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Wavefield Tools for Characterizing Building Damage

U.S. Geological Survey Award No. 07HQGR0006

Element III

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Abstract

We computed signatures of realistic damage scenarios for the densely instrumented 17-story Factor building (a typical urban, steel moment-frame building) using a computer model of the building in finite-element dynamic analysis simulations. The Factor building is a prototype ANSS instrumented structure for use in structural health monitoring and engineering research applications. We computed the signatures of damage in three complementary types of data recorded by building arrays: mode shape, spectral, and wave propagation properties. The simulations use a variety of scenario input ground shaking scenarios applied to a range of damaged building scenarios obtained by altering our model in ways that simulate expected damage events, for example, breaking the welds on a particular floor. We built a catalog of the resulting damage event signatures that may eventually be used in computational tools that incorporate the complementary data to estimate location and time of damage occurrence. During the course of this research, we also began investigation of using time-reversed Green's functions obtained from hammer blow data to locate weld fractures whose high-frequency signals are superimposed on the longer-period signals that describe the overall motion of the structure.

Introduction

An increasing number of agencies are making it their long-term goal to heavily instrument buildings (e.g., ANSS, NEES). These networks are producing orders of magnitude more data than previously instrumented buildings, thus it is becoming more difficult to wade through the volumes of data to determine whether something unique has happened and where in the structure it has happened. There is a pressing need for new computational techniques that will enable end-users to identify these damage events spatially and temporally, as well as to identify through predictive modeling (dynamic analysis) just how well-resolved hypothesized localized damage signatures are in the data.

We (Prof. Thomas Heaton, Caltech, Dr. Monica Kohler**,** Center for Embedded Networked Sensing UCLA, and Dr. Matt Muto, Caltech) investigated spectral and wave propagation behavior in a typical mid-level building for use in computational tools to detect hypothetical structural damage by comparing finite element simulation results with data from a densely instrumented building. The Factor building is a 17-story moment-resisting steel frame structure with an embedded 72-channel accelerometer array that is continuously recorded by 24-bit data loggers. The high spatial density of this seismic array presents a unique opportunity to develop hazard analysis tools that analyze the entire wavefield in both the space-time domain and the normal mode domain. Spatial aliasing prevents such analysis in most other instrumented structures. The Factor building is a prototype ANSS instrumented structure for use in structural

health monitoring and engineering research applications. It represents how permanently, densely instrumented structures can record spectral and waveform data on small spatial scales for damage detection computational developments.

In addition to high spatial density, the 24-bit continuous recording system provides high-resolution data for a wide variety of sources including earthquakes of all sizes, wind excitation, and ambient vibrations. We have observed dynamic characteristics not usually observable for long, continuous time scales and for different sources of excitation. Identification of the building's dynamic characteristics has already been made by independent research groups, thus there is a large body of knowledge about the building that serves as the backbone, pre-earthquake database of system identification measurements.

We are particularly concerned with the problem of identifying inelastic behavior, especially if this behavior can be used to detect structural damage. Our general approach is to look for ways to detect deviations from linear behavior of buildings. This can only be accomplished if we have a detailed understanding of the linear response of a building. To help us analyze this data, we have constructed both linear and nonlinear finite element models of the building that are faithful to the structural plans. We have two general strategies for identifying nonlinearity in the response of structures. The first is to quantify permanent changes in the dynamic characteristics of a building that are caused by large building deformations (e.g., weld fractures, cracks in structural and non-structural walls). It is one thing to recognize temporal changes in modal parameters but entirely different to uniquely identify the causes of those changes. Towards that end, we have utilized both spectral and time domain representations of the synthesized building response to characterize the relationship between damage patterns and motions recorded in the building. Vibration frequencies are known to change both permanently and temporarily due to strong shaking but frequency change alone may not be an accurate or complete measure of when or where a building has been permanently damaged. The combination of frequency change information coupled with that provided by wave propagation data helps to identify the time and location of damage more accurately.

We computed the signatures of damage in three different but complementary types of data recorded by building arrays: mode shape, spectral, and wave propagation properties. We simulated the response of the Factor building using a finite-element model. We used a variety of scenario input ground shaking scenarios applied to a range of damaged building scenarios obtained by altering our model in ways that simulate expected damage events.

The Factor Array

The Factor accelerometer array is composed of four horizontal channels per floor and an additional two vertical channels on the two bottom floors (Fig. 1). The horizontal sensors are oriented north-south and east-west along the mid-sections of each floor. Nine 24-bit Quanterra 4128 digitizers record the continuous 72-channel data in two data streams: one at 100 sps for long term archiving and one at 500 sps from which major events can be extracted. The Factor building array is complemented by two borehole seismometers consisting of an Episensor installed in a ~100 meter deep borehole and one at the wellhead, both approximately 25 m east of the Factor building. Structural health monitoring software is being used to monitor and archive the continuous 100 sps Factor building data. The array is being used to record weak and strong motions from local earthquakes. Based on our recordings of Factor data to date, the array is

recording several dozen local and regional earthquakes each year with good signal-to-noise ratios as well as ambient vibrations from which building output has been determined.

Building models

We used two different finite element codes to investigate the vibration properties of the Factor building. The first is the commercial engineering software ETABS. The major building elements were obtained from structural drawings of the Factor building in order to model the dynamic response (Fig. 2). ETABS has the capability of object-based physical member modeling; for example, the program has built-in steel sections which have been used in constructing the model of Factor. Although ETABS allows for static and dynamic, as well as linear and simple nonlinear analysis, we have limited our modeling with ETABS to the linear range.

In order to study the nonlinear and damage characteristics of Factor, we used FRAME3D, a finite-element method-based nonlinear structural analysis program that can simulate fracture in the moment-frame connection welds . The structural model uses elasto-fiber beam elements for columns and beams, and 3D cruciform joint elements to model panel zones. Damage to the Factor building model is introduced by reducing the fracture strain of the fibers and computing building properties before and after large amplitude motions. We investigated the scenario where the fracture strain of both top and bottom flange welds is reduced, resulting in failure of the shear tab that is bolted to the web of the beam and welded to the column. In reality the failure usually occurs at the line of bolts at the beam web, not at the weld to the column, though we are not modeling the line of bolts or the failures associated with bolt friction and shearing. We applied the strain reductions to the flange welds on the east wall in three separate damage cases that are shown in Figure 3.

Results

In order to detect changes in building response due to damage to welded connections we have run simulations of the dynamic properties of the building before and after damage caused by large simulated deformations of the building. We first compute the building response to the impulsive 12/16/04 ML=3.6 Santa Monica earthquake which occurred at a distance of 35 km. The simulated building deformations are qualitatively similar to those that were recorded in Factor for this earthquake. The recorded mode shapes, which are obtained by narrow band filtering of all records at the modal frequency, are shown in Figure 4.

We next simulate the response of Factor to the Tabas record of the 1978 Tabas, Iran, M 7.4 earthquake, which causes simulated weld fracture in the Factor model. Finally we again compute the response of Factor to the 12/16/04 ML=3.6 Santa Monica Bay earthquake, but now the Factor model has selected welds that were fractured from the Tabas shaking. The entire input ground motion sequence is shown in Figure 4. The simulated pre-Tabas mode shapes Factor are compared with the simulated post-Tabas mode shapes in Figures 6, 7, and 8. The drift mode shapes are obtained by taking the difference between mode shapes of adjacent floors. Mode shapes, frequencies, and damping are determined by applying a least-squares minimization

algorithm to a linear, multiple-degree-of-freedom system with observed earthquake time series input and output.

In these simulations, the changes in mode shape coincide spatially with the locations that experienced loss of stiffness due to weld fracture. However, modeling of connections with fractured welds depends strongly on the assumed strain state of the damaged building. In particular, if the fractured connections have a static equilibrium in which there is continuity in the connection despite the fracture (the crack is closed), then the connection will behave in an identical manner to an un-fractured connection as long as the deformations are small.

A less common approach to identifying damage behavior is to model the dynamic properties of structures through wave propagation methods. We used local earthquake data to identify the impulse response functions of the Factor building by deconvolving sub-basement level displacements from the upper floor displacements. This approximately removes the part of the motion that is due to the earthquake ground motion (the combined effects of the source and wave propagation through the Earth). These impulse response functions are approximately equal to the basal force Green's functions as long as the effects of soil structure interaction are small.

Figure 9 shows a comparison of impulse responses that are derived from stacking deconvolutions of data from twenty local earthquakes that were recorded by the Factor array. The leftmost panel shows the N-S floor response from a N-S displacement impulse at the basement level. The second panel is similar, except that it is for the E-W components. The third and fourth panels show the rotational motion of each floor (derived by differencing records at opposite sides of the building) excited by N-S and E-W displacement pulse, respectively. The Factor building is built on a south facing hill slope. This causes an asymmetry in the building stiffness for E-W motions, but not for N-S motions. This asymmetry causes the excitation of torsional waves at the base of the building when there is an impulse in E-W ground motion. This effect can be clearly seen in both the observed and simulated motions.

Of all techniques to recognize damage in the building model, the one that seems most promising is to detect changes in the excitation of torsional waves. In particular, torsional waves are difficult to excite as long as there are symmetries in the building structure. However, weld fractures typically cause asymmetry in the structure. For a propagating wave with rectilinear particle motions, there is a partial conversion of this wave type to torsional waves at the point where symmetry is broken. Figure 10 shows an example of the difference between the torsional impulse response of Factor assuming weld fractures at different elevations in the building. Clearly, torsional waves are converted from rectilinear waves at the floors in the building that have lost symmetry due to damaged welds.

Acknowledgments

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Recent Publications

Kohler, M. D., T. Heaton, and C. Bradford, 2007, Wave propagation in buildings, Bull. Seis. Soc. Am.,97, 1334-1345.

Kohler, M., and T. Heaton, 2007 The UCLA Factor Building Seismic Array, IRIS newletter, Issue 1, 5-7.

Olsen, A., B. Aagaard, and T. Heaton, 2008, Long-period building response to earthquakes in the San Francisco Bay area, Bull. Seism. Soc. Am., vol. 98, 1047-1065.

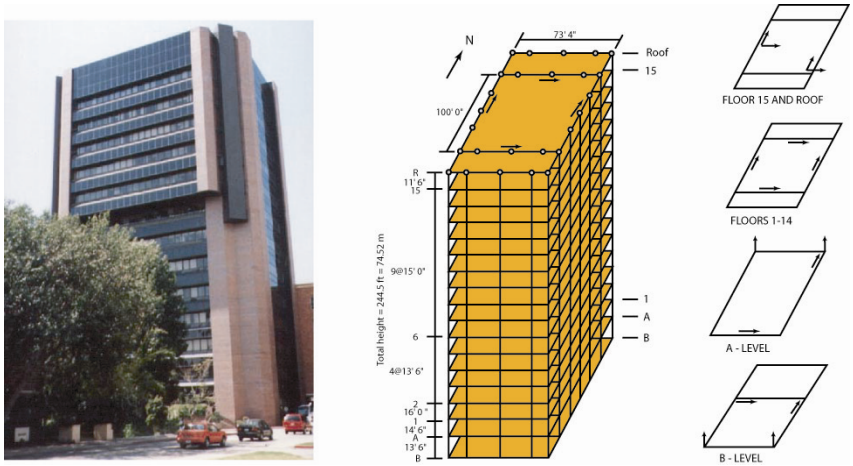

Figure 1. The Factor building and its seismic array. Arrows show locations and polarities of sensors on each floor.

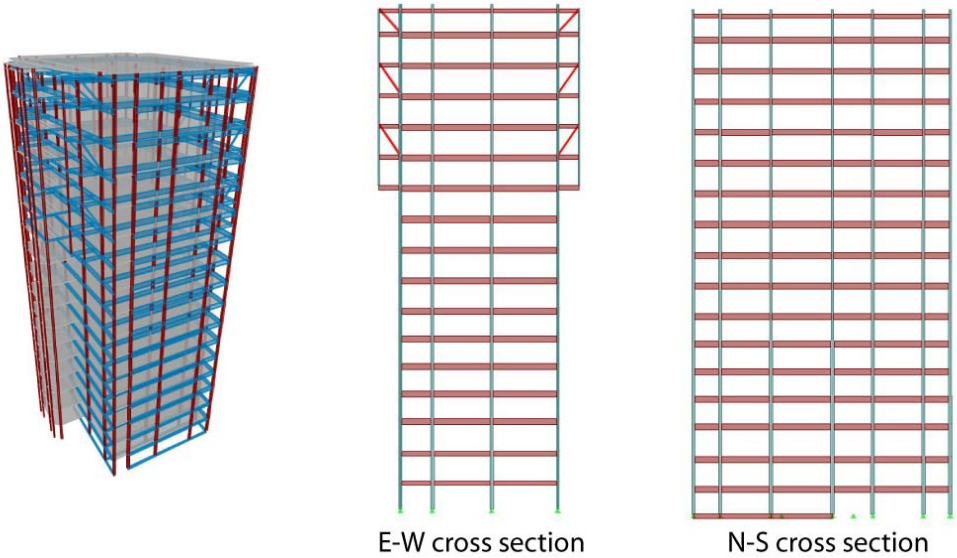

Figure 2. The ETABS model of the Factor building using physical object-based structural design with columns, moment-frame beams, slabs, walls and beam-column intersections, etc. The figure shows the primary major structural elements.

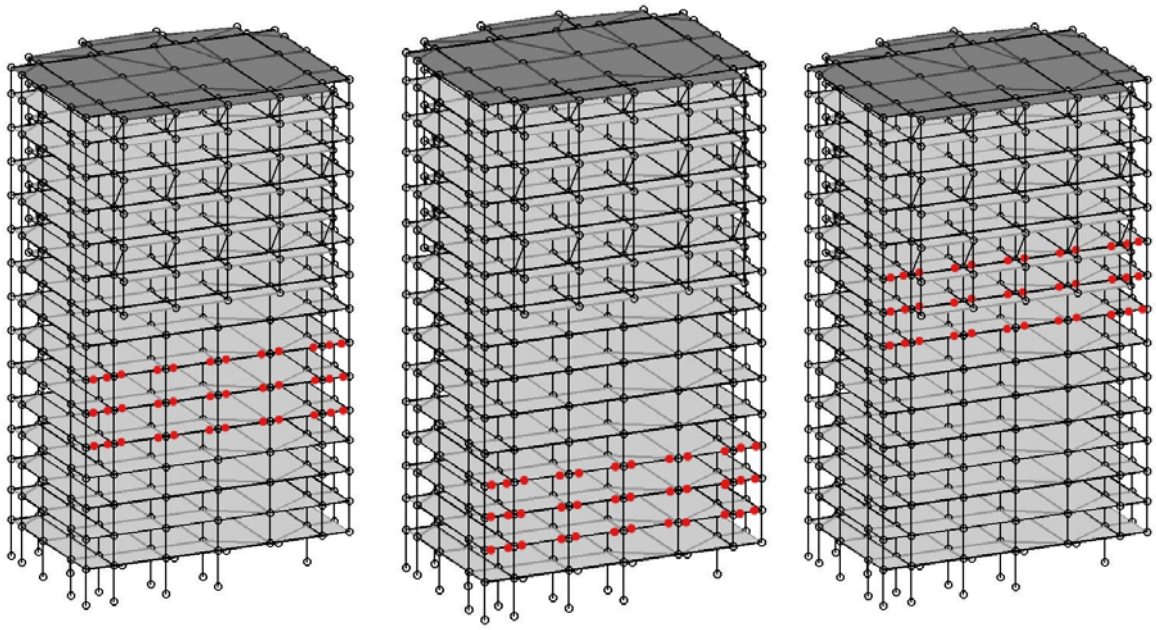

Figure 3. Frame3D realization of the Factor Building. Three separate damage patterns are simulated. The red dots show the locations at which we decreased the strain at which weld fracture is assumed to occur.

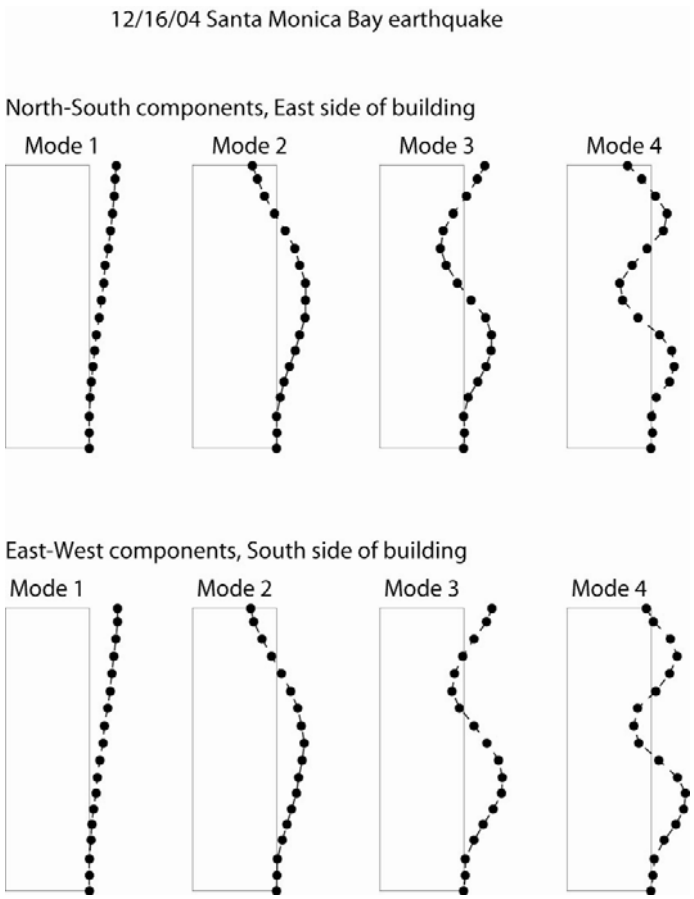

Figure 4. Mode shapes determined from observed displacements at the Factor building during the 12/16/04 Santa Monica Bay earthquake (distance=35 km, M_L=3.6).

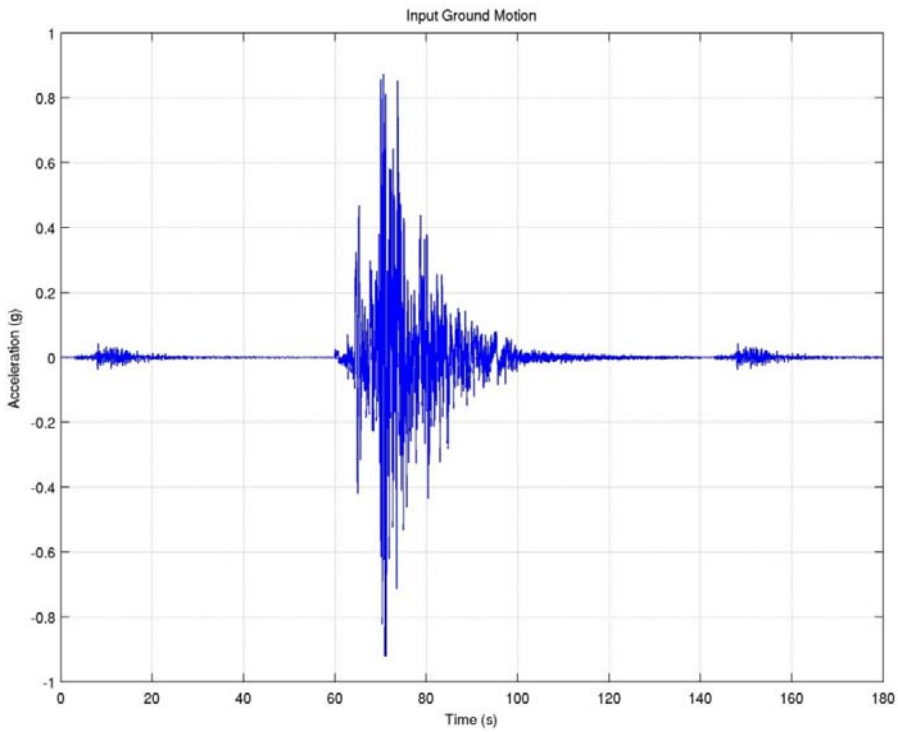

Figure 5. Changes in the response due to damage from a large event were studied by exciting the Factor building with a record from the Tabas earthquake. Before and after the earthquake, responses to excitation from the much smaller Santa Monica Bay earthquake were used to extract modal parameters using the program MODE-ID.

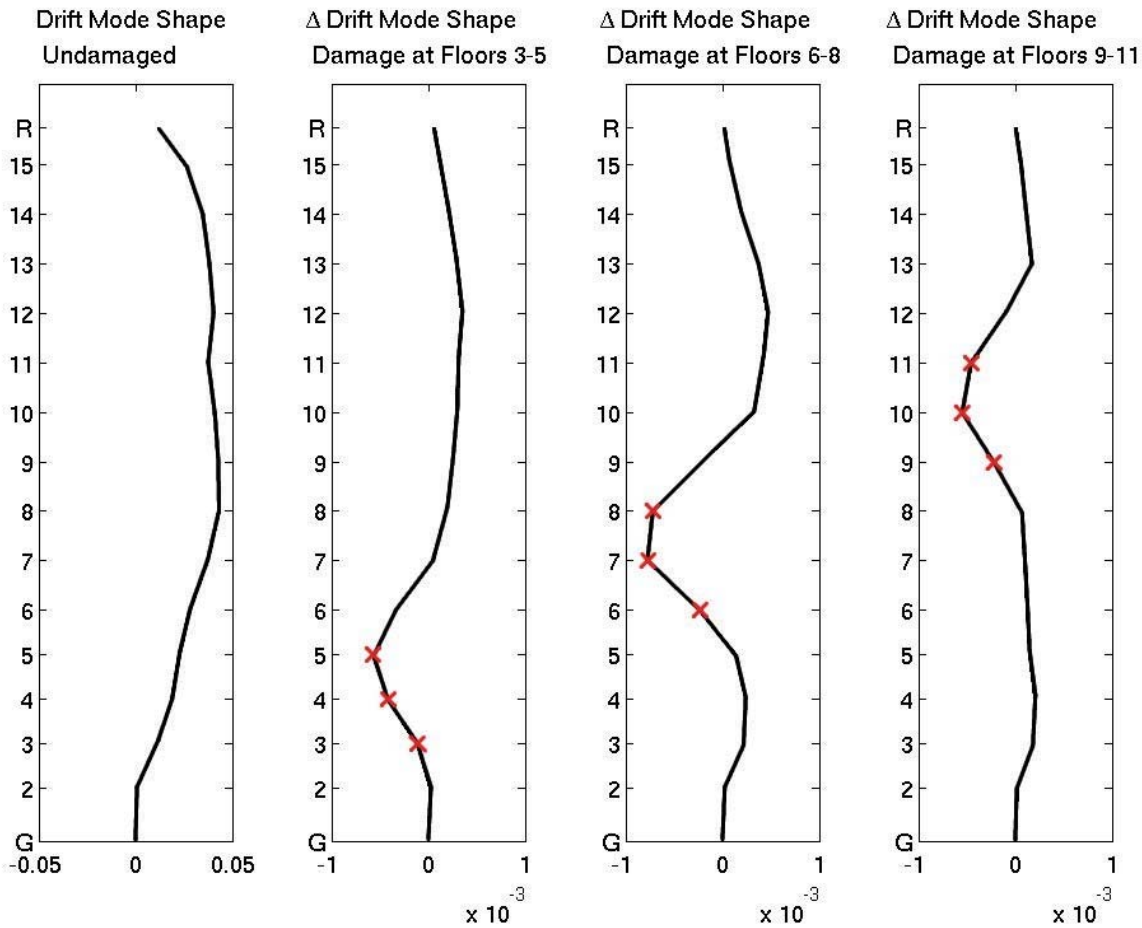

Figure 6. (a) First drift mode shape in the E-W direction. (b) Change in mode shape due to damage at floors 3-5 (location indicated by red x's in Figure 3). (c) Change in mode shape due to damage at floors 6-8. (d) Change in mode shape due to damage at floors 9-11.

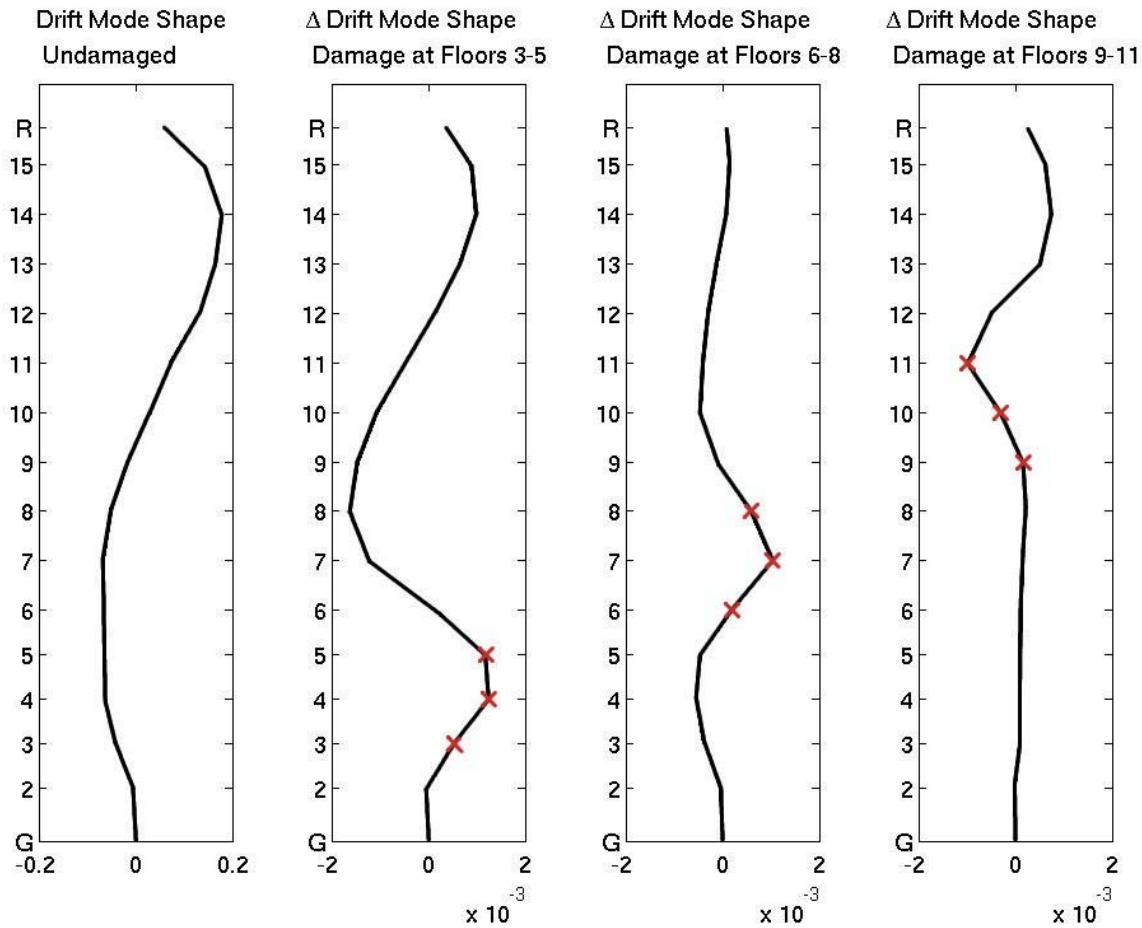

Figure 7. (a) First drift modeshape in the E-W direction. (b) Change in modeshape due to damage at floors 3-5 (location indicated by red x's in Figure 3). (c) Change in modeshape due to damage at floors 6-8. (d) Change in modeshape due to damage at floors 9-11.

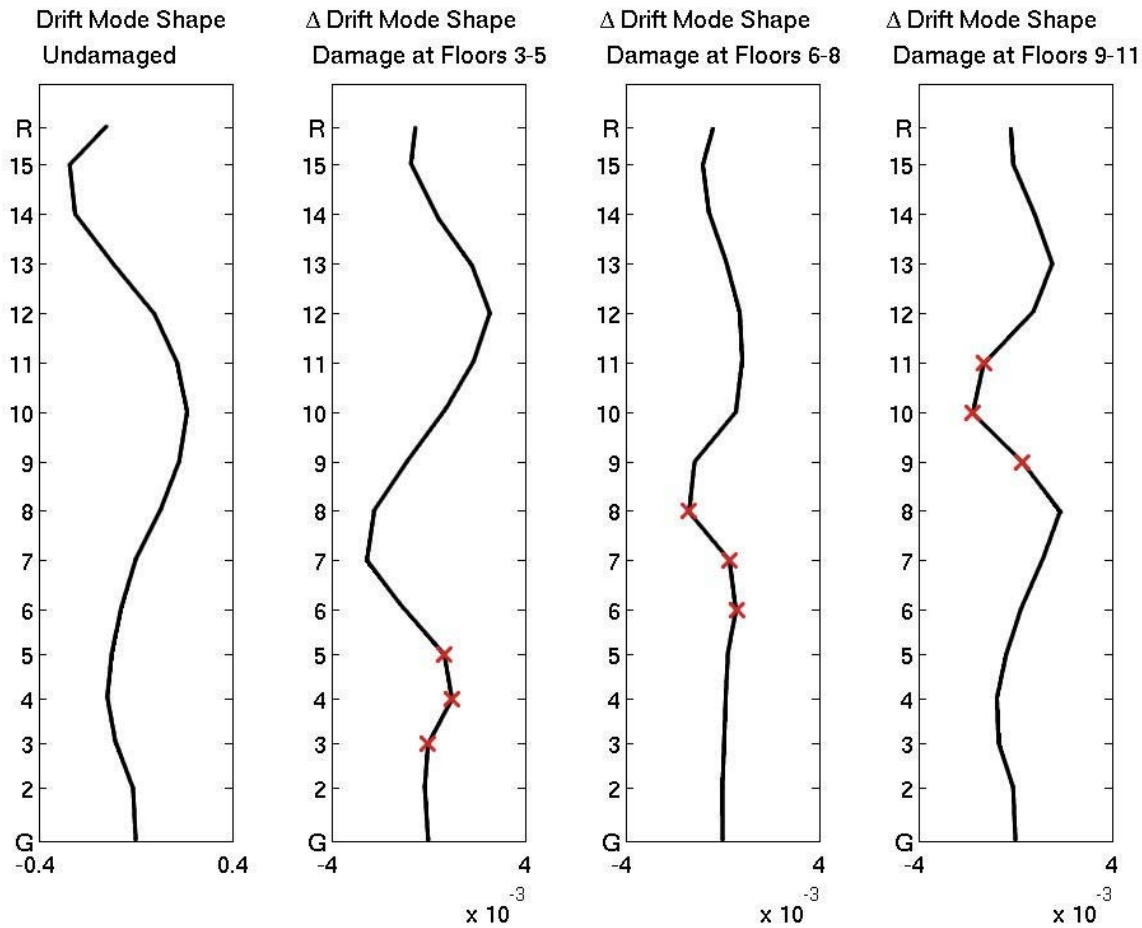

Figure 8. (a) Third drift mode shape in the E-W direction. (b) Change in mode shape due to damage at floors 3-5 (location indicated by red x's in Figure 3). (c) Change in mode shape due to damage at floors 6-8. (d) Change in mode shape due to damage at floors 9-11.

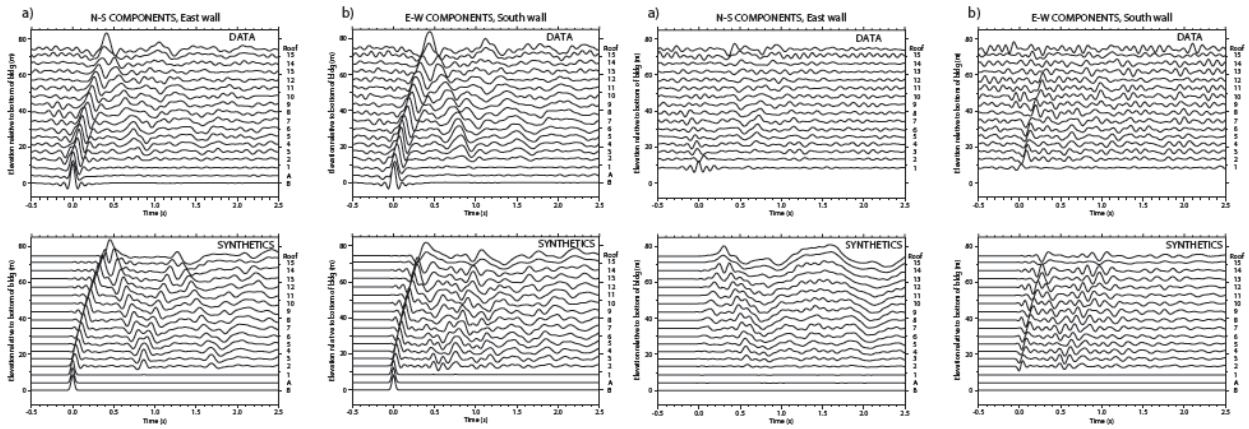

Figure 9. Observed and simulated response of Factor to an assumed impulse in displacement at the base of the building. The panels to the left show the linear motion of each floor for an impulse of displacement in the same direction. The third panel shows the torsional motion of each floor for a N-S pulse of displacement at the basement. The fourth panel is the torsional response from an E-W pulse at the base.

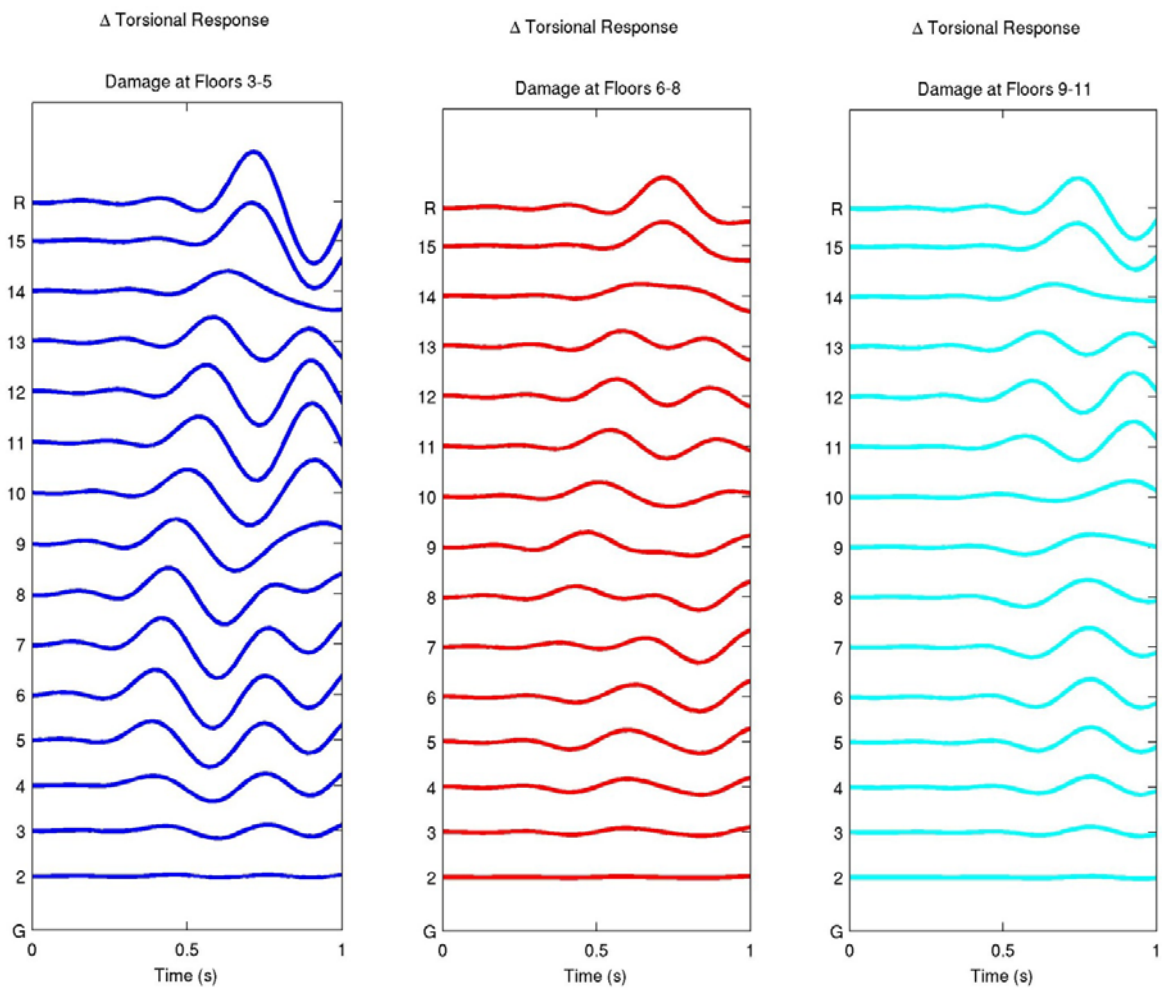

Figure 10. Change in torsional response to pulse excitation caused by damage at floors 3-5. These rotational motions (torsion about a vertical axis) obtained by taking the difference between the N-S motions on opposite walls of the same floor. Each curve shows the difference between rotations produced by the damaged and undamaged models for the three damage scenarios.