Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

STRUCTURAL HEALTH MONITORING THROUGH DENSE INSTRUMENTATION BY COMMUNITY PARTICIPANTS: THE COMMUNITY SEISMIC NETWORK AND QUAKE-CATCHER NETWORK

M. D. Kohler[1], T. H. Heaton[2], M. H. Cheng[3], and P. Singh[4]

ABSTRACT

The Community Seismic Network and Quake-Catcher Network involve participants from communities at large to install low-cost accelerometers in houses and buildings for assessment of shaking intensity due to earthquakes. The seismometers are designed for two types of connections: a USB-connected device which connects to the host's computer, and a stand-alone sensor-plug-computer device that directly connects to the internet. The three-component sensors report both continuous data and amplitude anomalies in local acceleration to a Cloud computing service consisting of data centers geographically distributed across the continent, or to a distributed computing system. The continuous time series waveform data are being used to evaluate response parameters such as peak acceleration, peak velocity, and inter-story drift values. In addition, modal properties such as fundamental and higher mode frequencies and mode shapes are being computed from small and moderate earthquake data from the building. Building motion is computed for every floor of the building using only earthquake records from a single floor. Visualization models that map the instrumented buildings' responses have been constructed using SketchUp and an associated plug-in to Matlab with recorded shaking data. This data visualization approach is different from other techniques because each building model is customized to show actual data recorded from that building on varying spatial scales, without the need for large-scale parallel computing facilities or complicated software that requires a steep learning curve.

[1]Senior Research Fellow, Dept. of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125
[2]Professor, Dept. of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125
[3]Graduate Researcher, Dept. of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125
[4]Undergraduate Researcher, Dept. of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125

Kohler MD, Heaton TH, Cheng MH, Singh, P. Structural health monitoring through dense instrumentation by community participants: the Community Seismic Network and Quake-Catcher Network. *Proceedings of the 10th National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

Structural Health Monitoring Through Dense Instrumentation by Community Participants: the Community Seismic Network and Quake-Catcher Network

M. D. Kohler[1] , T. H. Heaton[2], M. H. Cheng[3], and P. Singh[4]

ABSTRACT

The Community Seismic Network and Quake-Catcher Network involve participants from communities at large to install low-cost accelerometers in houses and buildings for assessment of shaking intensity due to earthquakes. The seismometers are designed for two types of connections: a USB-connected device which connects to the host's computer, and a stand-alone sensor-plug-computer device that directly connects to the internet. The three-component sensors report both continuous data and amplitude anomalies in local acceleration to a Cloud computing service consisting of data centers geographically distributed across the continent, or to a distributed computing system. The continuous time series waveform data are being used to evaluate response parameters such as peak acceleration, peak velocity, and inter-story drift values. In addition, modal properties such as fundamental and higher mode frequencies and mode shapes are being computed from small and moderate earthquake data from the building. Building motion is computed for every floor of the building using only earthquake records from a single floor. Visualization models that map the instrumented buildings' responses have been constructed using SketchUp and an associated plug-in to Matlab with recorded shaking data. This data visualization approach is different from other techniques because each building model is customized to show actual data recorded from that building on varying spatial scales, without the need for large-scale parallel computing facilities or complicated software that requires a steep learning curve.

Introduction

The Community Seismic Network (CSN) and Quake-Catcher Network (QCN) are dense networks of low-cost accelerometers that are deployed by community volunteers to record earthquake data in California [1-3]. CSN and QCN have as their objective the generation of high-spatial-resolution acceleration data that can aid in emergency response. CSN is an earthquake monitoring system based in the Los Angeles and Pasadena, California area whose primary goal is to create block-by-block earthquake intensity maps that can be used by emergency responders in the event of an earthquake to pinpoint areas that require immediate attention. Temporary

[1]Senior Research Fellow, Department of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125
[2]Professor, Department of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125
[3]Graduate Researcher, Department of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125
[4]Undergraduate Researcher, Department of Mechanical and Civil Engineering, Caltech, Pasadena, CA 91125

Kohler MD, Heaton TH, Cheng MH, Singh, P. Structural health monitoring through dense instrumentation by community participants: the Community Seismic Network and Quake-Catcher Network. *Proceedings of the 10th National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

international deployments of QCN accelerometers are conducted to record aftershock data in countries including New Zealand [2, 4], Chile, and Haiti. CSN and QCN rely upon a dense array of low-cost acceleration sensors to acquire data on shaking in buildings and on the ground. The accelerometers are installed in public spaces associated with civic services such as libraries and utility buildings, university and secondary school campuses, and business offices in high-rise buildings. Both CSN and QCN sensors can be connected to volunteers' computers via a standard USB connection. In addition, a stand-alone package has been developed that includes a sensor, digitizer, plug-computer, and in some cases additional battery for backup power. Both the USB-connected and stand-alone packages require power and an internet connection using either Ethernet or wifi.

Each sensor's host computer or dedicated processor runs a client application that reads in the continuous acceleration time series and executes an event-detection algorithm on the time series. This is to automatically detect earthquake or other shaking events that cause a vibration response in the buildings or ground. In the case of CSN, the data are sent to a Cloud service where the data are fused, and the event-detection is executed on the entire dataset in order to decide whether alert information should be issued [3]. The QCN sensors in buildings are connected to netbooks with continuous data streaming in real-time via the Berkeley Open Infrastructure for Network Computing (BOINC) software program to a server at Stanford University [1].

Nine buildings have been instrumented by CSN and QCN, with the long-term goal of being able to show building response in real time. To demonstrate how that goal might be achieved for multiple buildings for which only minimal structural information is known, simple approximate linear-elastic building models have been developed for the CSN-instrumented Millikan Library building on the Caltech campus in Pasadena, California and the QCN-instrumented Factor building on the UCLA campus in west Los Angeles, California. In each case, the building is represented as an elastic continuum of the appropriate elastic properties (Young's modulus, shear modulus, and average density) following the development in [5]. We apply the prismatic Timoshenko beam model with soil-structure interaction to approximate the dynamic linear elastic behavior of the 9-story concrete shear wall Millikan Library building, instrumented with 13 CSN accelerometers. The 15-story steel moment-frame Factor building can be well-approximated by a simple shear beam verified by examination of earthquake records from the building.

To aid in assessing and mitigating damage and loss, we developed software packages and scripts that produce 3D and 4D visualizations of building response during an earthquake using the observed earthquake waveform data. The acceleration data were recorded in buildings instrumented with multiple CSN and QCN accelerometers, and integrated into the visualization models. The models reveal details about a building's response that are not otherwise visible in waveform time series, spectral data, or other computed products. The visualizations are part of community-wide emergency response products being developed by CSN and QCN, and could help with procedures that target emergency response locations and to minimize response time. These visualizations are available to the public on the CSN website (csn.caltech.edu). The software scripts are also publicly available via csn.caltech.edu and can be customized for nearly any other structure.

Timoshenko/shear beam building models

On August 8, 2012, an M_L=4.5 earthquake occurred near Yorba Linda in southern California. The CSN detected and recorded this earthquake on its sensors throughout Los Angeles. The earthquake was recorded by the 9-story Millikan Library building on the basement, 1st, 2nd, 3rd, 4th, 5th, 7th, and 9th floors at a distance of 4.3 km. These records are used in the construction of a Timoshenko beam model for the building, and waveform prediction calculations based on analysis of data from only a single seismometer. On September 7, 2012, an M_L=3.4 earthquake occurred in Beverly Hills, CA and was recorded on the QCN instruments in the Factor building on the basement, 3rd, 6th, 10th, 12th, and 15th floors at a distance of 4 km.

Following the approach derived in [5], Millikan Library was modeled as an equivalent prismatic Timoshenko beam with soil-structure interaction (SSI). SSI is simulated with a translational spring and a rotational spring whose values are estimated from the soil properties, incorporated in the base of the building model. The dimensions of the building are 21 by 23 meters and its height is 44 m; thus its aspect ratio is approximately = 2. We use the acceleration time series recorded in the building to determine the first two natural frequencies, f_1 and f_2, of the building in each orthogonal horizontal direction. The accelerometers are oriented such that the horizontal measurement axes are parallel and perpendicular to the primary load-bearing walls. These frequencies are estimated from the spectra of the August 8, 2012 Yorba Linda earthquake accelerations. From the 5th floor sensor, f_1 = 1.7 Hz and f_2 = 7.1 Hz in the NS direction, and f_1 = 1.2 Hz and f_2 = 4.7 Hz in the EW direction. The frequency ratios f_2/f_1 (=4.2, 3.9) are quite different for each direction, suggesting that bending stiffness is significant for both directions in this building. [5] show the parameters for the Millikan Library building that comprised the input and output of the analytical model used here.

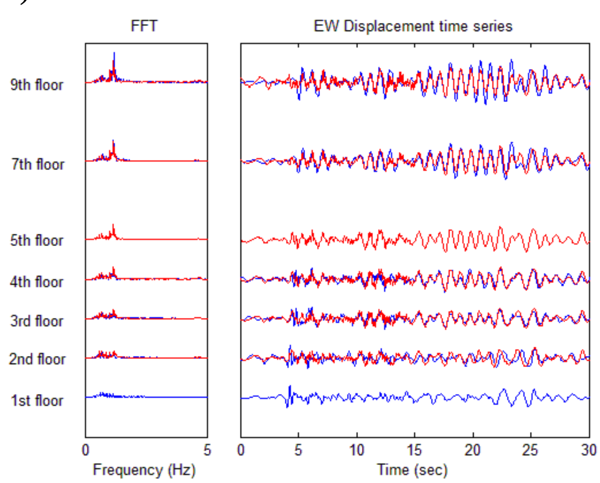
Using the Timoshenko beam model parameters for Millikan Library [5] and a single record from the 5th floor, the building's response to the Yorba Linda earthquake was modeled, and compared to CSN data recorded on nearly every floor. The building properties, including mode shapes, are computed knowing the ratios of the frequencies of the first two normal modes in the two orthogonal horizontal directions. The natural frequencies of the first two vibrational modes of a building have been identified by spectral analysis of Yorba Linda earthquake data from a seismometer located on the 5th floor.

The UCLA Factor building, in contrast, is well-approximated by a simple shear beam. Examination of the frequencies of vibration from the earthquake records from this building suggest simple shear beam behavior (f_1=0.59 Hz and f_2=1.83 Hz in the NS direction; f_1=.55 Hz and f_2=1.70 Hz in the EW direction) [6]. We calculate mode shapes for the Factor building's first two translational modes in the two orthogonal horizontal directions based on a simple shear beam analytical model; they match the true frequencies and mode shapes of Factor well [6].

Once the frequency ratio and mode shapes were determined for the buildings, their total responses were estimated using a traveling wave plus low-frequency modal response method. The calculations were applied to time domain datasets and consisted of estimating the initial broadband (0.5 to 5 Hz) shear wave propagating vertically up the building by estimating its average shear-wave velocity, numerically propagating an impulsive wave from the base to the roof, and modeling subsequent displacement by low-frequency modal response. We apply a weighting function that weights the traveling wave as the dominant source of building displacement during the first T/4 of response time, where T=the building's fundamental translational period. During the next T/4 time interval, a negative-slope, linear down-weighting is applied to the now down-going traveling wave and a positive-slope, linear up-weighting is applied to the low-frequency modal response. After T/2 time interval and for all times after that, the traveling wave no longer plays a role, and the low-frequency resonant modal response is the only source of the estimated response. For the simulations presented here, we use the first two translational modes in orthogonal directions for the modal response contribution.

Figs. 1 and 2 show the traveling wave plus resonant response modeling results and earthquake data for Millikan Library and the Factor building. In Fig. 1, the blue time series are the August 8, 2012 Yorba Linda earthquake spectral and acceleration data recorded by Millikan Library's CSN sensors on the floors indicated by numbers on the vertical axis. Fig. 1a shows data and predictions for the floors that recorded data (floor 5 was used in the single seismometer prediction calculation so the waveforms are overlying). Fig. 1b shows the displacement predictions calculated for every floor of the building. Fig. 2 shows analogous plots of data and predictions made for the response of the Factor building for the September 7, 2012 Beverly Hills earthquake. Floor 12 was used in the single seismometer calculation. Both figures indicate that the predictions improve in accuracy for the higher floors over the lower floors. Improvements can be made if the weighting function for the traveling wave vs. resonant response is customized to each building; for example for the Factor building, the reflected downgoing leg of the initial shear wave is significantly higher in amplitude than for other buildings [7]. Overall, the results indicate that the predictions produce amplitudes that are generally correct.

a)



b)

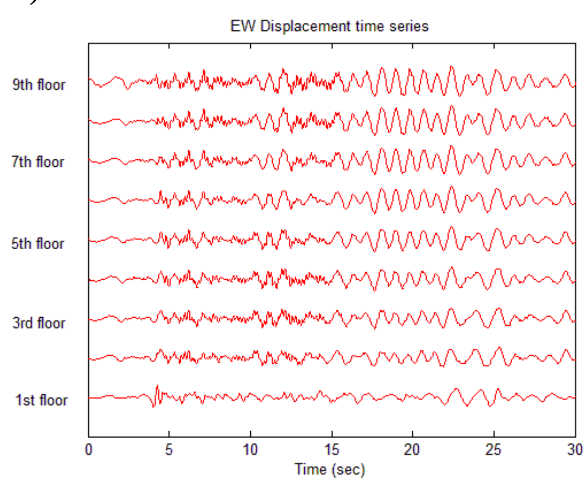


Figure 1. a) East-west spectra and displacement data, and Timoshenko beam model-based predictions for the Millikan Library building response using the August 8, 2012 M_L=4.5 Yorba Linda, CA earthquake waveform recorded by the sensor on the 5th floor. Data are shown in blue and predictions are shown in red. b) Displacement predictions computed for every floor. Floor numbers are indicated on vertical axes.

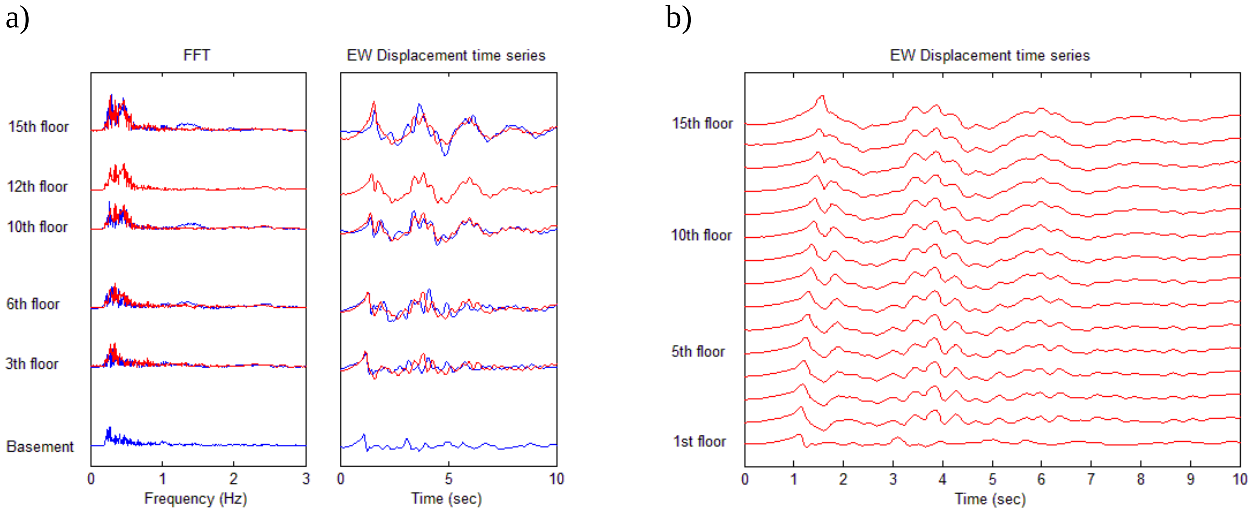


Figure 2. a) East-west spectra and displacement data, and simple shear beam model-based predictions for the Factor building response using the September 7, 2012 M_L=3.4 Beverly Hills, CA earthquake waveform recorded by the sensor on the 12th floor. Data are shown in blue and predictions are shown in red. b) Displacement predictions computed for every floor. Floor numbers are indicated on vertical axes.

Visualization

The purpose of CSN and QCN is to collect high-spatial-resolution measurements of shaking and wave propagation both horizontally over a wide region and vertically in buildings. The data can be used to assess potential damage in a building by plotting and assessing the peak accelerations and velocities, among other measurements, on various floors in a building. A visualization approach has been developed that is deliberately designed to be scalable to multiple structures on a city-wide scale. At the same time, it enables fine-scale level of building detail not found in other software packages. The Seismic Performance of Urban Regions (SPUR) pilot project, for example, included development of visualization tools for dynamic motion in three dimensions, in which buildings were modeled as multi-degree-of-freedom oscillators subjected to scenario excitation [8]. Visualization methods such as those produced for the SPUR project are capable of visualizing multiple variables including peak velocity and acceleration using simplified building models that do not need to be customized to illustrate the features and configuration (i.e., sensor layout) of permanently installed structural arrays. Numerous 3D graphics rendering software packages (e.g., OpenGL, ParaView, VisIt) are available for scientific visualization that are designed with sophisticated 3D rendering features; however, they are not capable of the data processing and analysis features necessary for dynamic structural analysis (e.g., Matlab's Signal Processing and System Identification Toolboxes). Our approach combines an easy-to-use structural model construction method in which building geometries can be customized for actual instrumented structures, with widely used seismic array data processing and analysis software.

The entire process for generating the visualizations is contained within two software packages designed to be modifiable for any building: *SketchUp*, a free 3D modeling program for architects and civil engineers developed initially by Google, and acquired by Trimble (www.sketchup.com; www.trimble.com/3d), and Matlab (www.mathworks.com). Example products for the 3D visualizations consist of peak acceleration, velocity, displacement, and inter-story drift values for each floor visually displayed on the building; the peak values are an indirect measure of potential damage. The 4D visualizations comprise movies of building displacement during earthquake shaking that allow the non-scientific community to see how the building responded to an earthquake.

The first step of the visualization process developed here was to create a 3D geometry-based model of a building using SketchUp. The models were constructed based on specific geometric building parameters including a geometric outline of the building floor plan (Google Earth was useful for this), and approximate measurements of building features such as horizontal dimensions, building height, the number of floors and the number of basements. If the building height was not known, we used a value of 5 m. To begin the construction of each model, we created an outline of the building (based on the known parameters) on a defined ground level and then used SketchUp's *Push/Pull* tool to pull the outline up to maximum building height. This created a box-like model of the building without any features such as floors, setbacks, tapering, or asymmetric elements. The outline was pulled to below ground level to add basements. We created a rectangular planar base at ground level that extended five meters horizontally beyond the building walls to clearly distinguish basement levels from above-ground levels. Individual floors were added by constructing outlines at the appropriate heights. SketchUp automatically created surfaces from the closed outlines.

Once the floors were added, additional features of the building such as cantilevered overhanging sections or asymmetric cladding features were added by extending each floor's outline to the desired customized values. Curves were added using SketchUp's *Curve* tool, which automatically creates curves with up to 23 sides, although for modeling purposes a 23-sided curve was unnecessary. Instead, curves with six or twelve sides were used since they rendered faster and proved to be geometrically sufficient. In the last step, all unnecessary lines and guides were deleted to clean up the model and the axes were oriented according to building north (the direction of the primary support walls closest to true North). Finally, the building was exported from *SketchUp* as an *object* (*OBJ*) file using the *OBJ Exporter* plug-in available online.

We next wrote a series of functions in Matlab that enable the transfer of the SketchUp model into Matlab, and the manipulation of the building model in Matlab based on data. The building object file can be read into Matlab with the *readOBJ* function which produces lists of vertices, faces and edges as output in the form of 3D matrices. The function reads each face of the building as a triangular mesh; thus squares and rectangles are read into Matlab as a set of two triangles. This creates extra diagonal edges in the model but these lines can be ignored when reconstructing the building since they are not necessary for defining building movement. We then used the faces and vertices lists to find the floors of the building and created an array of floor structures to store 3D location information about each floor. Each floor structure is thus composed of Matlab-defined fields representing the faces, vertices and exterior edges of the floor. The building was then plotted in Matlab by applying the *Patch* tool to these field values to create a polygonal surface based on the vertices. The vertical edges from the *edges* list was added to complete the full frame of the building structure. Movies of building shaking were created frame-by-frame using Matlab's *VideoWriter*.

Thus far, we have created models of the nine buildings that have been instrumented by CSN or QCN with between 3 and 34 accelerometers. Fig. 3 shows examples of SketchUp and associated Matlab models produced for the nine buildings in the Los Angeles area. The modeled buildings include the Millikan Library building and the Factor building. Near downtown Los Angeles, six buildings instrumented by CSN and QCN that are between 5 and 14 stories tall were modeled. Finally, a 23-story steel-frame and a 15-story moment-resisting space frame with concrete shear walls within a central core building, both in downtown Los Angeles were also modeled. In order to display these values in a visually intuitive manner, we wrote a software script in Matlab that generates plots of peak acceleration, velocity, displacement, and inter-story drift values for each floor of an instrumented building given earthquake acceleration data from the floors as input. The acceleration data were detrended and demeaned, and passed through a 3rd-order Butterworth filter to obtain a signal that was smooth and maximally flat in passbands appropriate for building type or signal of interest. The data were then integrated to obtain velocities and displacements. The robustness of numerical integration as a function of environmental and noise floor values associated with the CSN sensors has been previously determined with side-by-side measurements of data collected on a high-sensitivity, high-resolution Episensor-Q330 (accelerometer-digitizer) setup. The resulting calculations applied to earthquake data for peak acceleration, velocity, and relative displacement per floor, and inter-story drift were applied to the building models in Matlab. The floors were colored using a gradient feature according to values scaled by the maximum value.

An example of the application of the visualization procedure is described for the August 8, 2012 Yorba Linda, California earthquake recorded by Millikan Library. Fig. 4 shows maximum acceleration, velocity, and relative displacement recorded in Millikan Library The lower floors of the building experienced the greatest accelerations and velocities but it was the highest (9th) floor that experienced the largest relative displacement, though only 0.14 cm. (This was a small earthquake that resulted in linear-elastic structural response.) The distribution of maximum displacement relative to the ground illustrates the predominance of the fundamental resonant frequency of the building and is a signature of the mode shape associated with this frequency. Other earthquakes have produced different distributions of maximum values that are more clearly associated with the first translational overtone modes in which maximum displacement occurs at about 2/3 of the total building height. Prior to this, the Timoshenko beam model was successfully applied to a 12-story concrete-shear wall building near downtown Los Angeles that is instrumented with six CSN accelerometers [7]. Data from the Yorba Linda earthquake recorded in that building were well-approximated using the traveling wave plus low-frequency resonant mode approach, based on analysis of acceleration waveforms from a single accelerometer on the 9^{th} floor.

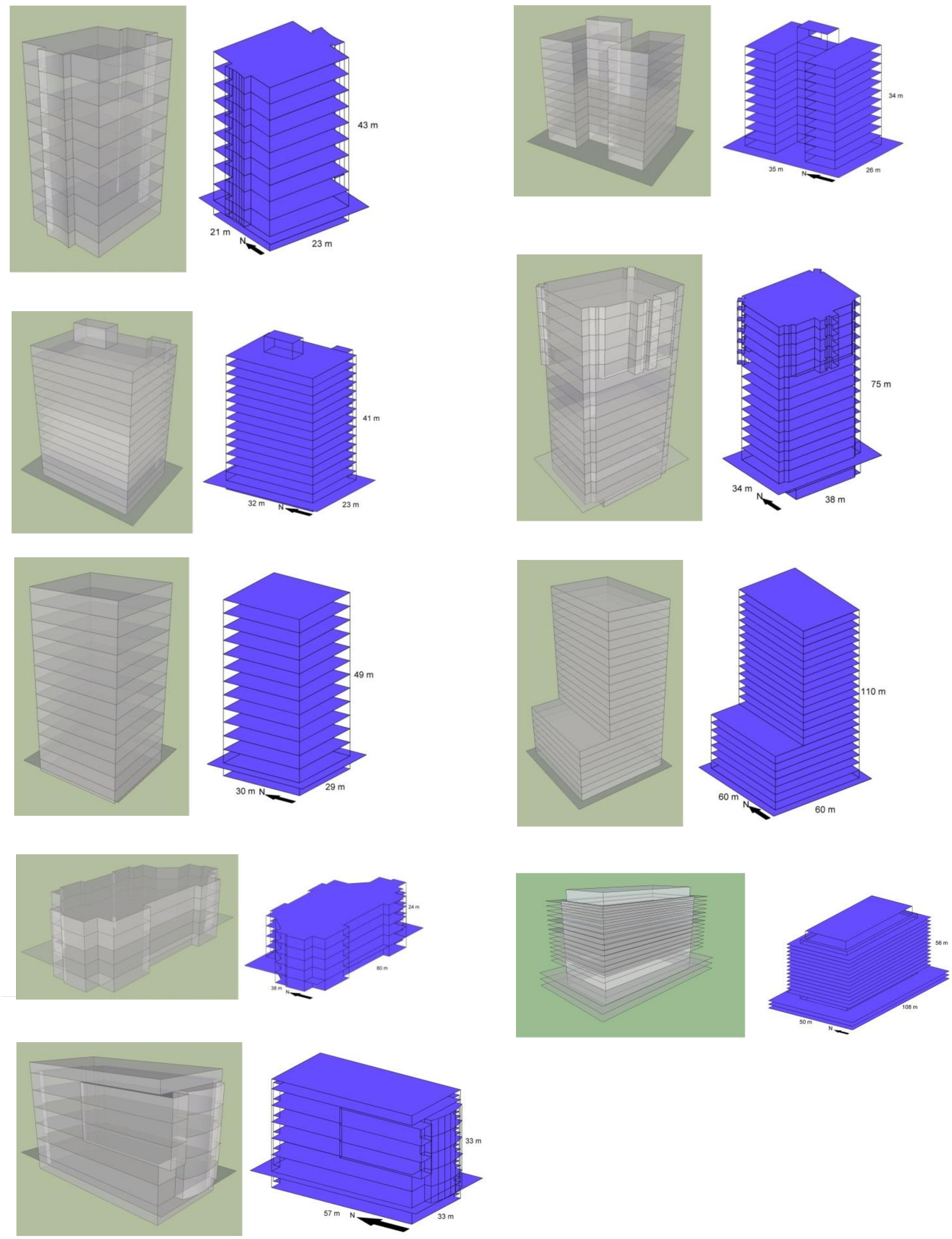


Figure 3. SketchUp-Matlab visualization models of CSN and QCN-instrumented buildings.

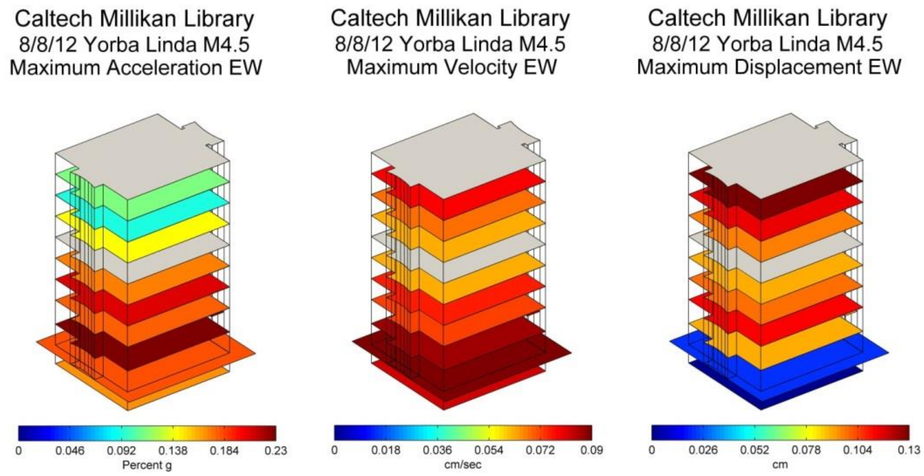


Figure 4. Maximum acceleration (left), velocity (center) and relative displacement (right) obtained from data collected in the 9-story Millikan Library building in Pasadena, California during the August 8, 2012 M4.5 Yorba Linda, California earthquake. Data are all from the east-west accelerometer component.

Conclusions

The modeling results yield insights into building response that are validated by comparison with recorded data from networks of inexpensive, volunteer-deployed accelerometers. Furthermore, when the data are input into the visualization models, the peak values and response parameters can be tracked as a function of time during the shaking. The results show that the building response can be modeled initially by a broadband traveling wave that begins at the bottom of the building with the ground motion excitation during the first few seconds of transient ground shaking. The frequency content of this wave is a function of both the resonant frequency response of the building as well as the frequency content of the ground motions, which are in turn a function of earthquake source and source-to-building propagation effects. After the excitation (transient) ground motion has terminated, the building response can then be modeled by free vibration resonant modal response dominated by the fundamental and first overtone translational and torsional modes. For tall buildings, the broadband frequency content of the initial traveling wave followed by the lower-frequency resonant modal response shows up clearly in our building response visualizations. The effects of distance and magnitude of earthquakes are also illustrated in the modeling results. Earthquakes at small distances result in nearly impulsive excitation with high-frequency traveling waves and only a short interval of low-frequency resonant modal response. Large magnitude earthquakes at large distances result in resonant low-frequency modal response from the beginning of shaking since the lower frequencies of the excitations, which are often surface waves, are closer to the building's natural frequencies.

The combined effects of the ground motion and building frequency content on building response are also apparent in the plots of peak acceleration, velocity and displacement (e.g., Fig. 4). Since the building response peak values occur as a combination of the traveling waves as well as low-frequency modal response, those values are not always a function of mode shapes associated with the lowest mode frequencies. As [5] point out, based on [9], the maximum response values may occur during the coherent impulsive near-field ground motions before the resonant modal response dominates. In cases where impulsive excitation from nearby earthquakes has produced high-frequency propagating waves followed by lowest-frequency modal response, the peak displacement values occur at approximately 2/3 building height. In cases where low-frequency excitation produces immediate low-frequency response, maximum relative displacement often occurs at the top of the building and maximum velocity values (in addition to acceleration) become important for monitoring shaking intensity. The visualization models developed here can be applied to nearly any structure and used as part of an emergency response decision-making analysis. We envision that future versions of the algorithms will incorporate a wide array of measured and computed parameters. With increased number of instrumented buildings and acceleration recordings from dense arrays such as CSN and QCN, the scalar and movie visualization products could be assembled on a 3D community-wide scale for shaking intensity and damage potential assessment from actual, not just simulated, structural data.

Acknowledgments

We acknowledge support from the Moore Foundation, National Science Foundation, George Housner Earthquake Engineering Research Endowment, Fred L. Hartley Family Foundation, the Croucher Foundation, and the Caltech Student Faculty Program.

References

1. Cochran, ES, Lawrence JF, Christensen C, Jakka RS. The Quake-Catcher Network: Citizen science expanding seismic horizons, *Seismological Research Letters*, 2009; **80**(1), 26-30, doi: 10.1785/gssrl.80.1.26.
2. Cochran ES, Lawrence JF, Kaiser A, Fry B, Chung AI, Christensen C. Comparison between low-cost and traditional MEMS accelerometers: a case study from the M7.1 Darfield, New Zealand, aftershock deployment, *Annals Geophysics*, 2011; 54, 728-737.
3. Clayton R, Heaton T, Chandy M, Krause A, Kohler M, Bunn J, Guy R, Olson M, Faulkner M, Cheng MH, Strand L, Chandy R, Obenshain D, Liu A, Aivazis M. Community Seismic Network, *Annals of Geophysics*, 2011; **54**(6), doi: 10.4401/ag-5269.
4. Lawrence JF, Cochran ES, Chung A, Kaiser A, Christensen CM, Allen R, Baker JW, Fry B, Heaton T, Kilb D, Kohler MD, Taufer M. Rapid earthquake characterization using MEMS accelerometers and volunteer hosts following the M_w7.2 Darfield, New Zealand earthquake, *Bull. Seis. Soc. Am.*, 2014; **104**(1), 184-192, doi: 10.1785/0120120196.
5. Cheng MH, Heaton TH. Simulating building motions using the ratios of its natural frequencies and a Timoshenko beam model, *Earthquake Spectra*, 2014; in press.
6. Kohler MD, Heaton TH, Bradford SC. Propagating waves recorded in the steel, moment-frame Factor building during earthquakes, *Bull. Seis. Soc. Am.*, 2007; **97**(4), 1334-1345, doi: 10.1785/0120060148.
7. Kohler MD, Heaton TH, Cheng MH. The Community Seismic Network and Quake-Catcher Network: enabling structural health monitoring through instrumentation by community participants. *Proceedings of the SPIE Smart Structures/Non-destructive Evaluation conference*, March 10-14, 2013; San Diego, CA.
8. Bielak J, Askan A, Fernandez A, Fenves GL, Stojadinovic B, Park J, Petropoulos G, Haupt T, King R, Meyer J. Simulation for determining the seismic performance of urban regions, *EURODYN* 2005; Soize C, Schueller GI (Eds.), Millpress: Rotterdam, ISBN 90 5966 033 1.
9. Iwan W. Drift spectrum: measure of demand for earthquake ground motions. *J. Struct. Engineering*, 1997; **123**(4), 397-404.