# Using embedded wired and wireless seismic networks in the moment-resisting steel frame Factor building for damage identification

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**Abstract:** Ideally both spectral and time domain data could be used to compute the total building response and to make predictions of damage patterns based on various input scenarios. The combination of frequency change information coupled with that provided by wavefield properties can pinpoint the time and location of damage more accurately, especially for densely instrumented structures such as the 17-story UCLA Factor building. The 72-sensor embedded seismic array in the Factor building, recording continuous waveforms at 500 Hz, makes it possible to observe subtle changes in dynamic characteristics between pairs of floors and to relate the measurements to system properties such as changes in stiffness due to a column failure. The high dynamic range of the 24-bit digitizers allows both strong motions and ambient vibrations to be recorded with reasonable signal-to-noise ratios. Temporary decreases in frequencies of Factor building modes of vibration have been correlated with moderate-to-strong shaking, and spectral amplitudes of ambient vibrations have clear daily and weekly patterns that correlate with working hours, wind speeds, and non-seismic vibrations. Waveform data from the Factor array are also being used in comparison with finite element calculations for predictive damage behavior. A three-dimensional model of the Factor building has been developed based on structural drawings. Observed displacements for 20 small and moderate, local and regional earthquakes were used to compute the impulse response functions of the building by deconvolving the subbasement records as a proxy for the free field. It can be shown that small but significant changes in the travel times, mode shapes, and frequencies are observed in the simulation results for strong ground shaking and for modifications to the structural model for hypothesized damage patterns such as broken welds on a particular floor. Wireless untethered devices whose design is guided by data analysis and simulations such as these can significantly increase the spatial resolution of structural response to earthquakes. A Mica-Z mote network controlled by Wisden software that monitors a local area such as a building is being assembled and tested. The software system addresses some of the challenges associated with high sample rates and limited radio bandwidth, yet allows structural data acquisition from a relatively large network of wireless sensors.

**Key words:** Wireless sensors, Structural monitoring, Damage detection, Wave propagation

## INTRODUCTION

We are using data analysis and predictive modeling of the wired UCLA Factor building seismic array to guide the design of a wireless network for structural health monitoring. Developments in wireless sensing for structural monitoring are becoming increasingly sophisticated (Lynch and Loh, 2006); however, there remain serious hardware and software limitations in the technology that preclude the measurement and detection of many types of useful signals. Common limitations are that digitizer resolution is 16-bit or lower and cannot record useful low-amplitude vibrations. Typically MEMS-type sensors have noise levels that are too high, especially for low-frequency signals from which to infer global structural properties. The vibration data often cannot be calibrated or validated because there are no analogous wired systems with which to compare the wireless data. Communications and power limitations often limit the number of nodes, components and sample rates of waveform data being recorded continuously for long periods of time.

The wired Factor building network is a testbed for observational and predictive modeling that is being used to design a structural monitoring wireless network. Changes in the mode shapes and frequencies are observed in the data and modeling results for strong ground shaking and for hypothesized damage patterns. Wireless untethered devices whose design is guided by the data analysis can significantly increase the spatial resolution of structural response to earthquakes. The wireless network uses a first-generation software system that allows continuous sampling and reliable logging of time-synchronized structural response data. The scaling provides flexibility in deployment in which nodes self-organize into a multi-hop network, and they can be inserted into and removed from the network dynamically. The result is that the installation can be faster and lower-cost.

In this paper we use the wired data to show that low-amplitude data provide a wealth of information that can be used in structural monitoring system design. 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. However, if we have any hope of examining small-to-moderate sized shaking events, we need to deploy better than 16-bit devices and low-noise sensors for low-frequency signals. Wireless deployments should include a high density of nodes with flexible placement, three components at each location, and sampling rates of at least 500 sps. These requirements point to the need for multi-scale analysis made possible by software that accommodates multi-scale deployments. Specifically, we show that by looking at spectral properties, wave propagation properties, and predictive modeling that low-amplitude data are being used in non-traditional ways to understand the nonlinear response of buildings.

We investigated spectral and wave propagation behavior in the Factor building by comparing finite element simulation results with data from the 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 large 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. Furthermore these data are being used to calibrate and validate the wireless recording package.

## The Factor Seismic 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 a shallow 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 response has been determined.

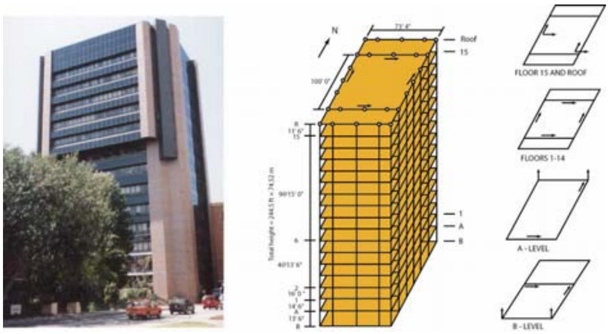


**Figure 1: The Factor building and its seismic array. Arrows show locations and polarities of sensors on each floor.**

DATA ANALYSIS AND MODELING

**Spectral Properties**

As part of the vibration monitoring of the Factor building done to date, a large quantity of 24-hour/day ambient vibration data, and several small but significant local earthquakes were recorded that show temporal changes in vibration mode characteristics. Our real-time monitoring program illustrates how changes could be continuously monitored to detect significant damage or breakage in a structure. It is generally assumed that nonlinear behavior is small unless a structure has experienced severe shaking from a large event. Our observations show that measurable nonlinear effects are occurring for small earthquakes due to changes in the stiffness of the building or soil when amplitudes get larger (Kohler et al., 2005). Upon inspection of hundreds of ambient vibration records for calm vs. windy days as well as for earthquakes (e.g., the 9/3/02 $M_L$=4.7 Yorba Linda and the 9/28/04 $M_L$=6.0 Parkfield earthquakes), a decrease in frequencies is obvious in the raw spectral data (Kohler et al., 2005; Skolnik et al., 2006). The frequencies return to previous ambient vibration levels within seconds of the high amplitude motions.

The decrease in frequencies is also obvious for wind excitation. Fig. 2 shows stacked data for two 24-hour periods for one calm day (12/25/04) and one windy day (11/28/04) for which the first few modal frequencies are obviously decreased. The climate data were collected by the UCLA Atmospheric Sciences Department at the nearby Math Sciences building that includes the maximum wind speed recorded during 10-minute intervals (similar to gust recordings). During the 11/28/04 period, average wind speeds were up to 25 mph and gusts were nearly 40 mph. It remains to be determined how the wind source excitation function may have influenced the frequency changes.

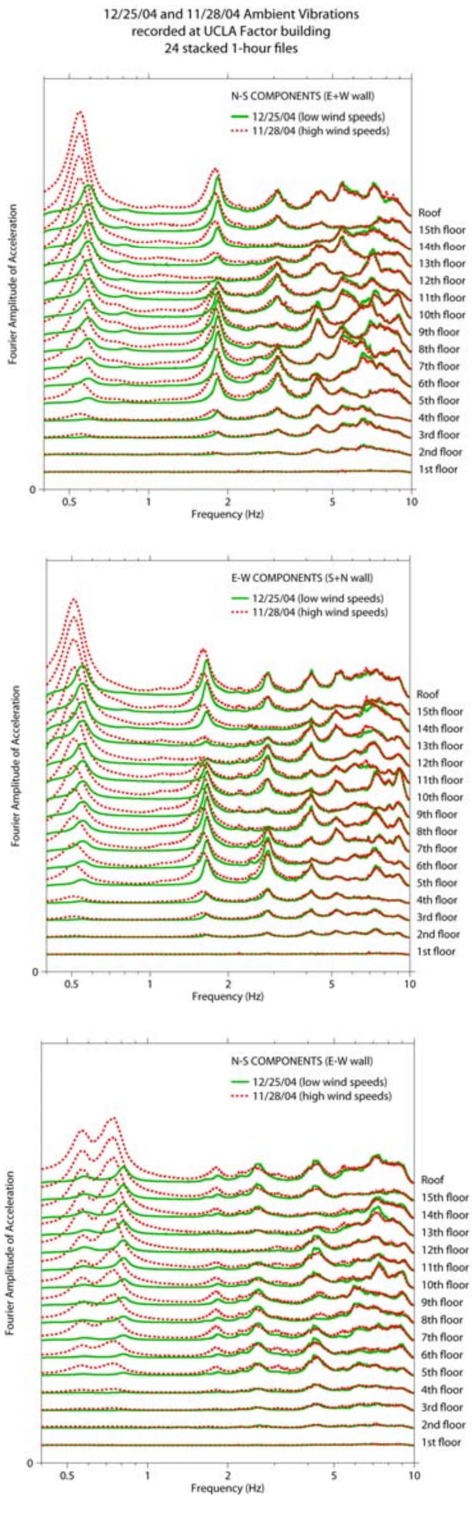


**Figure 2: Ambient vibration Fourier amplitude spectra recorded on 12/25/04 (a low wind speed day: solid curves) and 11/28/04 (a high wind speed day: dashed curves).**

## Wave propagation properties

It is increasingly common to consider the wave propagation response of buildings (e.g., Safak, 1999; Todorovska et al., 2001a; Snieder and Safak, 2006), especially when determining whether damage is detectable through monitoring of those effects (e.g., Todorovska et al., 2001b; Zhang and Iwan, 2002). One way to approach this problem is to model the dynamic properties of structures through wave propagation methods, specifically to predict the displacement response of a building when it is subjected to near-field or far-field shaking from an earthquake. We have computed propagating waves through the building model to examine the building's linear and nonlinear behavior for damage scenarios. For this, we calculated the propagating impulse response function and inter-story drift resulting from the different scenarios. From the results we are examining predicted travel-time variations, torsional, and nonlinear behavior.

We used the commercial engineering software ETABS to construct a Factor building model (Fig. 3). The dynamic simulations in the linear regime are carried out by entering ground acceleration excitation at the base in the form of dynamic linear time histories.

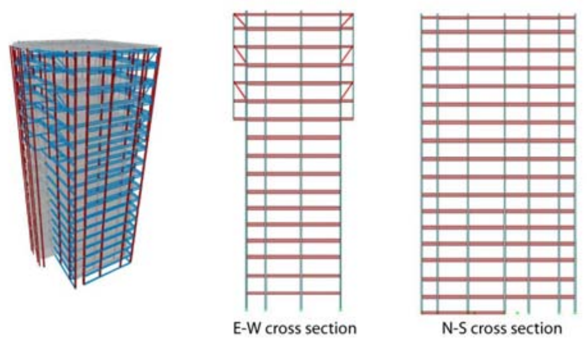


**Figure 3: The ETABS model of the Factor building showing the primary major structural elements, and cross sections of major structural elements.**

We used earthquake data in the form of impulse response functions to construct and validate our linear building model (Kohler et al., 2006). Observed displacements for 20 small and moderate, local and regional earthquakes were used to compute the impulse response functions of the building by deconvolving the subbasement records. We use the subbasement as a proxy for the free field, thereby separating out the source effects and propagation effects between the source and subbasement. The subbasement is the second level below ground and thus has soil-structure interactions included its recordings. We use small to intermediate earthquakes in our analysis, precluding the possibility of significant source effects (e.g., complex source-time functions, source complexity, directivity, and non-standard source spectrum) or significant soil-structure interaction. The impulse response functions were then stacked to bring out wave propagation effects more clearly (Fig. 4, top).

The simulation results using 2% damping with a Gaussian curve input are shown in Fig. 4 (bottom). This figure shows the synthetic propagating wave starting as a Gaussian impulse response function in the subbasement and extending to the top of the building. The primary pulse reflects off the top of the building. The synthetic seismograms also show the secondary reflections from the bottom of the $10^{th}$ floor, especially in the east-west components. Both data and synthetics for the north-south components clearly show a propagating pulse of S-wave energy traveling up and down the building three times during the 3 s of data.

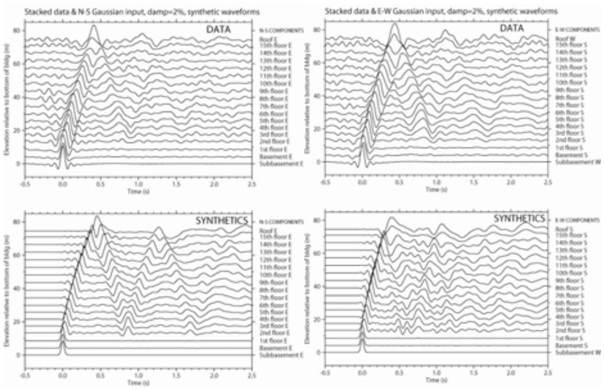


**Figure 4: Stacked impulse response functions for the north-south (left, top) and east-west (right, top) components, and associated synthetic waveform results (bottom) using the ETABS modeling for a Gaussian input with 2% damping.**

## Mode shapes

We have examined mode shapes both from real data and from forward modeling analysis for the Factor building to document what is actually happening and to examine what we might expect from strong shaking from different types of damage applied to the building model. Using mode shape changes to identify damage has been investigated before (Sohn et al., 2004), but never at the small observational scale available in the Factor building due to the density of the array. Investigation of horizontal displacement within narrow frequency bands has been conducted to verify Factor building modes and their shapes. Fig. 5 shows results of the maximum displacement measurements for the 12/16/04 Santa Monica Bay earthquake ($M_L$=3.6). These curves are typical of those obtained for small earthquakes and ambient vibrations (Kohler et al., 2005). The figure shows displacement for the N-S components (top row) and E-W components (bottom row) of the first eight horizontal modes.

It is likely that quantitative methods of measuring the mode shapes from a damaged building will eventually be used to determine whether a significant change has taken place, what stiffness changes may be responsible for the changes, and to map the stiffness changes into damage occurrence.

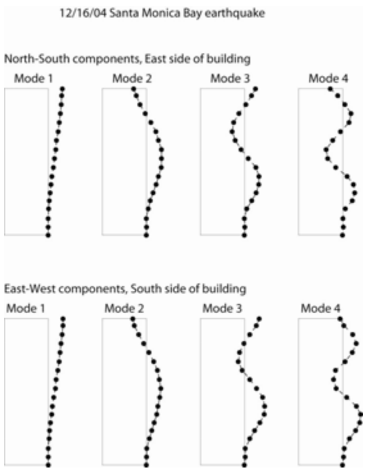


**Figure 5: Mode shapes determined from observed displacements (filled circles) at the Factor building during the 12/16/04 Santa Monica Bay earthquake (distance=35 km, $M_L$=3.6).**

In order to gain a preliminary understanding of what changes in mode shape we would expect from strong shaking, we have used our building model to show the effect of changing the moment framed connections on a specific floor to simple pinned connections. For this example we created two ETABS models identical to each other, with the exception of the connections on the 8th floor. We replaced every moment connection at this floor with a pinned connection as a proxy for connection failures throughout the floor. This is somewhat similar to breaking all the welds on that floor. This is not 100% realistic; the damage patterns would likely be more evenly distributed through the building, but this was a useful example. It is clear from the dynamic analysis results using ETABS that both the frequencies and the mode shapes change dramatically (Fig. 6). Though this is an oversimplified way to approach the problem, it gives us an initial idea of the potential use of the mode shapes to isolate where the source of stiffness change may have occurred and infer damage from them.

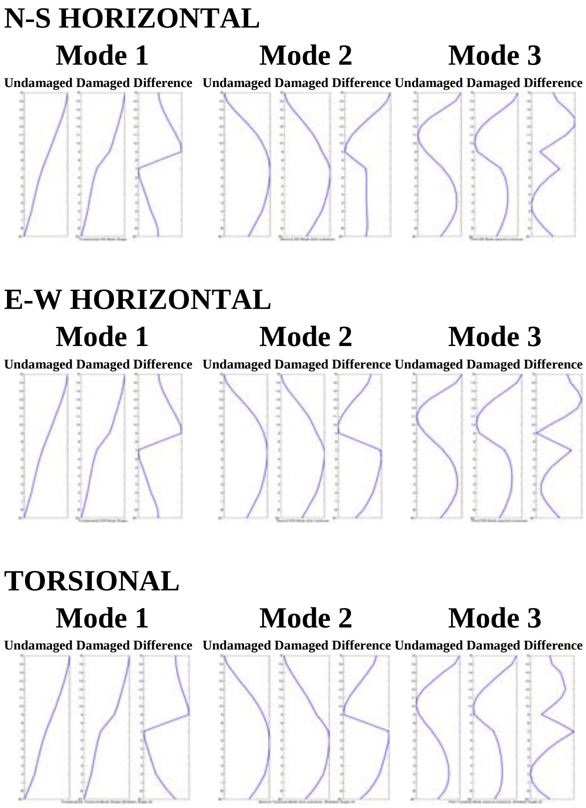


**Figure 6: Synthetic mode shapes from a hypothetical damage pattern that simulates broken welds on the 8th floor. The "Damaged" plots are for the model that simulates the broken welds. The "Difference" plots have been scaled by a normalization factor.**

## CONCLUSIONS

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. 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 could pinpoint the time and location of damage more accurately.

The Factor building on the UCLA campus, heavily instrumented with sensors embedded throughout its entire height, presents a unique opportunity to study the building response after removing the free-field response. Earthquake data are revealing changes in shear wave velocity where there are major changes in stiffness due to material properties and dimension changes in the structural elements. The wired data illustrate that low-amplitude data provide a wealth of information that should be considered in wireless system design.

## Acknowledgments

We appreciate discussions with Erdal Safak and advice on building the ETABS model from Swami Krishnan. The work was supported by the National Science Foundation through the Center for Embedded Networked Sensing under Grant No. CCF-0120778. Operations and maintenance of the Factor seismic array was supported by personnel and funds from the U.S. Geological Survey Advanced National Seismic System (ANSS) program and the NSF Center for Embedded Networked Sensing (CENS) at UCLA.

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