GUIDELINES FOR UTILIZING STRONG-MOTION DATA FOR POST-EARTHQUAKE EVALUATION OF STRUCTURES

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Abstract

This paper describes portions of the document, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, currently being developed by the Applied Technology Council for the California Geological Survey (formerly, California Division of Mines and Geology) Strong Motion Instrumentation Program 2000 Data Interpretation Project. The focus of the paper is on guidance for using strong-motion data to evaluate the performance of structures in the immediate earthquake aftermath. Topics addressed include strong-motion data sources and processing, damage indicators that can often be observed in recorded data, and methods for rapid interpretation of strong-motion data to evaluate structural performance.

Introduction

Instrumentation in current strong-motion networks in California has reached different stages along the steady technological upgrade from photographic paper recording to digital recording, with the accompanying improvement in the availability of data from a delay of several months or more, to a delay of only seconds after a seismic event. Instruments now in place record either analog film records or digital data, with the trend toward exclusive use of instruments that record digital data. In California the number of free-field sites, buildings, and other structures containing strong-motion instruments has expanded to more than 1000 since the original installation of nine strong-motion instruments in California in 1932. Today, the large number of instrumented sites and the rapid availability of digital data, including analog data converted to digital format, provide the real potential for using strong-motion data to evaluate the performance of buildings and other structures in the immediate earthquake aftermath. The use of strong-motion data for this purpose is, in fact, the original justification for code-required instrumentation that began to be mandated after about 1965 for most buildings over six stories in height in certain California cities like Los Angeles, which adopted the appendix to Chapter 23 of the 1967 *Uniform Building Code*.

Methods and techniques for evaluating the performance of buildings and other structures using strong-motion data have been available for several decades, but widespread use has been hampered for several reasons: (1) until recently, the delayed availability of data in digital format, and (2) the lack of concise descriptions of such methods readily available to structures' owners and their engineers. To help remedy this situation, the California Division of Mines and Geology (CDMG) awarded a Year 2000 California Strong-Motion Instrumentation Program

(CSMIP) Data Interpretation Project to the Applied Technology Council (ATC) to prepare guidelines on this subject. The guidelines now under development by ATC address not only postearthquake structural evaluation, but also the use of computer-generated ground-motion maps in postearthquake response and the collection of data on the performance and characteristics of structures located in the vicinity of strong-motion recordings sites, or in which strong-motion instruments have been installed. The results of the ATC effort will be published in the ATC-54 report, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation* (ATC*, in preparation*).

In this paper we focus on those portions of the ATC-54 report pertaining to guidance for using strong-motion data for postearthquake evaluation of structures. We begin with background information that in part summarizes the results from our literature review to determine the extent to which strong-motion data have been used to date to evaluate structures. The background information also identifies and briefly discusses (1) the general limitations of strong-motion data for the purpose of evaluating structures; (2) the principal operators of existing strong-motion networks; (3) available resources for strong-motion data; and (4) data-processing issues. The intent is to provide users of those portions of the ATC-54 *Guidelines* pertaining to structural evaluation, namely, facility owners and their engineers, with information that will enable them to understand the limitations of strong-motion data, as well as the means by which such data can be acquired and processed. The principal focus of this paper is the description of methods for rapid interpretation of strong-motion data in order to evaluate structural performance. A discussion of these methods is preceded by a discussion on damage indicators that can often be detected by visual inspection of strong-motion analog data. Due to space limitations we focus on methods for buildings, the type of structure for which such methods are best developed. The companion paper by Rojahn et al. (2002), “Guidelines for Utilizing Strong-Motion Data and ShakeMaps in Postearthquake Response, An Overview”, describes the contents of the ATC-54 *Guidelines*, and how the report was developed. The companion paper by King et al. (2002), “Guidelines for Utilizing ShakeMaps for Emergency Response”, provides more in-depth information pertaining to the use of ShakeMaps. Similar papers by Rojahn et al. (2001) and King et al. (2001) were also developed for the SMIP01 Seminar scheduled for September 2001 in Los Angeles.

Background

Prior Efforts Using Strong-Motion Data for Structural Evaluation

The great majority of relevant papers in the literature describe research that used data that was available anywhere from several minutes after an earthquake event to several months afterwards, even though the research itself was completed, and reported on, up to several years later. In large part, the technical literature indicates that strong-motion data have been used in complex system identification studies, and in the identification of potential global structural damage under various levels of shaking intensity. There have also been many instances where strong-motion data have been used as input in computer analysis programs to calculate structural component forces, moments, displacements, and rotations.

Interestingly enough, we could find no examples in the technical published literature of the analysis of a recording that led to an assessment of damage, that, alone, resulted in a decision or action that saved lives or property threatened by such damage. We are aware, however, as a result of interviews with various researchers and program managers, that there have been instances where strong-motion recordings have alerted building or structural personnel that steps should be taken to improve structural performance, or that a safety check should be run because ground accelerations were higher than code values. These have not been reported in the technical literature due to the sensitive nature of the situation. They include: (1) the transfer of occupants from commercial buildings so that the buildings could be demolished and rebuilt, (2) the temporary shutting down of a power-generating plant for inspection due to ground accelerations higher than design code levels, and (3) retrofitting a government office building with damping devices after records confirmed that modal oscillations continued for longer durations than expected.

Limitations and Uses of Strong-Motion Data for Structural Evaluation

For complex structures, such as bridges, dams, lifeline structures, and buildings of complex shape, strong-motion recordings of seismic response have been used for research on system identification, in order to improve computer models of the structure. Such models include the mass and stiffness of structural components, if it is a linear model, and yield points and ultimate strengths, if it is a nonlinear model. Computer modeling of instrumented structures is a prerequisite if a detailed time-history analysis of linear or nonlinear structural response is contemplated, with a view to searching for the existence and extent of damage, directly from the records.

Most structures have separate structural components whose nonlinear behavior is difficult to model and is difficult to determine from a system identification analysis. Therefore, a rapid time-history analysis that uses all of the available strong-motion records of structural response, in conjunction with a computer model of the structure, is unlikely to reveal the precise location of local component degradation or serious damage.

Global structural degradation damage parameters, however, such as total horizontal drift at the roof level, or permanent lengthening of the fundamental period (first mode) of vibration, can be determined from a rapid time history analysis, with or without requiring a computer model of the structure. With a computer model, a best-fit matching of the structural strong-motion recordings with computed structural recordings, can be used to verify or calibrate an existing computer model, which can then be used to provide estimates of inter-story drift time-histories throughout the height of the structure, as well as information on period lengthening. Without a computer model, inter-story drift can be determined by differencing selected displacement time histories of structural response (computed by double integration of acceleration time histories), and estimates of the fundamental mode shape. As described later in this paper, the lengthening of the first natural period of vibration can also be determined visually from plots of acceleration time history response as well as Fourier analysis of strong-motion records using recognized moving-window procedures.

Assuming the mass of a building remains the same, the relationship between building stiffness and building period is defined by the following equation:

$$w = \sqrt{\left(\frac{k}{m}\right)}, \quad T = 2p\sqrt{\left(\frac{m}{k}\right)}, \tag{1}$$

Based on this relationship, for example, a period lengthening of 25% in a frame building, indicates a drop in stiffness to 64% of its original linear value.

In the years following the damaging 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes, structural instrumentation projects have concentrated more specifically on the search for damage assessment capability. A thoroughly instrumented building has more potential for the determination of the general location of damage, but not precise locations. The appearance of bursts of high-frequency acceleration in adjacent structural records is an indicator of possible local damage, but could also be the recording of elevated contents or nonstructural components falling to the floor.

Existing Strong-Motion Networks

The major strong-motion networks operating in California include structural instrumentation of various complexity. The three larger networks are: (1) the California Strong-Motion Instrumentation Program, California Geological Survey, Department of Conservation, operating throughout California and headquartered in Sacramento (Shakal et al., 1989b); (2) the National Cooperative Strong-Motion Instrumentation Network, U.S. Geological Survey, (USGS), headquartered in Menlo Park, California, and operating throughout the nation, and (3) the Southern California Instrumentation Network, headquartered at the University of Southern California (USC), and operating throughout the Los Angeles region. Smaller networks, which also include structural instrumentation, include the Army Corps of Engineers, the U.S. Bureau of Reclamation (Viksne et al., 1993), the Metropolitan Water District of Southern California, and the Los Angeles Department of Water and Power.

The instrumentation networks of CSMIP and the USGS contain ground-motion stations, instrumented buildings and other instrumented structures. The number of channels at a ground-motion station is generally three. The number of channels in a specific structure depends on the time it was first instrumented and the vibrational questions for which answers are sought, ranging from perhaps six to several dozen or more. The average is approximately sixteen. The instrument coverage in Los Angeles, in San Francisco, in California, on the Pacific coast, and across the nation ranges widely, but the percentage of the three different station types providing useful records from an urban earthquake can be judged from the numbers from the 1994 Northridge earthquake, namely, 250 ground-motion stations, 400 buildings, and 50 other structures.

Almost all instruments now record digitally at a sample rate between 50 and 200 samples per second on each channel. Often, the sensor has a wide frequency range, and the data are shared with researchers from the strong-motion seismology field. If data communication is possible between the recorder and the network central headquarters, and is not damaged nor interrupted by the earthquake, then data can be transmitted to the central headquarters for processing and dissemination to people needing to make rapid decisions. For those recorders without communication to central headquarters, a technician recovers the digital data during the days following the earthquake.

Data Sources and Processing

The technical literature and world wide web contain numerous resources describing existing strong-motion data and data processing techniques. In some instances the resources contain information on a wide variety of strong-motion recording sites and data, including both free-field sites and instrumented structures; others refer primarily to data sets from specific types of structures. Two of the most popular current resources are the COSMOS Virtual Data Center (db.cosmos-eq.org), which is operated by the Consortium of Organizations for Strong-Motion Observation Systems, and the Pacific Earthquake Engineering Research Center (PEER) Strong-Motion database (peer.berkeley.edu/smcat). The COSMOS site provides links to nearly all of the major strong-motion data providers and is a well-designed web site for quickly identifying available strong-motion data, as well as listings of current stations.

The literature also contains numerous examples of studies and descriptions of strong-motion data sets from instrumented buildings, bridges, and dams. Citations for data from buildings, for example, include Shakal et al. (1989a), Reichle et al. (1990), Huang et al. (1991), Graizer et al. (1998), Porcella and Switzer (1989), Archuleta et al. (1999), the proceedings of the annual CSMIP seminars: Huang et al. (1992, 1993, 1994, 1995), and descriptions of data from specific events, such as described by Darragh et al., (1995) and Shakal and Huang (1995) for the 1994 Northridge earthquake. The instrumentation and records from a 2540-foot-long interchange bridge excited by the 1992 Landers and 1992 Big Bear earthquakes have been described by Huang and Shakal (1995). Similarly, significant earthquake strong-motion accelerograms recorded on or near dams, and current developments in instrumentation, including near-real-time strong-motion recording, are discussed in Shakal and Huang (1996).

With improvement in the instrumentation, and the increase in magnitude of the earthquakes producing the records, there is less need for elegant processing to push the envelope of useful data beyond that envisioned by the instrument manufacturer. The recording instruments and processing techniques now used by the principal providers of data (CDMG, USC, and USGS) provide strong-motion data that exclude stray digital points and incorporate (1) a high-frequency limit defined by both the sampling rate and the instrument response characteristics at high frequencies (for which corrections are made), and (2) a long-period limit defined by the signal-to-noise ratio at long periods and the duration of both the strong shaking and the total record (the larger the amplitudes over a long duration, the longer will be the selected cut-off period). Digital instruments also provide a pre-event memory capability to ensure that earthquake acceleration, calculated velocity, and calculated displacement all commence with zero amplitude.

Damage Indicators Evident in Strong-Motion Structural Records

As described below, certain characteristics evident in strong-motion records of ground motion or structural response may be indicative of structural damage. The appearance of these characteristics may warrant further inspection and evaluation of the structure for structural damage by a structural engineer experienced in seismic design.

1. Acceleration Response Exceeding Code Design Values

Design code values of effective peak ground acceleration, or acceleration response, are used in the design process. The distribution of forces along the vertical axis of the building is normally defined by an equation provided in the code, and the building is designed as if these distributed forces (a constant acceleration times mass) were acting at the various floor and roof levels. Maximum acceleration spectra computed using basement, ground level, or nearby free-field can be compared to design values to determine if the ground motions experienced by the structure exceeded those used in design. Similarly, design acceleration time histories recorded in the upper stories can be used to estimate base shear values, which can then be compared to those used in design. This process requires careful consideration of design assumptions, including assumed material strengths (e.g., ultimate strength versus working stress design) and parameters, such as R values and k value, used in the design process. The data interpretation process also requires careful consideration of the site soil conditions and the frequency characteristics of the input ground motion. For example, at high frequencies, the velocities and displacements have low amplitudes, and the structure may resist with ease apparent high amplitude motions (e.g., a sinusoidal acceleration amplitude of 0.5 *g* at 10 Hz produces a displacement amplitude of 0.05 inches). Guidance on these issues is provided in the ATC-54 *Guidelines*.

2. Lengthening of the Modal Periods

The lengthening of modal periods has been described by several researchers, including a summary by Naeim (1996) of work investigating the response of 20 CDMG-instrumented buildings during the 1994 Northridge earthquake. This summary includes buildings whose periods lengthened during the response. In a later work on the same 20 buildings, Naeim (1998a) observes that the second and third modes of vibration contribute significantly to the overall response in the cases of two buildings of 13 and 20 stories.

It has been known since the 1971 San Fernando earthquake that a lengthening period can be associated with damage to some extent. The increase in period can be visually read in a record of sufficient clarity containing a single mode response, or can be studied analytically with Fourier moving-window analyses (see Figure 1). For a structure shown later to have no structural damage, the lengthening of the period is small, and the period returns to its original value before the end of the record. Structural damage, on the other hand, lengthens the period to greater levels, and the period does not return to its original value. Rezai et al. (1998) analyzed the important San Fernando and Northridge records from a 16-channel recording system installed in a 7-story building. During the San Fernando earthquake, structural damage was minor. During Northridge, the period lengthened by 66% in one direction, and by 100% in the other. These percentages correspond to drops in stiffness to 0.36 and 0.25, respectively, of original values. Major structural damage occurred, and it is clear, from the lengthened period on the record, when this damage commenced.

Based on the above it is apparent that period lengthening indicates a decrease in stiffness. Separation of partitions from structural framing and structural walls, separation of structural

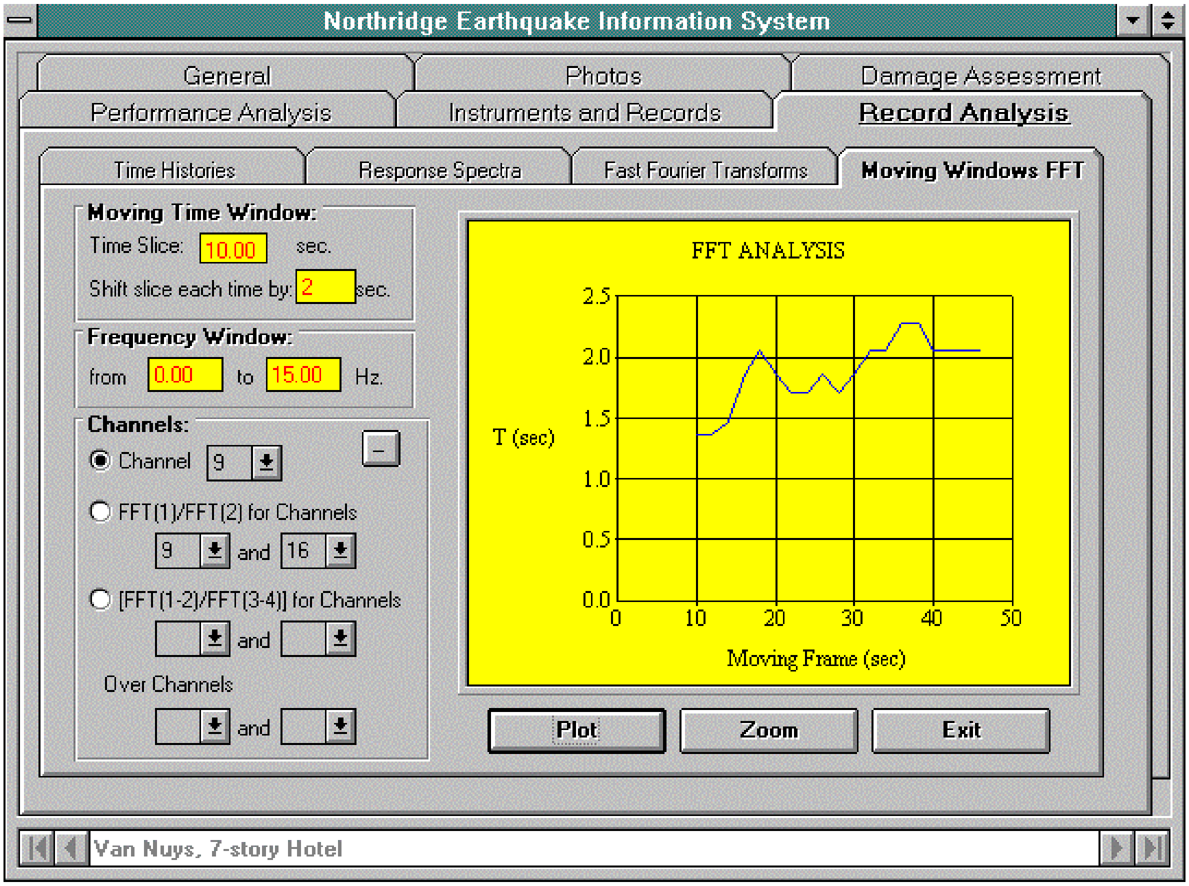

Figure 1. Moving window Fast Fourier Transform analysis showing significant softening of a 7-story hotel in Van Nuys, California, during strong ground shaking (from Naeim, 1998b).

infill from structural framing, and structural damage to seismic-resisting elements may contribute to this decrease in stiffness. Guidance on these issues is provided in the ATC-54 *Guidelines*.

3. High-Frequency Bursts of Acceleration

Damage occurring in a structure introduces impulsive forces created by the initial damage to steel and its connections, concrete and its reinforcing, masonry and its reinforcing and mortar, or wood and its connectors, followed by more impulsive forces created as damaged areas continue to impact on themselves as the response to the earthquake proceeds. The resulting compression and shear waves travel throughout the structure almost instantly. Those with audible frequencies are not recorded on the typical strong-motion recorder (these frequencies are too high) but waves with frequencies within the range of instrumental response, that is, up to 50 Hz or 100 Hz, are sensed by such recorders. The presence of a specific frequency in this range can be identified on an analog film record, but identification from a digital record depends on its sampling rate.

Damage may be indicated if a high-frequency burst of acceleration is identified on the record from several closely-spaced transducers, the high-frequency bursts continue to occur as time progresses, and it is evident that at the same time, modal periods lengthen and stay that way until the end of the record. An example of such a condition is shown in the records from the Imperial County Services Building (see Figures 2 and 3), which was extensively damaged by the 1979 Imperial Valley earthquake. It is necessary to distinguish this damage indicator from other possible causes, such as the falling to the floor of heavy elevated contents in the vicinity of a transducer. High-frequency bursts from such a cause will not be seen on distant recordings elsewhere in the structure, and will not be accompanied by lengthening periods. Guidance on this issue is provided in the ATC-54 *Guidelines.*

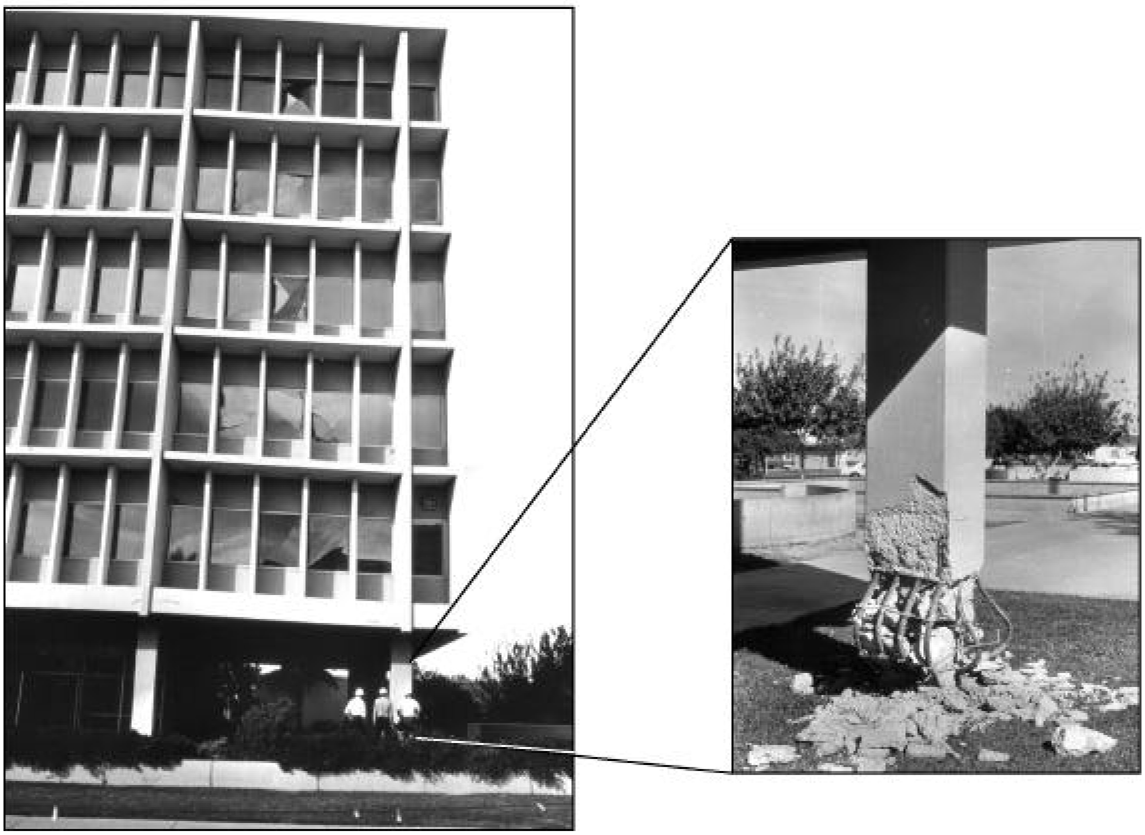

Figure 2. Photos of south face (left) and failed reinforced concrete column (right) at base of Imperial County Services Building, which was damaged by the 1979 Imperial Valley Earthquake. The burst of high frequency motion occurring simultaneously with column failure is shown in Figure 3 (from Rojahn and Mork, 1982).

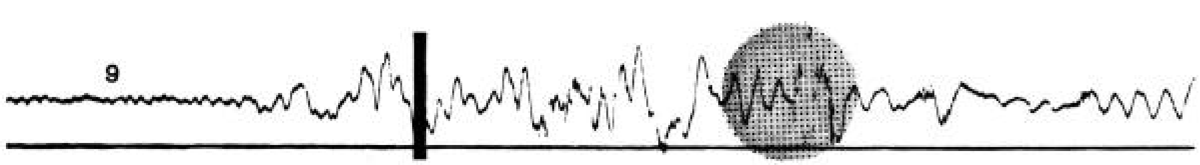

Figure 3. Copy of north-south analog acceleration time history recorded in North-South direction on second floor level (Trace 9), directly above the failed reinforced concrete column shown in Figure 2. Burst of high-frequency motion is shown in shaded circle. Vertical bar represents the time when the onset of damage is inferred to have occurred (from Rojahn and Mork, 1982).

Procedures for Using Strong-Motion Data to Evaluate Structural Response

Chapter 3 of the ATC-54 *Guidelines* provide step-by-step procedures to evaluate the response of structures (buildings, bridges, and dams) using recorded strong-motion data. For each type of structure, a variety of approaches are described, including assumptions about structural properties, applicable structure sub-types, minimum instrumentation and data required, steps to be taken, outputs, and example applications. It is assumed that the user is unfamiliar with strong ground-motion recordings. Also, a summary of available structural analysis programs and their capabilities for assisting in the interpretation of strong motion data is provided in an appendix of the *Guidelines*.

Procedures described in the ATC-54 *Guidelines* include those for:

- rapid estimation of changes in building period during strong ground shaking, using visual inspection and Fourier analysis techniques;
- hand modal analysis of strong-motion data from instrumented buildings to estimate maximum shear forces at the base of the structure (briefly summarized in Rojahn et al., 2001);
- rapid estimation of inter-story drifts, including estimates based on displacement time-history analysis involving differencing of displacement time histories calculated from acceleration time-histories recorded at different story levels;
- rapid estimation of maximum roof displacement using available methods for the design of building structures using nonlinear static analysis procedures, such as the Coefficient Method described in the FEMA 273 *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (ATC, 1997); and
- procedures to define and verify mathematical computer models of building behavior.

For illustrative purposes we briefly describe results from an analysis of strong-motion data from an extensively instrumented, severely damaged building to obtain estimates of inter-story drift.

Estimate of Inter-Story Drifts in the Imperial County Services Building During the 1979 Imperial County Services Building

Within days after the occurrence of the 1979 Imperial Valley, California, earthquake of October 15, 1979, researchers at the U. S. Geological Survey and other institutions commenced the process of analyzing strong-motion records from the severely damaged Imperial County Services Buildings (Figure 2), which contained an array of 13 accelerometers (Figure 4). By double integration of the acceleration time histories, and careful filtering of the data, it was possible to prepare displacement time histories of the response of the structure. By differencing the calculated displacement time histories (subtracting one from another) from horizontal transducers located at the roof, second floor, and ground levels and plotting the results on a single plot, it was possible to estimate drifts between selected floor levels, which could then be used as a basis for estimating inter-story drift. The results from this effort are shown in Figure 5.

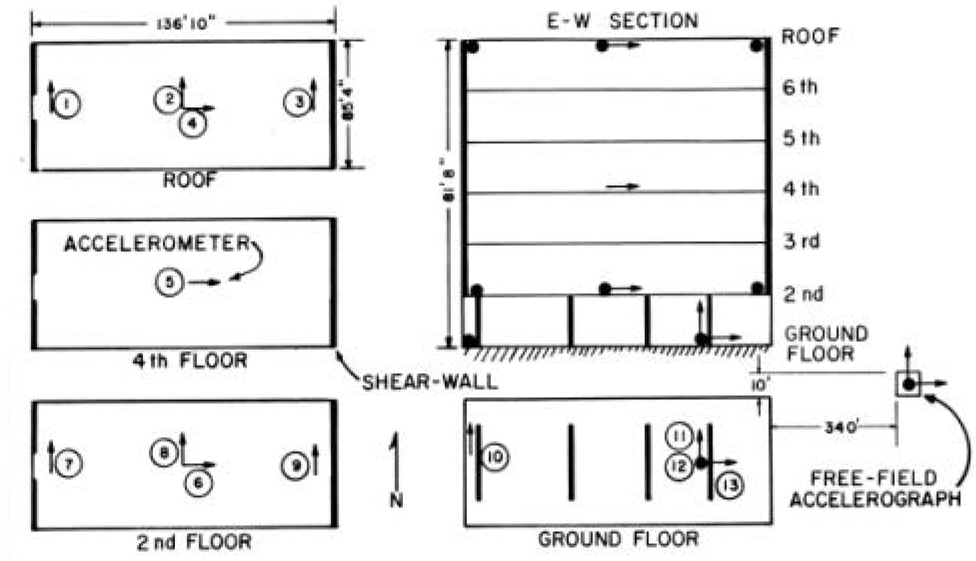

Figure 4. Locations of force-balance accelerometers (arrows with numbers) and SMA-1 accelerograph at Imperial County Service Building and adjacent free-field site (after Rojahn and Ragsdale, 1980). Arrows denote direction of positive acceleration on trace.

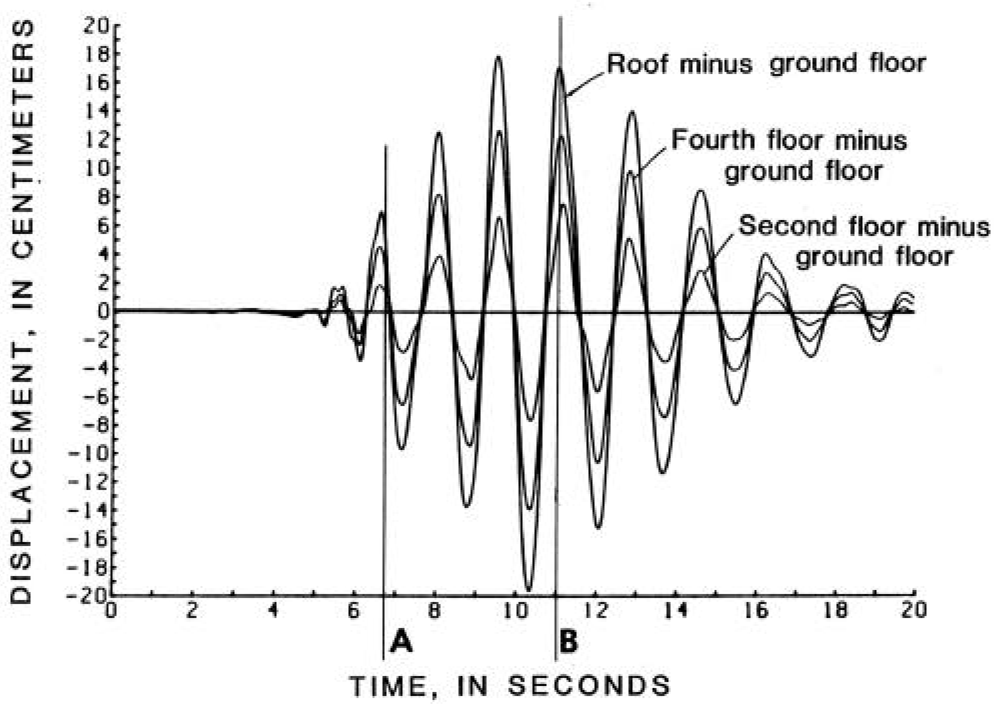

Figure 5. Time history of east-west relative displacement between roof and ground floor (difference of data from accelerometers 4 and 13), between fourth and ground floors (difference of data from accelerometers 5 and 13), and between second and ground floors (difference of data from accelerometers 6 and 13). A and B are interpreted to be the times at which damage initiated and the columns collapsed at the east side of the building (see Figure 3).

Concluding Remarks

This paper briefly describes that portion of the ATC-54 *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation* (currently under development by the Applied Technology Council), pertaining to rapid evaluation of structures using strong-motion data. The implicit definition of "rapid" is hours to days after a damaging earthquake occurs, as opposed to instantly, or in real time. Recommended procedures include methods for (1) determining the extent to which a structure's natural period of vibration has lengthened, either permanently or temporarily (if permanent, a loss in stiffness is implied), (2) evaluating recorded motions and comparing them to seismic design loading criteria, such as effective peak acceleration or acceleration response ordinates; and (3) estimation of roof drift and inter-story drift. The methods have been taken from the existing literature and no research was performed to develop new methods.

The ATC-54 *Guidelines* also provide information on sources of strong-motion data, and guidance on the limitations of strong-motion data, as related to rapid evaluation for determination of possible earthquake-induced structural damage.

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