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DENSE BUILDING INSTRUMENTATION APPLICATION FOR CITY-WIDE STRUCTURAL HEALTH MONITORING AND RESILIENCE

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Abstract

The Community Seismic Network (CSN) has partnered with the NASA Jet Propulsion Laboratory (JPL) to initiate a campus-wide structural monitoring program of all buildings on the premises. The JPL campus serves as a proxy for a densely instrumented urban city with localized vibration measurements collected throughout the free-field and built environment. Instrumenting the entire campus provides dense measurements in a horizontal geospatial sense for soil response; in addition five buildings have been instrumented on every floor of the structure. Each building has a unique structural system as well as varied amounts of structural information via structural drawings, making several levels of assessment and evaluation possible. Computational studies with focus on damage detection applied to the campus structural network are demonstrated for a collection of buildings. For campus-wide real-time and post-event evaluation, ground and building response products using CSN data are illustrating the usefulness of higher spatial resolution compared to what was previously typical with sparser instrumentation.

Keywords: damage detection, structural health monitoring, seismic instrumentation, earthquake engineering, resilient cities

1. Introduction

Modern cities are more technologically interconnected today than ever before. Reliance on common, inter-dependent systems (water, power, telecommunications) require metropolises to be more aware of the overall status and health of infrastructure as a whole, particularly when the system is placed under extreme stress (earthquakes, hurricanes, floods). Ascertaining useful information in real time in the past was almost exclusively acquired from human intelligence/point sourced information; however in a more connected world, a transition to data-driven solutions is now at the forefront of many innovative networked systems. By using sensor technologies in various types of infrastructure, continuous monitoring of sensor output and network status is influencing the way modern cities function. Incorporating these types of networks into seismology and building infrastructure is another step forward in understanding and responding to the status of cities before, during, and after an extreme event. New information on what is happening within a city at any moment can be used to make manual and automated real-time decisions by incorporating high-density seismic instrumentation, both at the ground level and on upper floors of buildings.

The Community Seismic Network (CSN) at the California Institute of Technology is working with private and public partners to deploy seismic instrumentation throughout the built environment at high spatial density. To date, CSN has instrumented 15 mid to high-rise buildings with over 170 sensors, as well as deployed a ground station array of nearly 400 seismometers. These data contribute to existing and emerging products within the USGS (such as ShakeCast [1] and earthquake early warning [2]) as well as to the development of new ground and structural response display portals for building owners and decision makers.

Taking advantage of dense instrumentation deployments in building structures (at least one triaxial sensor on every floor of the structure), we also perform analysis on a floor-by-floor scale. Ascertaining strong motion data from every floor of a building allows for localization of acceleration, velocity, and displacement which facilitates calculating inter-story properties (such as drift, potential damage, and internal forces) robustly. These high-density deployments and data processing methods are made possible by the development of low-cost accelerometers, continuous data archiving, and cloud-based technologies to construct a dynamic network.

Finite-element modeling is also performed when feasible to create a computational understanding of structures that are instrumented. We use these models in computational studies of damage detection, and also for compiling a pre-event database for inverse problems that seek to obtain the demand on the system. For example, a unique set of data was collected from a CSN instrumented 52-story building in downtown Los Angeles in February 2015 shortly after a large explosion occurred at an ExxonMobil oil refinery at a distance of 22 km. These responses and a finite-element model were then used to determine the pressure exerted over the height of the building by an air pressure wave resulting from the explosion [3]. Understanding how explosion pressure waves propagate through a cityscape is of significant interest with respect to homeland security. Data from incidents such as these can be used to develop procedures for blast effects mitigation, as well as to independently quantify the size of the explosions. This type of analysis also emphasizes the usefulness of continuous data collection coupled with finite-element modeling of structures. Had the acceleration data not been collected continuously, but instead stored only in short time durations limited to strong-amplitude triggering, this information would not have been recorded. Further, by having ground instrumentation and building instrumentation working in tandem, the decoupling of the atmospheric pressure wave and ground motions was possible.

The developing field of using crowd-sourced seismometers to measure the vibrational properties of every building in a city represents new technologies lying at the intersection of earthquake engineering, earth sciences, and computer sciences that are revitalizing civil engineering work. The combined datasets from ground sensors and building sensors illustrate the value of densely instrumenting both the free field and buildings with the goal of providing assessments of strong shaking and structural damage from events such as earthquakes and explosions.

2. Instrumentation and Data Collection

Cost reduction is critical to making spatially dense seismic instrumentation a reality. Traditional strong-motion equipment used in earthquake engineering comes at a price point that prevents commercial partners from having their properties monitored. CSN has developed affordable seismic instrumentation at a fraction of the cost of more traditional strong-motion sensors and data loggers. CSN seismometers use Class-C MEMS triaxial accelerometers (capable of recording up to ±2 g accelerations on-scale with a sensitivity of ~70 micro-g) coupled with a small onboard 1.2 GHz ARM processor with 512 MB SDRAM running LINUX. This instrumentation can be placed anywhere internet connectivity is available, and has made dense monitoring a convenient reality for building owners, and feasible from a network operations perspective.

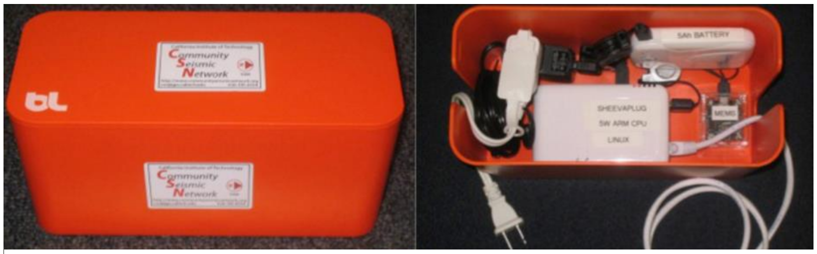


Fig. 1 – CSN instrumentation showing MEMS accelerometer, onboard computer and backup battery.

In more critical locations, instrumentation is also deployed with backup battery supplies, as well as onboard data storage for storing approximately two weeks of continuous data in the event of loss of internet connectivity. This adds to the robustness of the network in case a large event causes secondary systems (such as power and/or telecommunications) to fail, as the data would be of great value if structural damage or failure also occurred and was recorded.

When there are no connectivity issues, all data are stored continuously for either real-time or post-event processing in the Google Cloud. Once data has been transferred to the cloud, Google's App Engine tools are used to perform processing. Data are also stored in a locally accessible database for researchers and other interested parties. For additional information about the network and sensor technology, see [4], [5], [6] and [7].

3. JPL Proxy City

3.1 About JPL campus

The NASA Jet Propulsion Laboratory (JPL) has partnered with CSN to use their campus (Fig. 2) as a proxy for a densely monitored city of the future. Campus instrumentation includes over 50 ground stations and approximately 50 elevated stations in five buildings to date (Fig. 3). This deployment has resulted in the development of new/improved products for both ground motion information (such as ShakeMaps [8] with more refined, site-specific data) as well as new visualization tools to better understand the structural state-of-health over the entire campus.

Many of the significant facilities at JPL date back to the 1960s or earlier. There continue to be concerns with the construction practices of the time (e.g., brittle welding that has the potential to fracture during strong shaking) and the building stock resilience to the local earthquake hazard. CSN is working with NASA to create visualization tools and resources that will give JPL, and other potential adopters, the ability to know what has happened to their facilities during a large event. We are also computationally exploring localized damage detection methods through investigation of different types of signatures that may be present in waveform data.

The campus also allows us to explore ideas of what city planners and business owners would want with respect to data reduction. Developing data driven products that give decision makers the information they need in the event of a critical event is a fundamental priority of this endeavor. This includes but is not limited to simplistic evaluation of localized deformation characteristics, as well as allowing interpretation and user prioritized levels of alert values for parameters, such as acceleration and drift, which would indicate poor performance of a structure. Currently a web platform is under development to allow users the ability to access this information remotely and securely.

Fig. 2 - Aerial view of the NASA Jet Propulsion Laboratory showing the various types of structures on the campus and how density is similar to a cityscape (*Google Earth*).

3.2 Pseudo free-field instrumentation

For the purpose of understanding the earth's subsurface properties at high resolution, instrumentation is distributed at a spacing of approximately 70 m at the ground level of nearly every structure on the campus (Fig. 3). Fig. 3 shows current and planned deployments of the network in the pseudo free field, of which many of the newest instrumentation locations will be deployed on a mesa in the foothills of the San Gabriel Mountains. Recent studies focus on the surface effects of waves traveling through local topographic guides [9], and these data are expected to contribute to a better understanding of this phenomenon, as well as provide information about the fragility of JPL assets on the mesa vs. those on the edge of the shallow sedimentary valley to the south.

Subsurface geological structure can contribute significantly to the response of the earth locally, and current networks deployed throughout the Los Angeles basin do not have sufficient resolution to capture these local effects. In particular, values from a microzonation map showing variations in seismic response amplification of the ground in a targeted area can be used to estimate the variations in shaking that will occur within a relatively small area. Microzonation of the JPL campus is being carried out using local earthquakes that are recorded by CSN sensors distributed around campus. These have already shown evidence for amplification variation, as a result of the 7/25/2015 M4.2 Fontana, CA earthquake. Amplification is a function of the azimuth of the incoming seismic energy as well as the subsurface geological structure, e.g., low-velocity basin sediments vs. hard rock sites. The Fontana event suggests that amplification occurred at sites adjacent to the San Gabriel Mountain foothills which may have experienced a basin-edge effect in which the geometry and impedance contrast between the sedimentary valley to the south and hard rock mountains to the north are affecting the campus response on a length scale of 10-100 meters. The most effective way to produce a comprehensive, accurate microzonation map is to analyze multiple events with different magnitudes as well as originating from different locations sending seismic energy into the JPL campus at a variety of azimuths.

Seismic stations in dense urban monitoring deployments typically have 3 to 4 km spacing [10], and interpolations of the data must be made for mid-station locations. Los Angeles, and other seismically active regions with regional seismic arrays, have broadband stations with 10-20 km spacing, nowhere near the resolution of what is classified as "dense urban monitoring." Further, USGS guidelines [10] suggest that to capture local amplification effects, arrays need station spacing of 1 km or less.

By using the JPL campus as a proxy for dense ground instrumentation, localization of seismic demand on a building-by-building basis becomes possible, and peak characteristics which are used in various analysis products (such as ShakeCast [1]) will have local, site-specific data streams to feed into fragility curve assessments. Our concentrated array of instruments is significantly denser than 1 triaxial station/1 km and makes it possible to observe differences in local demand between adjacent sites in a cityscape.

Furthermore, dense station spacing can contribute to very high-resolution maps of amplitudes and shallow crustal seismic velocities through cross correlation of ambient noise time series [11] [12]. Spatial and frequency-dependent amplitudes and velocities are obtained by computing phase velocities and amplitude gradients for different frequency bands between points in a grid occupied by a dense ground array. Tomographic inverse methods are used to produce a map of the lateral variations in the phase velocity for that frequency, followed by an inversion which maps phase velocities into shear velocity as a function of depth. When this is done for long time windows encompassing a large azimuthal range of environmental vibration noise sources, site amplification maps across such dense arrays can be turned into microzonation maps for quantitative constraints on structural response to future strong ground shaking at a specific location.

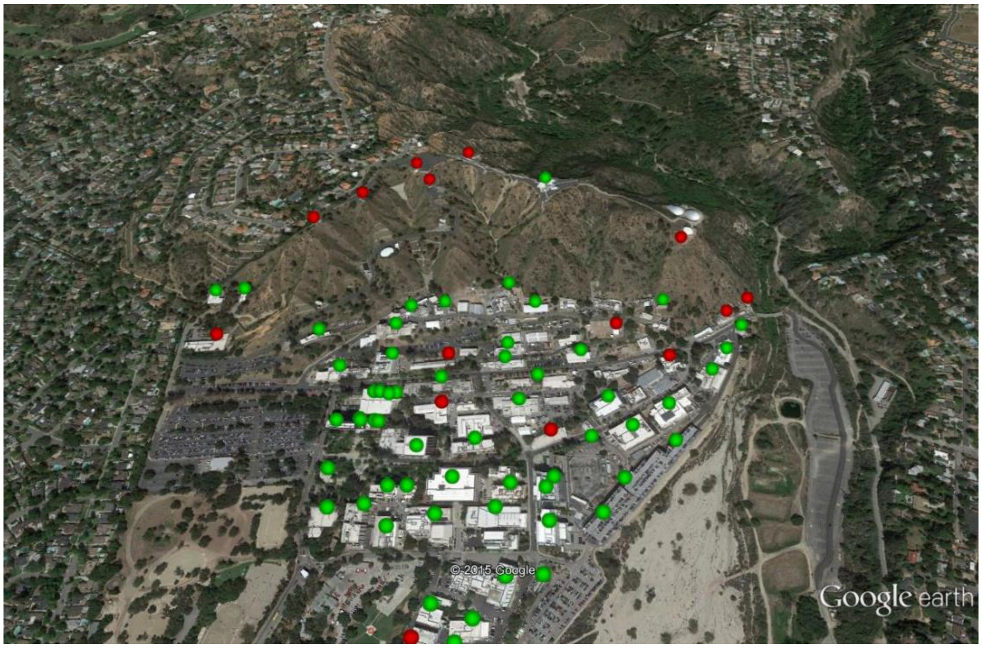


Fig. 3 – 2015 CSN ground and building sensor installations (green=existing; red=planned).

3.3 Building instrumentation

To date, CSN has instrumented five primary buildings at JPL, for which structural drawings have been obtained for three. The lateral systems of two of these structures (JPL Buildings 180 and 183) are a trussed frame (180) and a more traditional moment frame (183), while both are 9-story buildings built in the early 1960s. Different potential failure mechanisms being explored include but are not limited to truss bar failure, moment connection fracture, strong beam-weak column mechanisms, and lateral torsional buckling of unbraced trusses.

Another unique structural feature of JPL Building 180 is the length-to-width ratio of the structure's exterior dimensions (Fig. 4). The lack of depth in the north-south direction makes the structure prone to large deformation associated with torsion, as well as to potential differential diaphragm displacements. CSN typically places two triaxial sensors on each floor of a building to capture translational motion as well as torsion. Due to the length of this building, a third sensor was deployed on each floor to determine whether amplification could be observed along the diaphragm length. During the 7/25/2015 M4.2 Fontana, CA earthquake, amplification of floor diaphragm deformation was observed to contribute to large variations in the north-south translational responses along the length of the building. Additional instrumentation in the other buildings on the JPL campus will further increase CSN's database of building types, including concrete moment frames and shear wall structures.

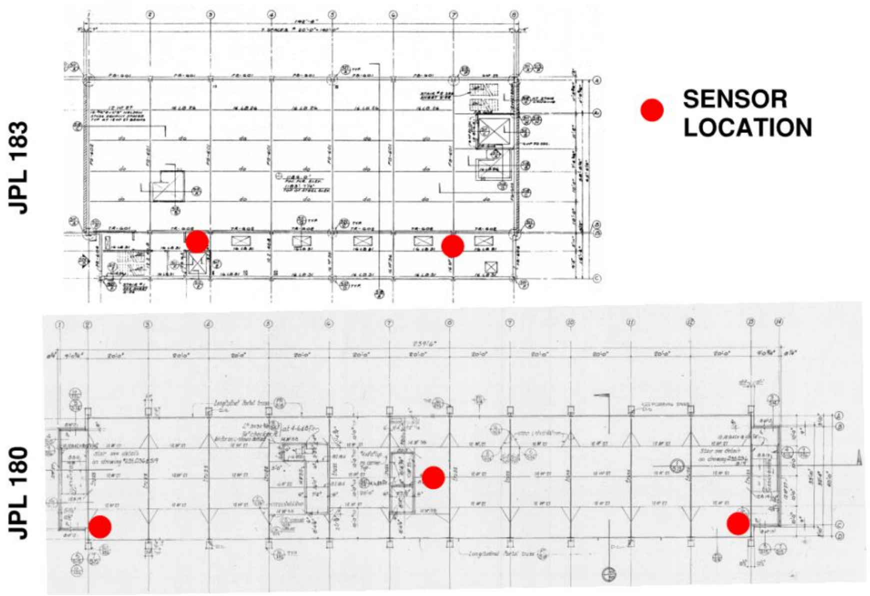


Fig. 4 – Typical instrumentation locations on upper-level floors shown on scaled structural drawings for JPL Buildings 183 (top) and 180 (bottom). Note that the Building 180 deployment has an additional center seismometer for assessing diaphragm bending along frames.

3.4 Finite-element modeling

For most of our mid and high-rise deployments, we request that building owners provide us with the structural drawings of the building. JPL has provided structural drawings from which we were able to construct finite-element models (Fig. 5). The model outputs are then validated against measured data, and used to predict response for various time history inputs. The models have been compared with modal information obtained from CSN sensor measurements from local earthquakes, and are found to be in good agreement. The models are now being used in dynamic simulations with damage imposed computationally to determine how best to post-process and evaluate dense instrumentation data from potentially damaged buildings.

The finite-element models are also used for constructing pre-event information for inverse problems. By understanding the structure in the level of detail needed to construct an accurate finite element model, we can take responses from measurements to determine forcing functions and structural demands during an event. This information can be used by building owners to determine applied forces on a floor-by-floor basis, and assess what peak structural demands are from the perspective of force as well as drift. This information can be useful with respect to computing average façade loading from wind events such as hurricanes and tornados, as well as integrating demand over the height to determine structural shears and overturning moments.

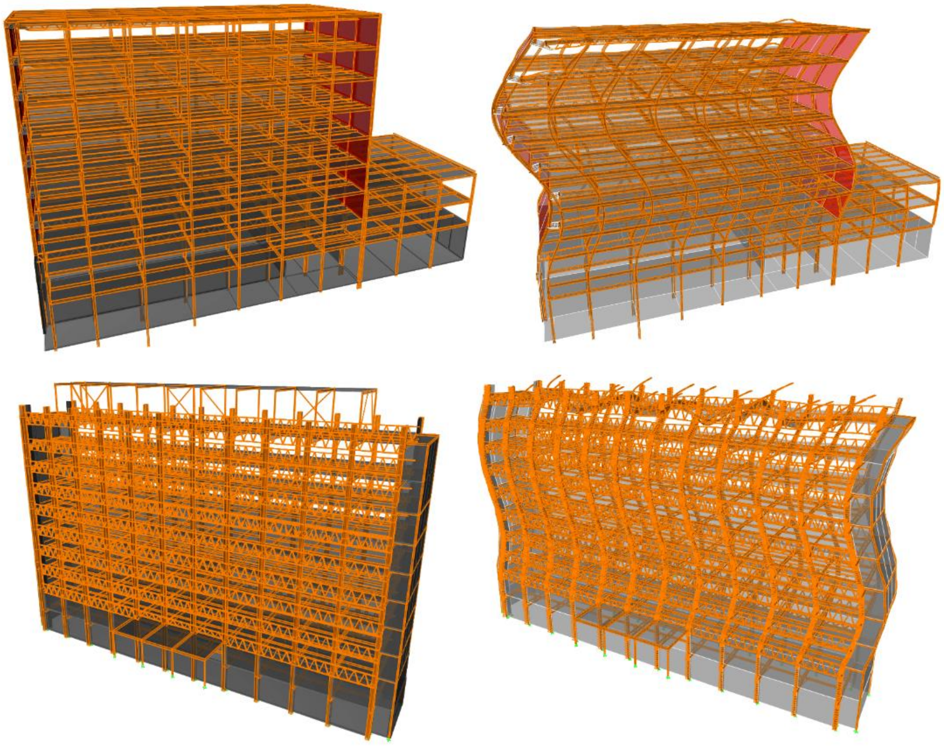
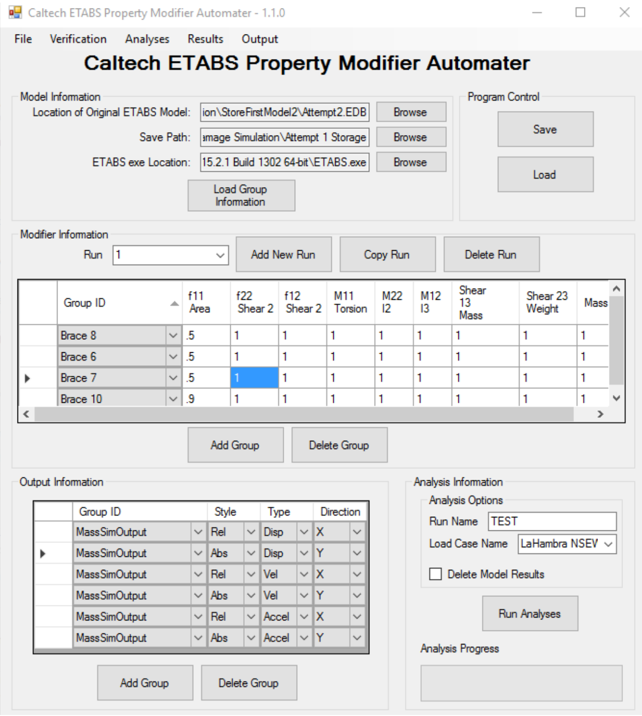


Fig. 5 – Finite-element models used in performing damage detection studies for JPL Building 183 (Top left: undeformed. Top right: deformed eigen mode analysis) and Building 180 (Bottom left: undeformed. Bottom right: deformed eigen mode analysis).

4. Computational Experiments in Damage Detection and Citywide Assessments

4.1 Mass simulation of linear models

To explore the potential uses of dense instrumentation in damaged structures, robust computational studies are performed on finite-element models of those structures. Custom software ("Caltech ETABS Property Modifier Automater") was recently developed by Computers and Structures Inc.'s Christopher Janover, allowing us to perform thousands of analyses in order to explore processing techniques on a large scale. Working with ETABS finite element software, we vary the levels of stiffness in our structures as a proxy for damage scenarios, and simulate the resulting variations in wave propagation. Computational results are extracted from the modified models and processed to isolate small-scale damage in various ways. In the case of the truss building, this structure may be prone to local buckling of individual truss components (diagonals and chords). Damage scenarios thus include modified models in which buckling of truss components on parts of individual floors and over multiple floors has been imposed.



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ETABS exe Location: 15.2.1 Build 1302 64-bit\ETABS.exe

Run: 1

Group ID	f11 Area	f22 Shear 2	f12 Shear 2	M11 Torsion	M22 I2	M12 I3	Shear 13 Mass	Shear 23 Weight	Mass
Brace 8	.5	1	1	1	1	1	1	1	1
Brace 6	.5	1	1	1	1	1	1	1	1
Brace 7	.5	1	1	1	1	1	1	1	1
Brace 10	.9	1	1	1	1	1	1	1	1

Group ID	Style	Type	Direction
MassSimOutput	Rel	Disp	X
MassSimOutput	Abs	Disp	Y
MassSimOutput	Rel	Vel	X
MassSimOutput	Abs	Vel	Y
MassSimOutput	Rel	Accel	X
MassSimOutput	Abs	Accel	Y

Run Name: TEST

Load Case Name: LaHambra NSEV

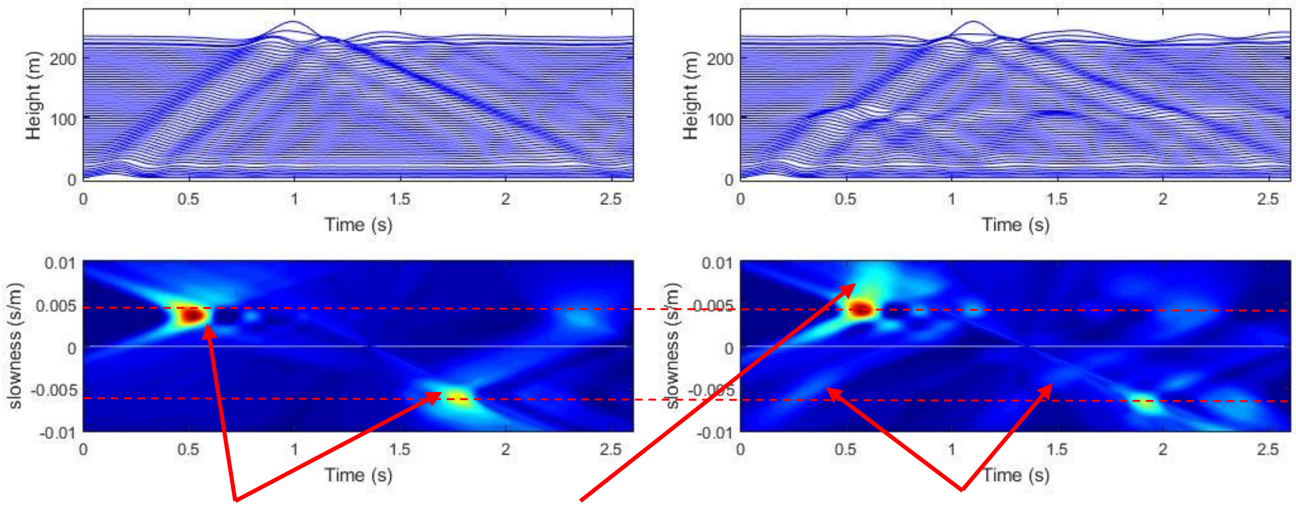
☐ Delete Model Results

Fig 6 - Custom software for mass simulation using variations in computational model linear properties.

4.2 Radon transform methods

Densely deployed strong motion instrumentation allows for tracking pulses of energy propagating over the height of the structure. When these pulses (or waves) reach a level of impedance associated with a loss in stiffness, a reflection is observed in the wave. These reflections may be indicators of damage at a particular floor, but depending on the scale of the damage, the reflected wave amplitude can be difficult to detect. The amplitude is directly proportional to the level of impedance in the system relative to the original state. By varying the damage state and examining the amplitudes of the reflectors, we are testing which methods are the most effective for different types of damage states.

While traditional means of examining traveling waves have been explored, a variation on methods inspired by medical imaging and geophysics is adopted. Radon transforms are often used for measuring impedance in contrast when direct measurement cannot be made. Radon rays integrate along a specific angle and distance from the center of an image, and then use the sum of the amplitude of the ray along the length to associate an amplitude with a ray angle. Taking radon transforms of traveling waves through buildings, the slope of the lines at those angles represent the inverse of shear-wave velocity (or slowness) through the structure. At any impedance, a reflected wave in the opposite direction is observed, and the radon transform highlights this reflection with an increase in amplitude and slowness (Fig. 7).



Waves propagate at higher velocities

Diffuse region due to lower propagating velocities

Primary reflections, at higher velocities

(a)

(b)

Figure 7 - Radon transform of displacement data collected from (a) undamaged and (b) lower level damaged finite-element models of a 52-story building subjected to a gaussian input.

4.3 Variation and decomposition of response in a nonlinear event

For some structural systems, such as braced frames, deformation can be segregated into linear and nonlinear responses. For instance, in the case of a braced frame, braces contribute to shear stiffness and columns contribute to bending stiffness. In a nonlinear excursion, the braces are anticipated to yield and/or buckle, while column axial stiffness is expected to remain linear. With underlying assumptions such as these, element level strains can be extracted to determine the state of a brace after a significant event with minimal levels of structural information (column size and floor height as an example). Fig. 8 shows how a lateral system can be broken up into nonlinear and linear responses to isolate how and where damage occurred. By developing a linear model of what the anticipated displacements would be for a structure, and examining the deviations from the linear response, nonlinear strains can be extracted. More complex systems than the one shown in Fig. 8 (such as dual or outrigger systems) are difficult to separate. We are working toward determining means of decoupling linear and nonlinear behaviors to assess damage states using only limited amounts of information which allows for rapid interpretations of response behavior in an event. The JPL campus has many types of systems beyond brace frames for which this type of analysis is being investigated. With continued effort, we aim to develop the ability to extract floor level synopsis of element performance (i.e. braces anticipated to have reached a certain level of nonlinearity) for owners to use in developing response and inspection plans.

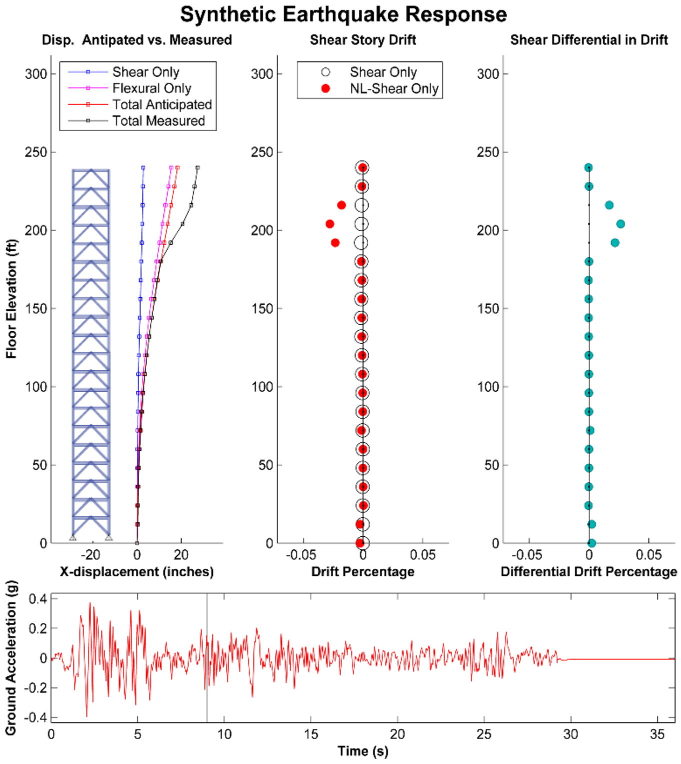


Fig. 8 - Damage detection based on differential damage

4.4 Proxy city specific implementation and products in development

Of interest to building owners on a day-to-day basis is real-time information about the deformation of the structure over the height. We have constructed a tool that makes this information available on a web interface for instrumented structures. The tool updates in real time, and can be viewed by any user with access to the internet. To calculate this information, a server polls each sensor in the building in order to obtain the latest sensor acceleration data. The data are integrated to velocity and displacement by the server, the maximum observed displacements are updated, and then all the sensors' data streams are assembled into a time-ordered list. This list is retained in cache, and access to it is made available via a REST (Representational State Transfer: a networking architecture communications http protocol) interface. The user-facing web page includes JavaScript that calls the REST interface periodically, and updates the display, as shown in Fig. 9 & 10. The display

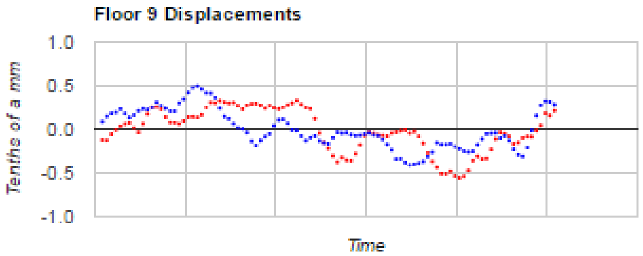
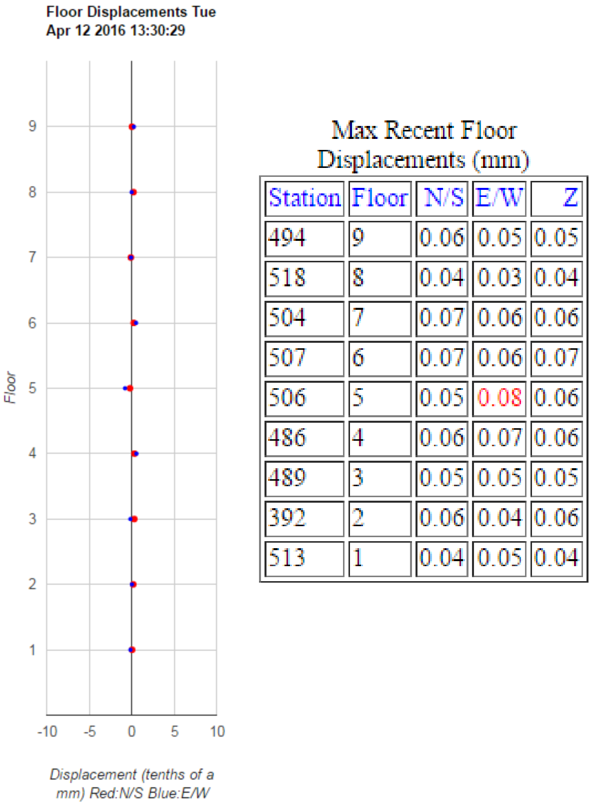


Fig. 9 – Screenshot of real-time display of JPL Building 180 displacements on a single floor

includes a graph of recent displacements as a function of time selectable by floor number, a table showing recent displacement maxima per floor and per axis, and a dynamic chart that shows the positions of all the sensors on each floor of the building. We are developing and enhancing the web interface based on user feedback. Interpretation of these data is left to the user; however basic information such as acceleration maxima and suggested limitations on occupant comfort is useful for owners who want to showcase or evaluate performance parameters from shaking events.

Beyond real-time information, an event-based peak demand profile tool has been developed (Fig. 11) to assess structural performance. In addition, peak acceleration on a floor-by-floor perspective could be used to interpret nonstructural damage expectations. Associating this information with floor level fragilities would be useful in facilities where floor usage varies significantly (such as lab space, operation rooms, server rooms). Similarly, maximum drift can be used for both structural and nonstructural assessments of building components that span the space where drift was measured (for example façade glazing and structural braces).



Max Recent Floor Displacements (mm)

Station	Floor	N/S	E/W	Z
494	9	0.06	0.05	0.05
518	8	0.04	0.03	0.04
504	7	0.07	0.06	0.06
507	6	0.07	0.06	0.07
506	5	0.05	0.08	0.06
486	4	0.06	0.07	0.06
489	3	0.05	0.05	0.05
392	2	0.06	0.04	0.06
513	1	0.04	0.05	0.04

Fig. 10 – Real-time display of all floor level displacements and peak values over a time window

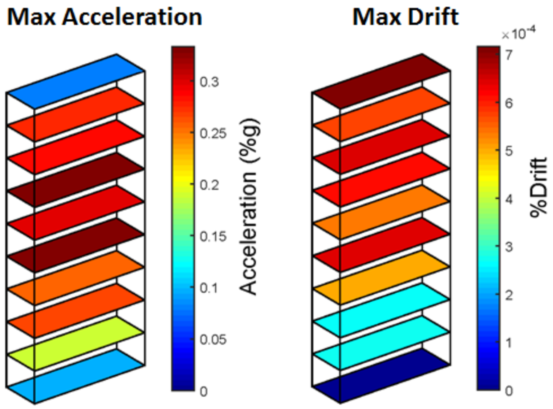


Fig. 11 - Peak engineering demands on a floor-by-floor basis of JPL Building 180, computed from acceleration time series recorded during the 7/25/2015 M4.2 Fontana, CA earthquake.

5. Conclusions

Structural health monitoring has been an active research endeavor for many decades now, and most of the effort in structural identification and damage detection has focused on the use of limited instrumentation to develop useful information. CSN provides a platform that allows for dense instrumentation in the built environment, and alleviates many of the concerns associated with missing or uncertain parameters from a sparsely instrumented structure. Further, by instrumenting more buildings overall at the base level, significant information for both the civil engineering and seismological community can be used to better understand what happened to a cityscape overall at the interface of the built environment and the earth. JPL acts as a proxy city for CSN to demonstrate what can be done with a high density array, and the team continues to develop unique and new ways to make use of this information.

6. Acknowledgements

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