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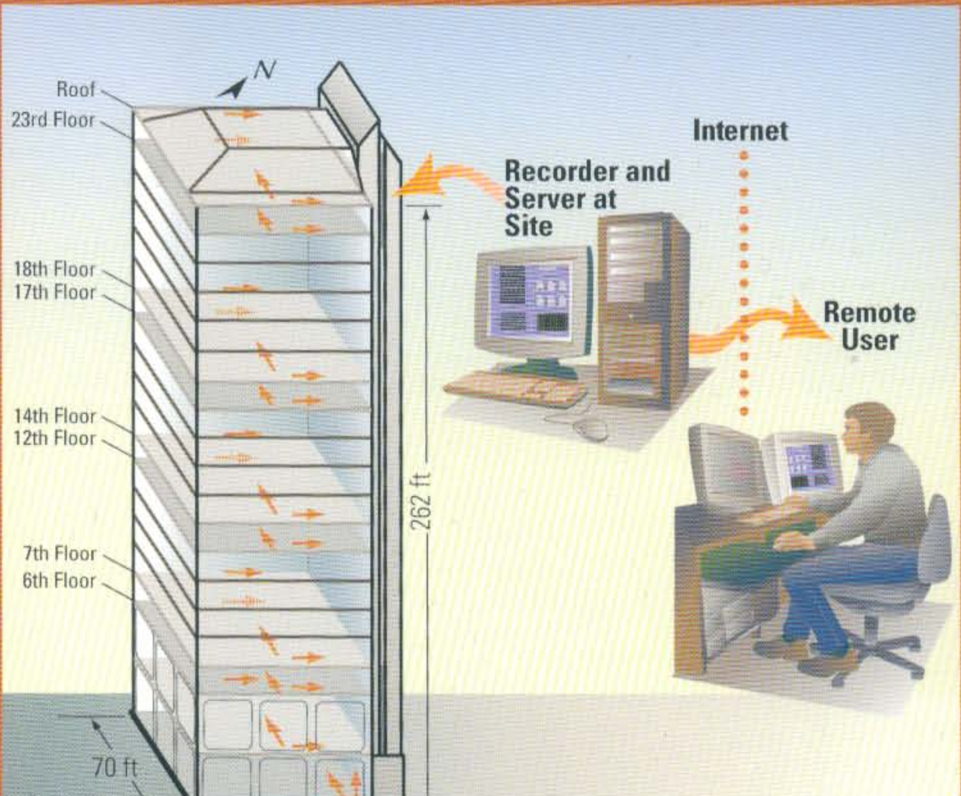

Real-Time Seismic Monitoring Needs of a Building Owner—and the Solution: A Cooperative Effort

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A recently implemented advanced seismic monitoring system for a 24-story building facilitates recording of accelerations and computing displacements and drift ratios in near-real time to measure the earthquake performance of the building. The drift ratio is related to the damage condition of the specific building. This system meets the owner's needs for rapid quantitative input to assessments and decisions on post-earthquake occupancy. The system is now successfully working and, in absence of strong shaking to date, is producing low-amplitude data in real time for routine analyses and assessment. Studies of such data to date indicate that the configured monitoring system with its building specific software can be a useful tool in rapid assessment of buildings and other structures following an earthquake. Such systems can be used for health monitoring of a building, for assessing performance-based design and analyses procedures, for long-term assessment of structural characteristics, and for long-term damage detection.
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INTRODUCTION

In all seismic areas, local and state officials and prudent property owners establish procedures to assess the functionality of buildings and other important structures such as lifelines following a significant seismic event. Immediately following such an event, the decisions of functionality and occupancy of a building in most cases are based on visual inspections of possible damage to the structure. If the structure appears damaged, it is necessary to further examine and assess whether the damage condition of the structure presents an unsafe environment for the occupants or users of that structure. Therefore, to have instrumental measurements of shaking of a building or even a nearby ground site provides valuable information to decision makers.

In general, a system for seismic monitoring of structures must fulfill a stated need—that is, during and after a strong shaking event, the monitoring system should yield data that serve the specific purposes for which it has been planned. Each user of the structural response data may have a different objective. In general, from the viewpoint of an owner, the objective could be to use such data obtained by monitoring to increase the likelihood that the building will be permitted to remain functional following an event. In practical terms, this means whether, immediately after occurrence of an event, a building

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will be tagged as green ("no restriction on use or occupancy"), yellow ("limited entry, entry is permitted only by the owner for emergency purposes, at his or her own risk"), or red ("unsafe, the structure poses an obvious safety hazard") (ATC 1989).

When seismic monitoring has been considered and implemented, in general, the principal objective has been the quantitative measurement of structural response to strong and possibly damaging ground motions for purposes of improving design and construction practices. Thus it is expected that an instrumented structure should provide enough information to (a) reconstruct the response of the structure in enough detail to compare with the response predicted by mathematical models and those observed in laboratories, the goal being to improve the models, and (b) make it possible to explain the reasons for any damage to the structure. The nearby free-field and ground-level time history should be known in order to quantify the interaction of soil and structure.

Therefore, the main objective to date has been to facilitate response studies in order to improve our understanding of the behavior and potential for damage of structures under the dynamic loads of earthquakes. As a result of this understanding, design and construction practices can be modified so that future earthquake damage is minimized. Up to now, it has not been the objective of instrumentation programs to create a health monitoring capability for structures.

However, structural engineers increasingly want the measurement of displacements in order to assess drift ratios during strong shaking events. In order to achieve these, the approach used in this paper is a suitable and technologically feasible way for real-time assessment and alarm system based on computation of drift ratios from double-integrated acceleration measurements. This approach can also be used for performance evaluation of structures. The described system is considered as a building health-monitoring system.

The objective of this paper is to describe a specific case whereby the owner of a building, in collaboration with a federal agency with expertise in seismic monitoring of buildings, private consulting engineers, and a supplier, facilitated development and implementation of a state-of-the-art seismic monitoring system for a 24-story steel frame building in San Francisco, California. The objectives and implemented characteristics of the system meet the specific needs of the owner. This case illustrates that building-specific monitoring systems can be developed to meet the needs of owners of other buildings and structures.

BUILDING AND CHARACTERISTICS

The building was designed according to the 1979 *Uniform Building Code* (ICBO 1979) and its construction was completed in 1982. The ground floor (plaza level) with a height of 50 ft (15.2 m) appears as two nominal floors of the 284 ft (86.6 m) tall building. The building has a 70 ft×90 ft (21.3 m×27.4 m) plan.

Perimeter steel moment-resisting frames with welded connections are continuous from grade to roof level. The columns and beams are steel wide flange and box sections. Reinforced concrete on metal deck floors function as rigid diaphragms and transfer lateral loads to the perimeter moment frames. The perimeter moment-frame beams are typically not composite with the metal deck floor system. The moment frames are expected to behave as strong-column/weak-beam frames resulting in development of hinges at the beams. The building structure is therefore considered as a “pre-Northridge” perimeter welded-steel moment frame.

There is a partial basement; however, the steel columns typically terminate at just below grade. The foundation of the building consists of 12 in (0.305 m) square, reinforced, precast piles driven to approximately a 60 ft (18.3 m) depth. The reinforced concrete pile caps are interconnected by a grid of reinforced concrete grade beams.

A general three-dimensional schematic of the building with its overall dimensions is provided in Figure 1.

DISCUSSION OF NEEDS

The building owner is in need of reliable and timely expert advice on whether or not to occupy the building following an event. Furthermore, information gathered from the building during strong-shaking events will help the building owner to further assess technical issues as related to possible post-earthquake connection inspection, retrofit, and repair of the building. For this reason, the following decisions have been made:

1. The building has been designated as part of the Building Occupancy Resumption Program (BORP 2001). “This award-winning program (BORP) of the San Francisco Department of Building Inspection, developed in cooperation with SEAONC (Structural Engineers Association of Northern California), BOMA (Building Owners and Management Association), and AIA (American Institute of Architects) allows building owners to pre-certify private post-earthquake inspection of their buildings by qualified licensed engineers” (BORP 2001). The owner’s engineers post red/yellow/green placards in accordance with *ATC-20* guidelines (ATC 1989) in lieu of the city-authorized inspectors who would typically be unfamiliar with the building and may not be available for several days following the earthquake.
2. The owner and the consultants have agreed that general building-related evaluation work will commence in the building by cognizant personnel to reach decisions on the suitability of reoccupying the building following any one of the following events, or exceedence of thresholds that may be cause of possible damage in the building:
   a. a state of emergency in the city or county of San Francisco has been declared,
   b. a $M \geqslant 6.0$ earthquake on the San Andreas or Hayward or Rodgers Creek faults, or
   c. the building experiences a peak ground acceleration greater than 0.25 g (this is intended as free-field motion and adopted from Table 3-1, *FEMA-352* [SAC 2000]).

Damage in steel moment-frame structures generally is due to yielding or fracture of the welded connections. The damage is frequently not immediately visible due to the presence of building finishes and fireproofing. In the absence of visible damage to the

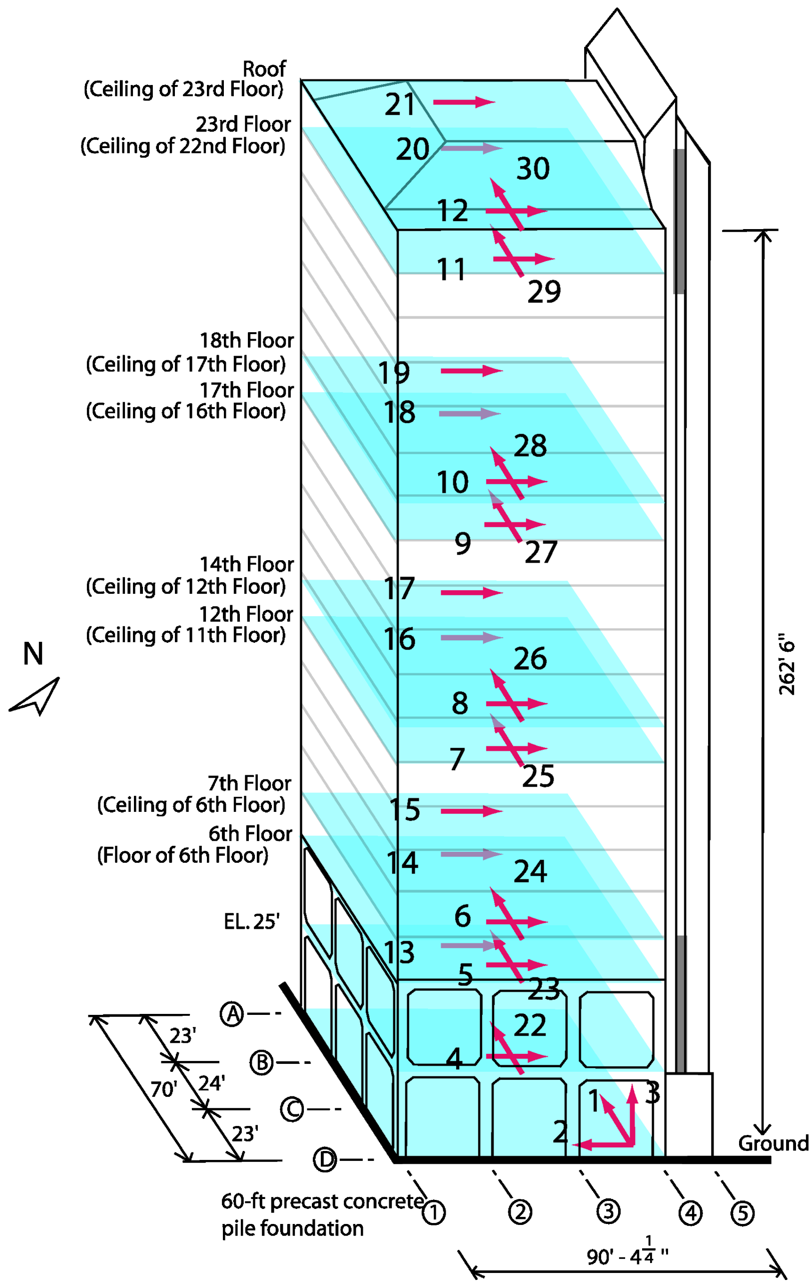

Figure 1. General three-dimensional schematic of the building. Also shown are the 30 accelerometers (heavy arrows) deployed throughout the building.

building frame, most steel moment-frame buildings will be tagged based on visual indications of building deformation, such as damage to partitions or glazing. Lack of certainty regarding the actual deformations that the building experienced will typically lead the inspector toward a relatively conservative tag—e.g., yellow tag instead of green.

The city of San Francisco has yet to adopt or develop criteria for post-earthquake inspection and assessment of pre-Northridge welded moment-frame structures beyond the *ATC-20* (ATC 1989) tagging requirements. Similar to the process that occurred in Los Angeles following the 1994 Northridge earthquake, the city of San Francisco will likely require detailed inspections of the welded connections in high-rise steel moment-frame structures in the area of strong ground shaking. It is reasonable to expect that these will be based on the most sophisticated set of requirements developed to date, *FEMA-352: Recommended Post-earthquake Evaluation and Repair Criteria for Welded Steel Moment-Frame Buildings* (SAC 2000).

Application of the *FEMA-352* requirements for the subject building would result in inspection of 10% to 15% of the connections in the building. The building owner and engineers anticipate using the data provided by the system to justify a reduced inspection program than that which would otherwise be required by the city of San Francisco for a similar non-instrumented building in the same area. Depending on the deformation pattern observed in the building, it would also be possible to direct the initial inspections toward locations in the building that experienced peak drifts during the earthquake.

These objectives are best accomplished by deploying accelerometers at specific locations in the building to facilitate measurement of the actual structural response, which may indicate occurrence of damage and lead to making consequential decisions in a timely way. For this reason, in addition to measurement of ground-level input motions, measurement of structural response is needed to compute parameters that will relate to the damage status of the structure.

The most relevant parameter in this case is the measurement or computation of actual or average story drift ratios. Specifically, the drift ratios can be related to the performance-based force-deformation curve hypothetically represented in Figure 2 modified from Figure C2-3 of *FEMA-274* (ATC 1997). When drift ratios, as computed from relative displacements between consecutive floors, are determined from measured responses of the building, the performance and as such "damage state" of the building can be estimated as in Figure 2.

Therefore, the problem and the challenge are: to compute displacements from recorded acceleration responses in real time or near-real time. Measuring displacements directly is very difficult and, except for tests conducted in a laboratory (e.g., using displacement transducers), has not yet been feasibly achieved for a variety of real-life structures. For long-period structures such as tall buildings and long-span bridges, displacement measurements using Global Positioning Systems (GPS) are possible (Çelebi and Sanli 2002), but limited in application (e.g., GPS technology is limited to sampling rates of 10–20 Hz and, for buildings, measurement of displacement only at the roof is possible).

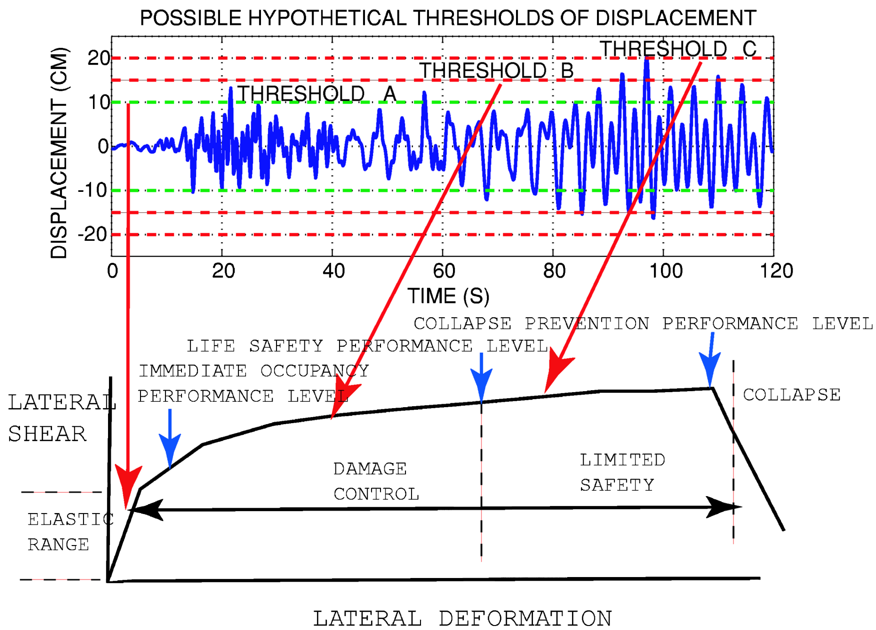

Figure 2. Hypothetical displacement time-history as related to *FEMA-274*.

ACCELEROMETERS IN THE BUILDING

As seen in Figure 1, thirty accelerometers are now deployed throughout the building. This number of accelerometers is within the current norm that is recommended (COSMOS 2001). Deploying accelerometers on every floor would have been too costly both from the point of added hardware and cabling required, and also the additional demands on digitizing of analog signals, recording, data streaming, and transmission capabilities.

A tri-axial accelerometer is on the ground floor to provide requisite reference input motions to the building. Then at each of nine levels (at elevation 25 ft [7.6 m.], 6th, 7th, 12th, 14th, 17th, 18th, 23rd floors, and the roof), three uniaxial accelerometers are deployed. It is noted herein that in the building there is no 13th floor designation. At each of these levels, two parallel accelerometers are deployed, in the nominal EW direction, one at the north end and the other at the south end. The third accelerometer is deployed in the nominal NS direction. The configuration is the optimal distribution of accelerometers.

The purpose of this deployment scheme is to facilitate the computation of either actual drift ratios at several pairs of consecutive floors, or average drift ratios over various combinations of non-adjacent floors.

GENERAL DESCRIPTION OF REQUISITE MONITORING SYSTEM

The unique aspects of the requisite monitoring system that will facilitate the needs of the particular owner are generally described as follows:

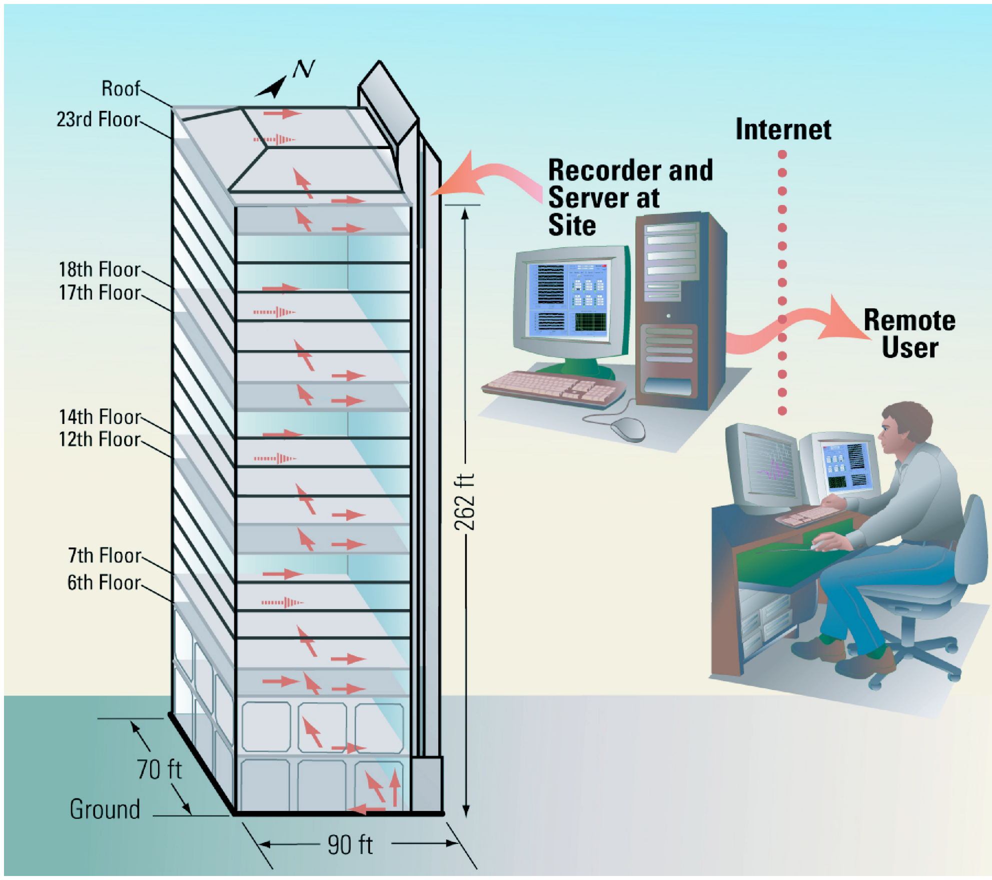

Figure 3. General schematic of data acquisition and transmittal for seismic monitoring of the building.

- The monitoring system must facilitate rapid assessment of the building integrity following an earthquake;
- The monitoring system must provide data in a form that is easy to correlate with known and building specific engineering parameters (e.g., drift ratio), which in turn must relate to the expected damage condition of the building; and
- The monitoring system must deliver the data within a relatively short time (a few minutes if not in seconds), if not in real time, to facilitate informed decision making regarding post-earthquake building occupancy.

The PC-based monitoring system for the building described in this paper has a server at the site and can be remotely accessed as schematically shown in Figure 3. The figure also depicts the data management, communication, and transmittal setup.

RECORDING AT THE SERVER/RECORDER AT THE SITE

The system has the standard recording capability (of continuously streamed acceleration data) at the site server PC. Recording starts when pre-assigned thresholds of acceleration are exceeded at selected locations in the building (where accelerometers are deployed as seen in Figure 1). This is similar to the standard way such recording is initiated with most current systems. As in most newer recording systems, this new system also can trigger at thresholds defined at ten locations. Data stored at the server can be retrieved manually at the site, retrieved remotely or transferred automatically to a predefined location. The system is (high-speed) Internet connected. Users are able to connect to the server via the Internet and are able to view or record the real-time streamed data remotely.

The server/recorder at the site is controlled by specific software that is multithreaded. The system digitizer, an analog to digital (A/D) converter, within the server/recorder, processes the analog signals from all of the 30 sensors. The raw data thread acquires data from the system digitizer at 1000 samples per second (sps), scales it to cm/s/s using sensitivity information of each channel, digitally low-pass filters the data, decimates to 200 sps, and sends it continuously to the triggering and broadcasting threads. The triggering thread of the software continuously monitors the trigger conditions by comparing the amplitude level on any ten (user selected) channels with the predetermined trigger thresholds. When the exceedance criteria (e.g., 0.3% g) is met, the system will start recording raw data in an event file. Recording capability with pretrigger (pre-event) memory (e.g., 20 seconds), assures recording of the start of the shaking at the ground or basement level. The recording thread records raw data based on the trigger threshold exceedance. When one or more channels exceed their assigned trigger threshold (based on the trigger exceedance algorithm), acceleration data are recorded by the server as “raw data.” The broadcasting thread broadcasts data to multiple clients continuously via the Internet, and only when at least one client is connected. The posting thread sends the recorded raw data to pre-addressed users using FTP. Alternatively, events recorded at the site can be retrieved at the site or remotely via the Internet.

THE CLIENT SCHEME

Streamed real-time acceleration data are acquired with the building “Client” software, which is configured to proceed with computation of velocity and displacement and select number of drift ratios. Figures 4 and 5 show two PC screen snapshots of the client software display. Figure 4 shows 12 channels of streaming acceleration time series. Each paired set of acceleration response streams is displayed with a different color. The upper right shows amplitude spectra for one of the channels and is selectable by the user. It is noted that several frequencies are clearly identifiable (as discussed later in the paper). In the lower left, time series of drift ratios are shown for six locations, each color corresponding to the same pair of data from the window above. In order to get the drift ratios, real-time double integration of filtered acceleration data are computed. Specific filter options are built into the client software for processing of the acceleration data. To compute drift ratios, story heights, as shown in Figure 5 need to be manually entered. This figure also shows the computed pairs of displacements that are used to compute the drift ratios. Corresponding to each drift ratio, there are four stages of colored indicators.

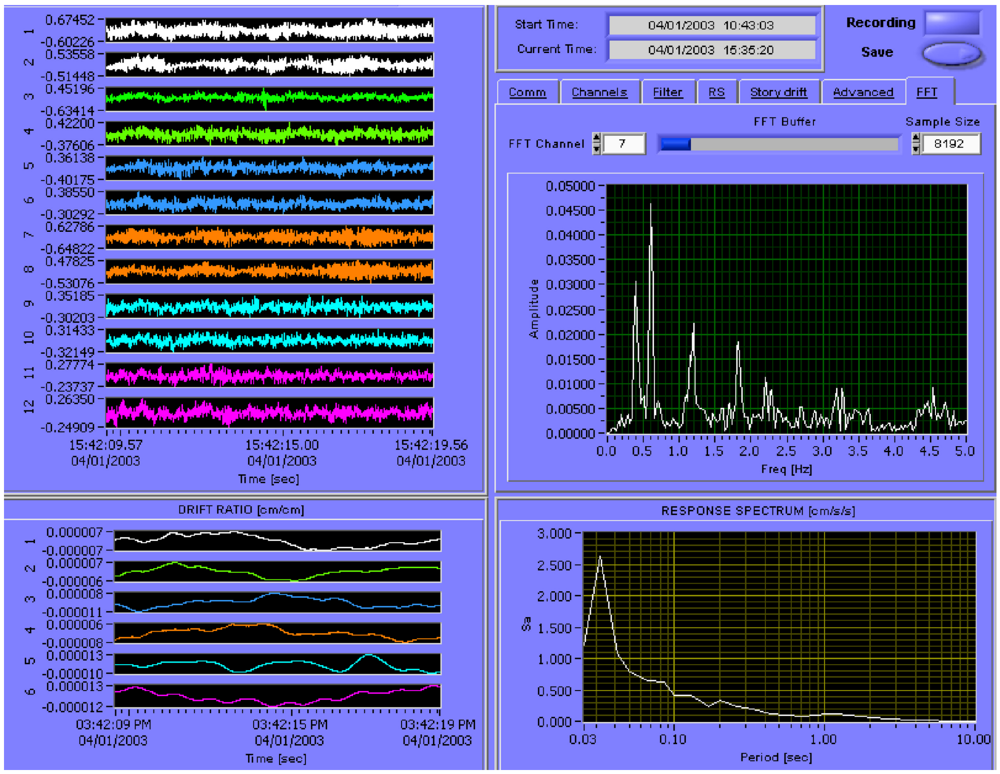

Figure 4. Screen snapshot of client software display showing acceleration streams and computed amplitude and response spectra.

When only the "green" color indicator is activated, it indicates that the computed drift ratio is below the first of three specific thresholds. The thresholds of drift ratios for selected pairs of data must also be manually entered in the boxes. As drift ratios exceed the designated three thresholds, additional indicators are activated with a different color (Figure 5). The drift ratios are calculated using data from any pair of accelerometer channels oriented in the same direction (e.g., such as 18 and 19 or 16 or 17, as shown in Figure 1). The threshold drift ratios are computed and decided by structural engineers using structural information and are compatible with the performance-based theme, as illustrated in Figure 2 (Figure C2-3 of *FEMA-274*). Figure 5 hypothetically shows that the first level of threshold is exceeded, and the client software is recording data as indicated by the illuminated red button.

The thresholds for the present installation are based on performance limits of the welded beam-column connections, established using *FEMA-352*. This allows the various drift ratio thresholds to be matched to a probability of connection fractures in different areas of the building. At present, the first stage threshold corresponds to one quarter of the computed building yield level, approximately 0.2% drift. At this level of drift, no connection fractures are anticipated, although movement of the building should be de-

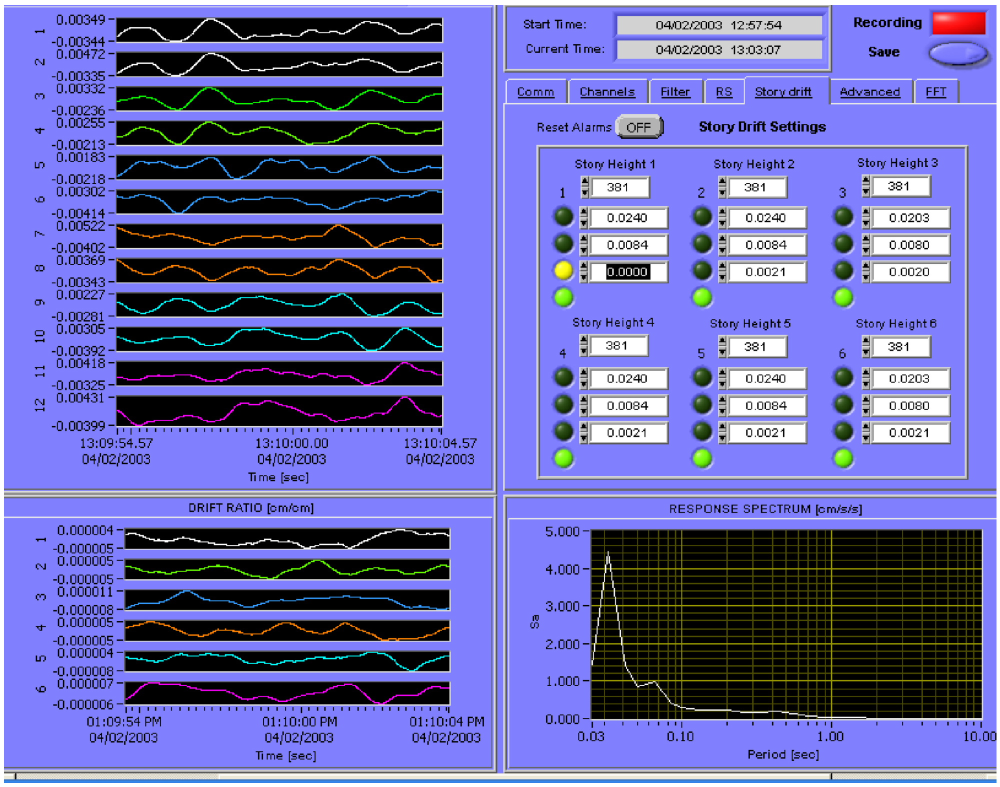

Figure 5. Screen snapshot of client software display showing 12-channel (six pairs with each pair a different color) displacement and corresponding six-drift ratio (each corresponding to the same color displacement) streams. Also shown to the upper right are alarm systems corresponding to thresholds that must be manually input. The first threshold for the first drift ratio is hypothetically exceeded to indicate the starting of the recording and change in the color of the alarm from green to yellow.

tectable by the occupants. The second stage threshold correspond to the building yield level, approximately 0.8% drift, which is the lower-bound drift for anticipated connection fractures. The third stage threshold corresponds to drifts at which the beam rotation demands equal the strength degradation value determined in accordance with *FEMA-352*. The third stage threshold varies between 1.4% and 2.2% drift, depending on the lo-

Table 1. Summary of threshold stages and corresponding drift ratios

Threshold Stage	1	2	3
Adopted Drift Ratio	0.2% 0.0021	0.8% 0.084	1.4–2.2% 0.0203–0.240

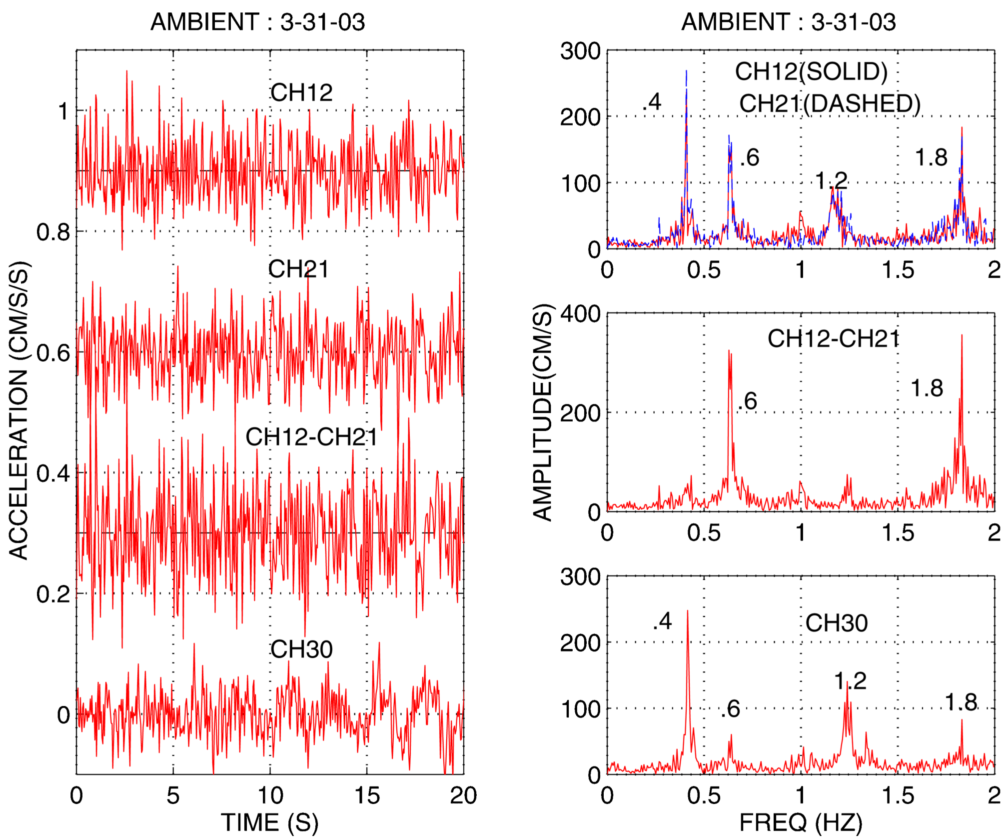

Figure 6. Twenty seconds of ambient acceleration response data obtained at the roof from parallel channels (CH12 and CH21), their difference (CH12–CH21), and from CH30, orthogonal to CH12 and CH21 (left) and corresponding amplitude spectra (right).

cation being examined in the building. At this level of drift, *FEMA-352* predicts that approximately 50% of the connections will have fractured. The levels of drift ratios and corresponding typical values for the subject building are summarized in Table 1.

Whenever recording is activated using the client software, raw acceleration data from all of the channels are recorded (at a designated location of the client PC). The recording is activated upon exceedence of a threshold or manually if the user needs to record data remotely. Any recorded data can be played back by the client software or can be processed by additional other software.

SAMPLE RECORDED DATA AND ANALYSES

Sample data obtained via the client software are shown in Figure 6. The data are from the two parallel channels (CH12 and CH21) and their difference as well as the orthogonal channel (CH30) at the roof recorded on 12 February 2003. The intent of the differential accelerations of parallel channels (CH12–CH21) is to identify the strong

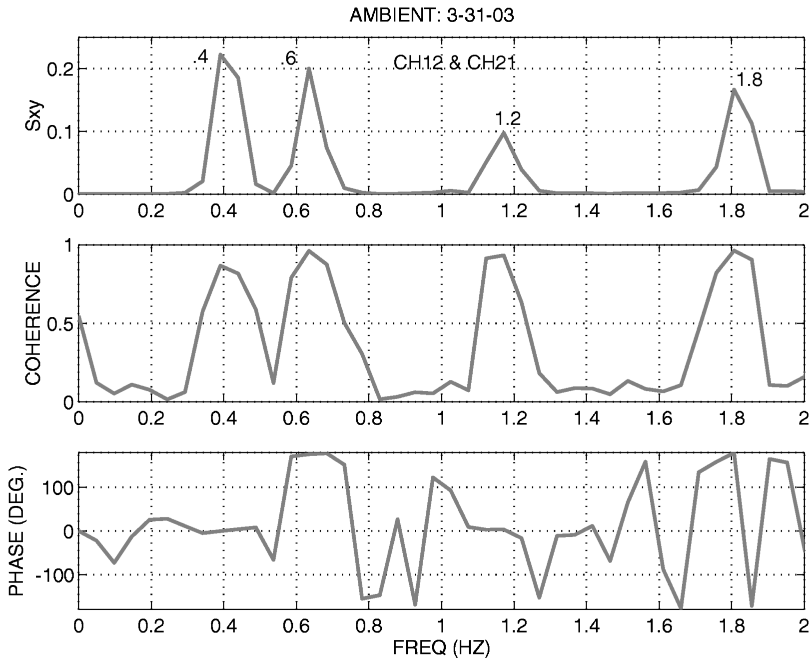

Figure 7. Cross spectrum, coherency, and phase angle plots of ambient acceleration response data obtained from parallel channels (CH12 and CH21) at the roof.

presence of torsion. The recorded peak accelerations are about 0.1–0.2 gals (~0.1–0.2 cm/s/s). The computed amplitude spectra clearly indicate a peak frequency for the fundamental translational mode (in both directions) at ~0.4 Hz (~2.5 second period) for all channels and at ~0.6 Hz (~1.67 s) for the torsional motion. Furthermore, the signals are good enough to identify the second translational mode at ~1.2 Hz (~0.83 s). Similarly, the second torsional mode is at ~1.8 Hz (0.56 s). The identified translational frequency is typical of a framed building that is 24 stories high. The identified modes and frequencies are further supported with the cross spectrum, coherency, and phase angle plots in Figures 7 and 8. The cross spectrum, coherency, and phase angle plots of the motions recorded by CH12 and CH21 (the two parallel accelerometers at the roof level) are shown in Figure 7. The cross spectrum actually exhibits all of the significant frequencies identified in Figure 6 with very high coherency (~1). At 0.4 and 1.2 Hz, the phase angles between the parallel motions are both 0 degrees, which indicate that they are in phase and therefore belong to translational modes. At 0.6 Hz and 1.8 Hz, the phase angles are ~180 degrees, which indicate that they are out of phase and belong to torsional modes. The strong torsional response is further illustrated through Figure 8 that exhibits cross spectrum, coherency, and phase angle plots of the motions recorded by differences of motions recorded by parallel channels (CH12–CH21) at the roof and (CH10–CH19) at the 18th floor. Again, at ~0.6 Hz, these torsional motions exhibit significant cross-spectral amplitude with very high coherency (~1) and 0-degree phase angle. Therefore, 0.6 Hz belongs to the first torsional mode.

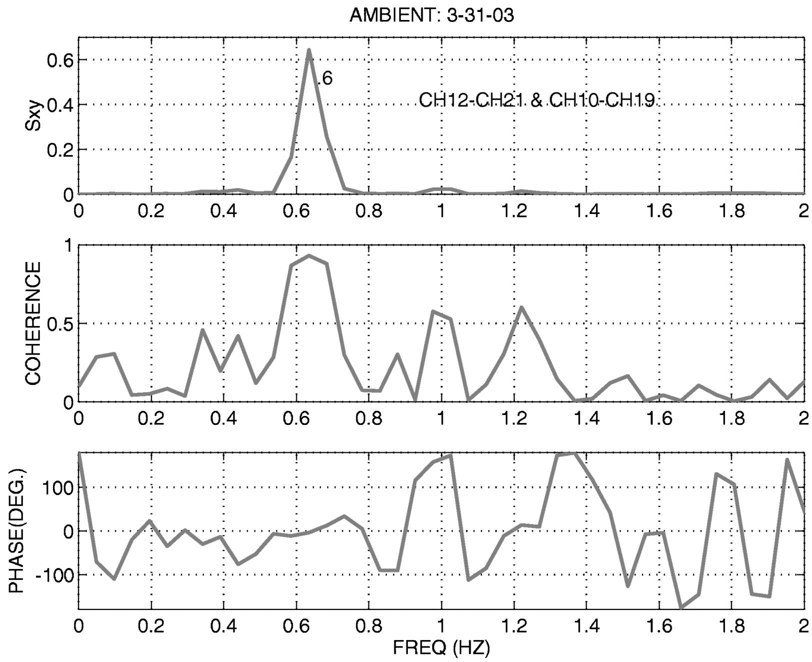

Figure 8. Cross spectrum, coherency, and phase angle plots of ambient acceleration response data obtained from differences of parallel channels, CH12–CH21 at the roof and CH10–CH19 at the 18th floor.

At the level of low-amplitude acceleration response recorded and exhibited in this set of sample data, the signal-to-noise ratio is quite high and satisfactory to indicate several modal frequencies. It is expected that the coherency of motions between such pairs of channels will further improve when the signal-to-noise ratio is even higher during strong-shaking events. Further detailed analyses of strong shaking data will be carried out when recorded in the future.

CONCLUSIONS AND BENEFITS

Capitalizing on advances in computational and data transmission technology, it is now possible, as described in this paper, to configure and implement a seismic monitoring system for a specific building with the objective of rapidly obtaining sufficient response data during a strong shaking event in order to help make informed decisions regarding the health and occupancy of that specific building.

To meet such an objective and needs of a building owner, a seismic monitoring system for a 24-story steel moment-frame building has recently been implemented. The system records accelerations and computes displacements (and drift ratios) in near-real time. The variable drift ratio is related to the damage and safe occupancy criteria of the specific building. Data can be streamed and recorded both at the server within the building and remotely by client software specifically configured for this building to meet the needs of the owner. The client software is capable of retrieving and recording real-time acceleration response data, and computing, in near-real time, velocity, displacements, and amplitude and response spectra of the streaming accelerations from selected accelerometers. Furthermore, the software can compute drift ratios using the near-real-time-computed displacements, and specific building data such as story heights. Alarms are related to thresholds of drift ratios computed for pairs of floors. The drift ratios are related to building performance and therefore are key in making occupancy and other decisions.

The monitoring system is now working successfully and, in the absence of strong shaking to date, is producing useful low-amplitude data in real time for analyses and assessment. This approach can be used for performance evaluation of structures, long-term assessments of structural characteristics, long-term damage detection, and health monitoring for buildings and other structures.

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