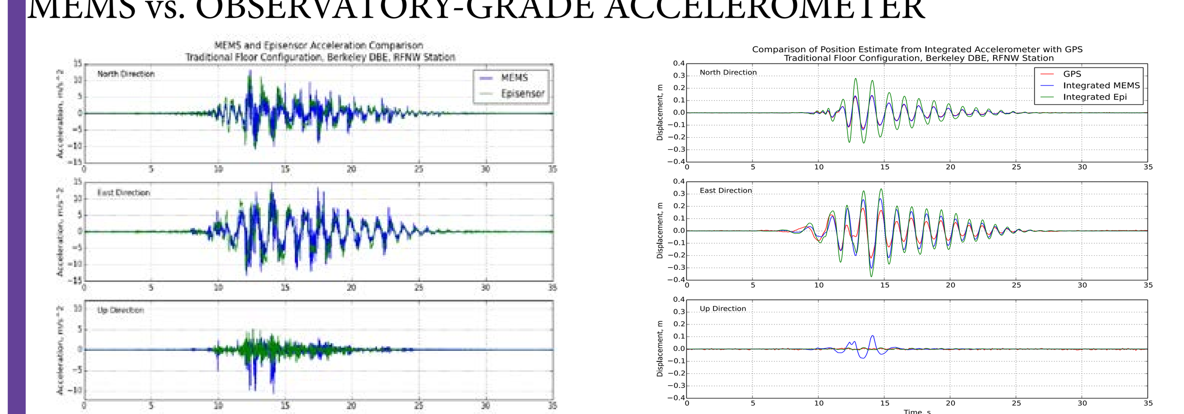
Local Reference Station

OBJECTIVES

1. Determine whether low cost SIO MEMS accelerometer meets accuracy requirements for large scale deployment
2. Quantify noise of MEMS accelerometer through comparison with observatory-grade accelorometer
3. Test seismogeodetic analysis approach for earthquake with high amplitude near-field ground motions and demonstrate attributes of seismogeodesy for engineering design and structural monitoring
4. Test the real time transmission, analysis and monitoring system for earthquake early warning

PERFORMANCE COMPARISON:

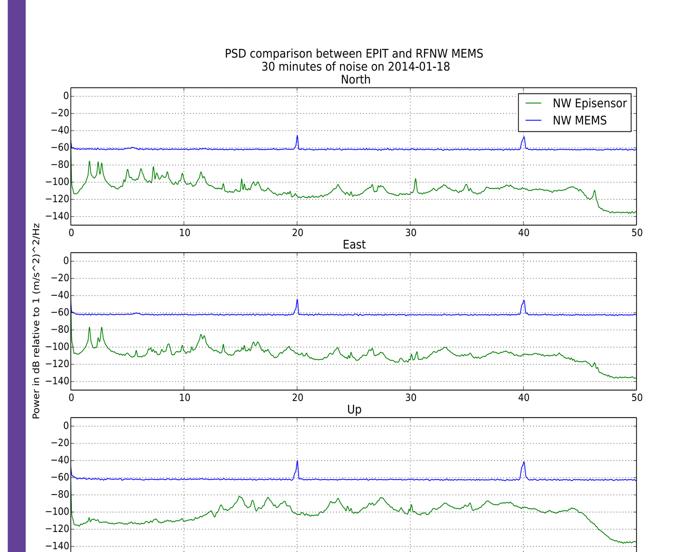
MEMS vs. OBSERVATORY-GRADE ACCELEROMETER



- Overall performance of MEMS is comparable to observatory-grade Episensor
- Bandlimited 33-40Hz noise present in MEMS that must be filtered out
- MEMS performance is reliable in the range ~1 to .1 s period
- Integrated MEMS displacement estimates in North and East directions in this case match GPS observations more closely than integrated observatory-grade accelerometer estimates
- Cross-channel contamination discovered in MEMS, especially visible in the vertical component, and is currently under investigation

BACKGROUND NOISE SPECTRA COMPARISON

Spectra for 30 minute section of ambient noise on January 18

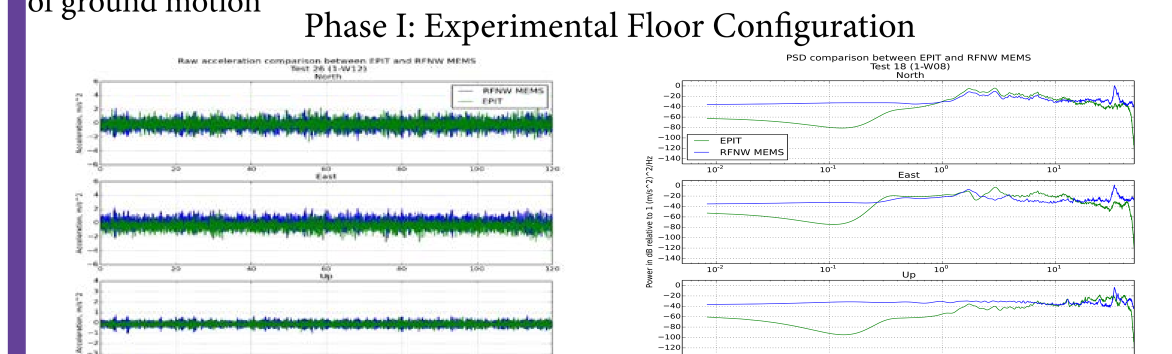


- The MEMS spectra for all components are flat at -60 dB with two spikes at 20 and 40 Hz
- With a Nyquist frequency of 50 Hz, signals at 120 and 60 Hz will be aliased to 20 and 40 Hz, respectively
- The -60 dB level corresponds to the resolution of the MEMS, which is ± 0.001 m/s^2 (~0.0001g)
- The Episensor spectra are at much lower power levels than the MEMS, generally ranging between -120 dB and -80 dB. Peaks are probably due to low level resonances in mechanical or electrical systems of the shaketable below the sensitivity of the MEMS

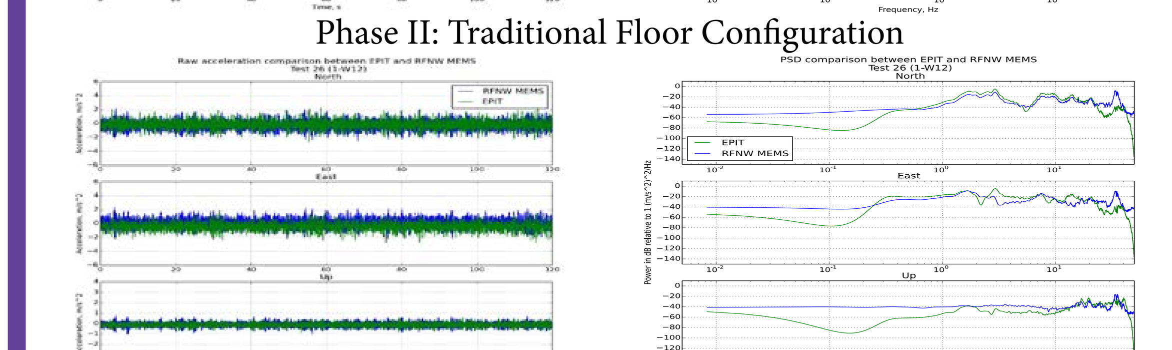
WHITE NOISE TEST COMPARISON

Prior to each earthquake test, a calibration test was carried out with white noise input time series in the 0.25 to 33 Hz range to confirm the plate responds with the desired level of ground motion

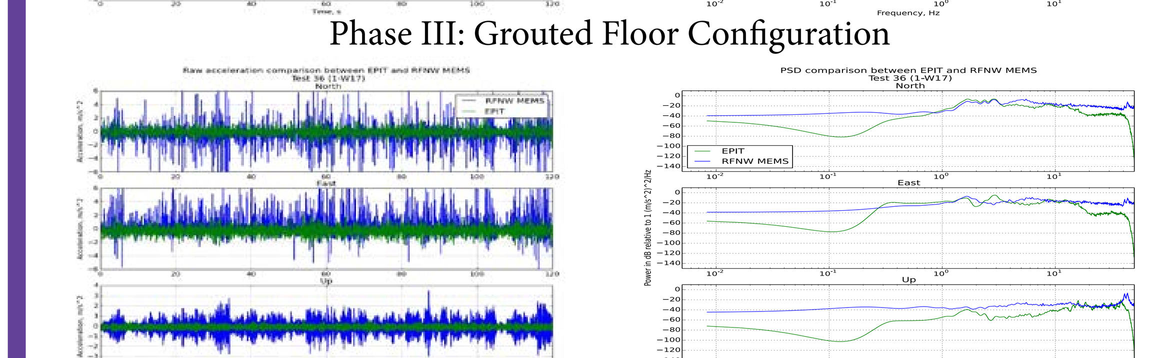
Phase I: Experimental Floor Configuration



Phase II: Traditional Floor Configuration



Phase III: Grouted Floor Configuration



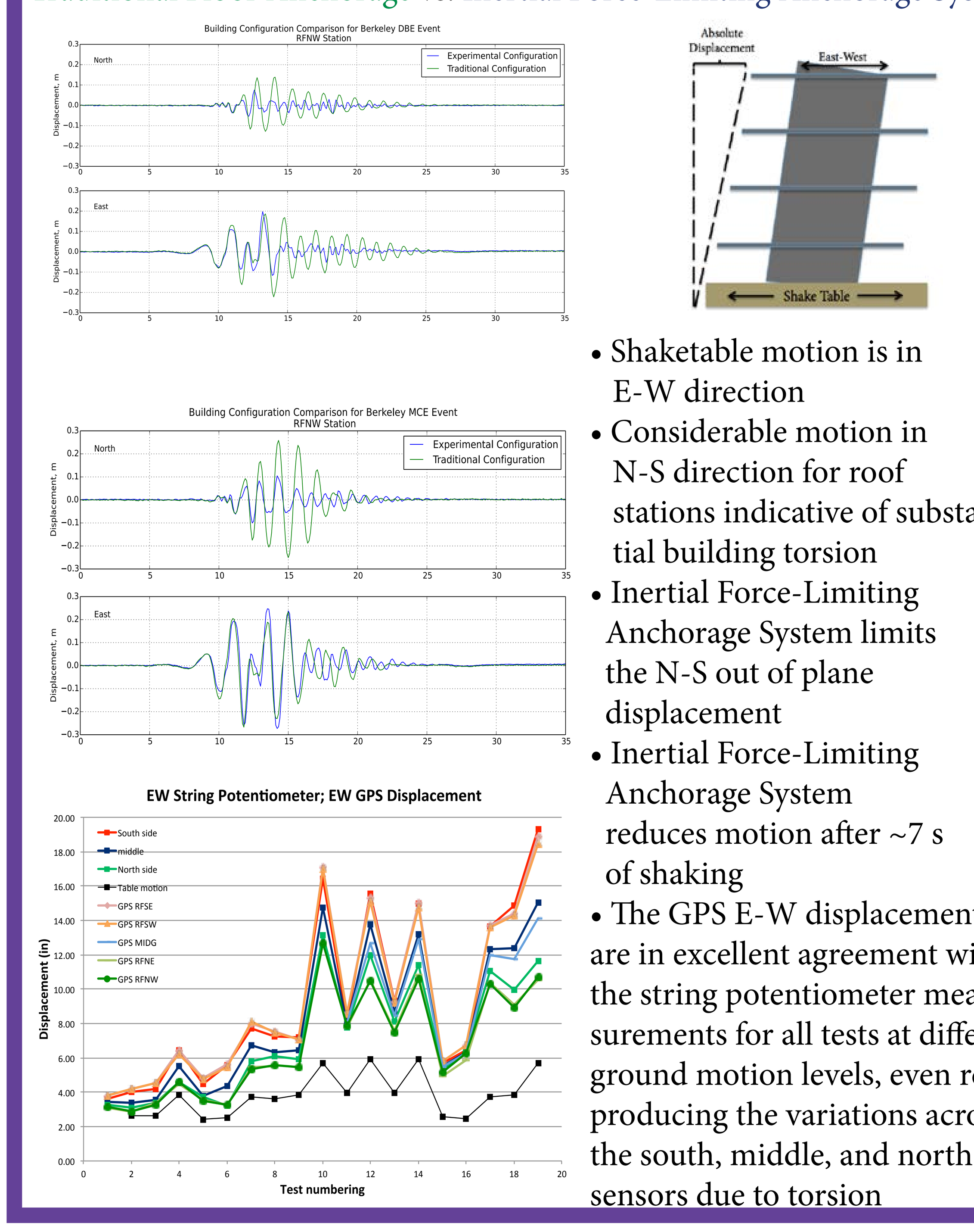
- MEMS and Episensor generally agree from 1 to 10 Hz for the North component
- Episensor and MEMS spectra differ significantly at 3Hz in the East component, which requires further investigation
- MEMS spectra show a peak at ~35Hz for Phase I and Phase II, sufficiently distinct from periods of interest for engineering and seismic source studies to be filtered out
- Physically unreasonable noise (i.e. one-sided on the East component) is present on MEMS channels during Phase III with a peak at ~40 Hz but contaminating the spectra to 15 Hz or lower
- Episensor power level is lower than MEMS for frequencies <0.25 Hz in all components, consistent with the sensitivity shown in the ambient noise tests

ENGINEERING OBJECTIVES

1. Test an innovative floor anchorage system intended to reduce inertial forces during major earthquakes
2. Demonstrate the designed differences in building response for increasing earthquake ground motion inputs representing the range of events of most concern for the western United States

BUILDING RESPONSE

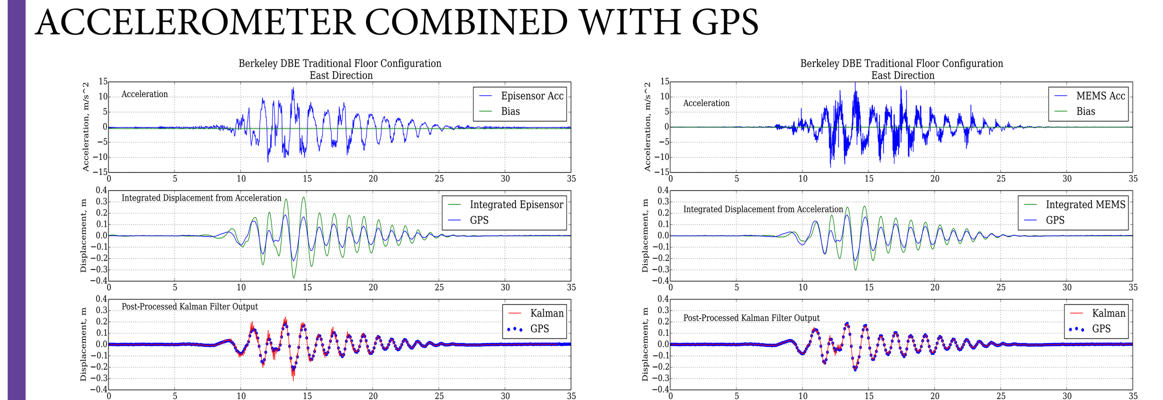
Traditional Floor Anchorage vs. Inertial Force-Limiting Anchorage System



- Shaketable motion is in E-W direction
- Considerable motion in N-S direction for roof stations indicative of substantial building torsion
- Inertial Force-Limiting Anchorage System limits the N-S out of plane displacement
- Inertial Force-Limiting Anchorage System reduces motion after ~7 s of shaking
- The GPS E-W displacements are in excellent agreement with the string potentiometer measurements for all tests at different ground motion levels, even reproducing the variations across the south, middle, and north sensors due to torsion

SEISMOGEODETIC SOLUTION:

ACCELEROMETER COMBINED WITH GPS



- Seismogeodetic Kalman filter output provides position data with improved low frequency accuracy (due to inclusion of GPS) and higher sampling rate (equivalent to that of the accelerometer)
- Seismogeodetic solution takes into account the variance of each instrument prior to shaking, weighting data accordingly such that solution minimizes error
- Accelerometer by itself cannot differentiate between translational and rotational movements, which may account for jaggedness in unsmoothed Kalman filter result. This can be solved with the new analysis technique that incorporates tilt into the calculation

CONCLUSIONS & FUTURE WORK

- The inexpensive SIO MEMS accelerometers performed well in this test of near-field strong ground motions, especially for the high accelerations (> 1.2 g) and ~1 s period resonance of the building response at the rooftop of the structure. Long-period (~1 s) motions were captured equally well for the MEMS and Episensor in the seismogeodetic combination.
- The seismogeodetic combination, because it reliably measures displacement as well as acceleration, has unique and valuable attributes for testing engineering designs, where it is important to assess the trade-offs in minimizing inter-story drift versus minimizing seismic forces.
- The GPS displacement data show that the new Inertial Force-limiting Floor Anchorage system, significantly reduces over-all floor displacement and out of plane motion produced by the torsion of the building.
- The GPS displacement data provide accurate measurements in the presence of torsion.
- A similar investigation of the stations co-located at the foundation will allow us to diagnose the inconsistencies seen between the two types of instruments.
- Visible building damage was observed following certain test events. Future seismogeodetic and spectral analysis may allow us to pinpoint the moment of damage and determine whether structural integrity was compromised beyond FEMA criteria.

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