A Proposal to the THOR Center

Instrumenting a Tall Building in Downtown Los Angeles

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Summary

We propose to place approximately 100 three-component motion sensors in a modern 52-story building in downtown Los Angeles. This will be a unique, showpiece facility for studying the motions of high-rise buildings that could potentially provide the basic observations that lead to a state-of-health monitoring system for earthquake safety in buildings. We will develop a finite-element model for the building that will be calibrated to motion sensor data, and will be used to test the detectability of various damage scenarios. The sensor array will be incorporated into the CSN project. The project will take one year.

Introduction

High-rise buildings present a special problem for determining the damaging effects of earthquakes because after an earthquake, the building can appear to be undamaged and yet have suffered dangerous structural degradation. It has been a long-term goal to determine the structural soundness of a building (state-of-health) quickly following an earthquake because these structures form such a concentrated part of our infrastructure. Detection of flaws by seismic methods, whether during the earthquake itself or with aftershocks appears to hold the most promise. What has been holding this back is the lack of well-instrumented buildings to use as test-beds.

Although legislation has mandated the seismic instrumentation of buildings for the past several years, this has only been done sparsely and with limited access to the data. There are a few exceptions - the Millikan Library building (20 sensors/9 stories) at Caltech and the Factor Building (72 sensors/17 stories) at UCLA have proven to be useful for studying building motions (Snieder et al, 2006; Kohler et al, 2007; Prieto et al, 2010). The Atwood Building (32 sensors/20 floors) (Celebi, 2006) in Anchorage has dense instrumentation but its use is limited because the continuous data are not preserved. There are similar issues with the recent efforts to instrument the VA hospitals (Ulusoy et al, 2012).

What is needed is the dense instrumentation of a fully-occupied, modern high-rise with continuous motion data that is freely available. This dream has never been realized for several reasons. First, high-quality sensors that are mounted directly on the primary structural elements (e.g., steel beams that make up a frame) of the building and that record with an on-site system are expensive; hence typically only a few sensors are installed and the data are only retrieved manually after an earthquake. Second, in multi-tenant buildings usually all parties need to agree before the whole building can be instrumented. Finally, there is a general reluctance by building owners to participate following the “ignorance is bliss” principle.
An opportunity to bypass all these impediments recently presented itself to Caltech through the CSN project. Brookfield Properties who owns the 52-story building at 601 S. Figueroa St. in downtown Los Angeles has agreed to allow us to place seismic instruments in their building. The building, shown in Figure 1, is composed of concentrically braced steel frames at the core with outrigger moment frames in both directions, and was constructed in 1998-1990. In addition to the 52 stories above ground, it has 5 stories of parking garage levels below ground. As such it is an ideal representative of a common, modern, high-rise construction style. It has its own private internet system and two communications closets per floor. Our plan is to place low-cost, three-component accelerometers in each of these closets and use the existing Internet connections to transmit the data in near-real time to the CSN cloud. The sensor we will use is the one developed by CSN and is shown in Figure 2. It is a standalone device; it has its own onboard computer and, hence, does not depend on any computing infrastructure in the building.

CSN has developed an extensible cloud-computing infrastructure for managing sensors, acquiring sensor data, and processing the data in a few seconds. The extensible nature of the infrastructure enables us to use the infrastructure with little additional work to acquire, organize, and analyze building data. The computing infrastructure will allow us to study a given building in detail and to carry out data mining on groups of buildings.

Brookfield Properties has signed a Memo of Agreement with Caltech, which is attached to this proposal. This company also owns a number of other high-rise buildings in Los Angeles, and if our efforts with this structure are successful, they will likely be inclined to have their other buildings instrumented.

The Analysis of Building Motions

The motions of high-rise buildings can be described in two ways, much like seismology applied to the whole earth. The first is in terms of modes of the building. The “swaying” of the building after excitation by an earthquake or by winds, can be described by a combination of low-frequency modes. The fundamental mode has a period that is approximately 1 sec for each 10 stories of the building height. The higher translational modes will have frequencies generally increasing in a $3f_i$, $5f_i$, $7f_i$, ..., pattern relative to the fundamental frequency $f_i$ if the building responds like a shear beam which is a close approximation for many tall steel frame structures when the majority of their mass and stiffness is concentrated in the floor
slabs. The other type of modes are torsional modes (twisting modes) which tend to be small in short buildings but can become significant for tall, relatively narrow structures, oddly-shaped asymmetric structures, or buildings that have lost their symmetry due to damage. They can also be significant when the structure is excited by earthquake forces in a non-symmetric way. Figure 3 shows the modes for a 54-story building also located in downtown Los Angeles.

Traveling waves (or body waves) describe coherent, broader-band shear waves propagating up and down the structure. These waves can be excited by earthquakes or can be generated by ambient noise correlation. The traveling waves reflect at the top and bottom of the structure, and at any floor where the average stiffness properties of the building change. An example of traveling waves observed in the 17-story steel-frame UCLA Factor building is shown in Figure 4.

To monitor the state of health of a building, we can potentially use characteristics of both broader-band waves and low-frequency modes to look for changes in building properties that might be caused by, for example, a beam-column connection failure (as was observed after the 1994 Northridge earthquake) or other types of damage. With low-frequency modes we would look for a change in the frequency of the mode, a change in mode shape (or more realistically drift mode shape since it is more closely related to the strain), and the production of new types of modes, for example torsional modes that are introduced by asymmetry due to damage in only part of the building. An example of changes in frequency using the Millikan Library building is shown in Figure 5 where it is clear that the fundamental mode frequency of the building changed during the 2010 Baja California earthquake. With traveling waves, we would look for a new set of reflections introduced by a compromised floor, a change in the impedance contrast (amplitudes) with existing reflections, and changes in travel times between floors or subsets of floors due to changes in elastic properties.

Figure 3. Modes and displacement response for a 54-story building in Los Angeles. Shown are the spectra (left panel) and seismogram synthetics (center panel) that are constrained by real data on 4 floors. We are expecting similar results for the Brookfield building, except that we will have measurements on all floors instead of only 4 floors.

Figure 4. A comparison of observed (top) and synthetic (bottom) traveling waves for the Factor building.
Numerical Modeling of Building Motions

We propose to develop and test finite-element models of the 52-story Brookfield building that will be used to simulate the effects of damage on wave propagation. The models will initially be calibrated with the traveling wave and low-frequency modal data. We will then produce time and frequency domain datasets from a series of damage scenarios to see if the differences can be detected by CSN sensors given the noise levels of the real data. We will also look for new modes or waves that may arise as a result of material asymmetries introduced in the structure as a result of the damaged elements.

We have already constructed a model of the UCLA Factor building using commercial engineering software ETABS (distributed by Computers and Structures Inc.) (Kohler et al., 2007) (Figure 6). The major structural elements were obtained from structural drawings of the Factor building and utilized the object-based physical-member modeling of ETABS, which for example, has built-in steel sections. ETABS allows for static and dynamic simulations, as well as linear and simple nonlinear analysis through insertion of plastic rotation elements such as frame hinges. We plan to do the same analysis with
the Brookfield building, with dynamic simulations carried out with both actual earthquake records and with simulated scenario-event ground motion.

Calibration of the models to observations is critical due to the semi-empirical elements used in the model. The models will be matched to the mode frequencies and shapes, as well as the velocities and amplitudes of the traveling waves. Having a densely instrumented building will mean the modes and traveling waves are well sampled on a relatively small spatial scale, which is important for this step. An example of simulation results and traveling waves generated by deconvolution of recorded earthquake ground level waveforms from upper floors is shown in Figure 4, where the impulse response function can be seen traveling up and down the height of the building in both the synthetics and observations. There are also secondary reflections from the bottom of the 10th floor, the location of a significant structural change in the building.

In the future, it may be also possible to directly detect the damage event itself. That is the fracture or weld break may emit energy that can be detect and located (by reverse-time migration) (Heckman, 2013), if it is within the pass-band of the sensors and can be distinguished from the background noise. This may require additional software in the sensor boxes to run the detection on the raw sensor output, which is sampled at a rate considerably higher than is archived.

Visualization of Building Motions

One important aspect of this project is the display of the results in order for subtle changes in motion to be recognized by humans so that specific detection algorithms can be implemented. Aspects of this work have been done by SURF projects (Kohler et al., 2013), and we plan to continue with that line of development. An example of this work is shown in Figure 8. The movies of building motions are one of the most effective ways of communicating this research to the general public.

An engaging display of the motions is also important to convince other building owners to participate in the project. It will also be important for selling the project to other possible participants who would host seismometers such as insurance companies.

Figure 7. Effect of Damage on Mode Shapes. On the left is the simulated fundamental mode shape of the Factor building in the N-S direction. The center trace is the mode shape when broken welds are introduced on the 8th floor of the finite-element model. The right is the full-scale difference.

Figure 8. Visualization Example. The Factor building shown in the left panel is converted to a systematic mesh by first modeling in Google SketchUp, and then converting it to a 3D mesh model using Matlab. The final product can be used to make movies of the 3D motions of the building.
Relationship to the Priorities of the THOR program.

1) Instrumenting this 52-story building is unique opportunity that will provide a database to advance state-of-health monitoring in occupied, full-scale structures. We believe it will form the basis of proposals to NSF to fund research with the data, and be a showcase to entice other building owners to instrument their buildings. We believe the use of low-cost sensors and existing Internet connectivity will appeal to owners.

2) We plan to place the data in the public domain and provide it through the CSN servers. The visualization component of the project should make the results appealing to both scientist and non-technical members of the southern California community.

3) We envision that the modus operandi of this project will be to convince building owners to pay to instrument their buildings. The insurance industry may influence this too with rate adjustments for instrumented buildings, and perhaps with direct support of the research.

References


