GUIDELINES FOR UTILIZING STRONG-MOTION DATA FOR POSTEARTHQUAKE 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 Division of Mines and Geology's 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 *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 of this technology has been hampered for several reasons: (1) until recently, the relatively slow availability of data in digital format, and (2) the lack of concise descriptions of such methods in a resource 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 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. (2001), “Guidelines for Utilizing Strong-Motion Data and ShakeMaps in Postearthquake Response, An Overview”, describes the contents of the ATC-54 Report, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, how the report was developed, and some of the preliminary recommendations for improving the technology and processes for using strong-motion data and computer-generated ground-motion maps for emergency response and postearthquake structural evaluation. The companion paper by King et al. (2001), “Guidelines for Utilizing ShakeMaps for Emergency Response”, provides more in-depth information pertaining to the use of ShakeMaps.

BACKGROUND

<u>Prior Efforts Using Strong-Motion Data for Structural Evaluation</u>. 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 system identification studies, some of which have been quite sophisticated, 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 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. The global dynamic seismic response of complex structures (including bridges, dams, lifeline structures, and complex buildings) is not yet well understood. Interpretation of strong-motion recordings of this seismic response for details of damage is not possible. For these complex structures, such records are used for research on system identification, in order to improve the current structural model. Structural models include the mass and stiffness of all components if it is a linear model and includes in addition, yield points and ultimate strengths if it is a nonlinear model. This preparatory 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. A rapid time-history analysis that takes advantage of all the structural records, but has only an imperfect model to work with, cannot accurately show the location of local component degradation nor the location of serious damage.

Global degradation is a different matter. Without knowledge of structural detail, a rapid time-history analysis of the records alone, for example the calculation of all the floor displacements from the recorded accelerations, leads to the total drift at roof level, relative to the ground, which is a recognized global damage parameter. A time-history analysis using the ground-level input accelerations and the best available nonlinear structural model, together with a best-fit matching of the structural recordings with computed structural recordings, leads to reliable interstory drift time-histories throughout the height of the structure, which is a reliable damage indicator. At the same time, it is well-documented that the first-mode period of a building lengthens as the building and its individual components become nonlinear. Presuming that the period lengthening is caused solely by a drop in stiffness, the mass of the building remaining the same, and that the stiffness varies inversely as the square of the period,

$$\text{that is, } w = \sqrt{(k / m)},\ \ T = 2\pi \sqrt{(m / k)},$$

a period lengthening of 25% in a frame building, say, is due to the stiffness dropping to 64% of its original linear value. Damage to the partitions and other nonstructural components occurs first in contributing to this loss; damage to the seismic-resistant elements occurs next. Fourier analysis of strong-motion records using recognized moving-window procedures are successful in determining when period lengthening and damage probably occur.

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 a 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, Division of Mines and Geology, Department of Conservation, operating throughout California and headquartered in Sacramento (Shakal et al., 1989); (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. (1989), 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. Because of the recording instruments and processing techniques now used by the principal providers of data (CDMG, USC, and USGS), the users of the data can be confident that: (1) there will be no stray digital points in the data; (2) the high-frequency limit will be defined by the instrument response characteristics at high frequencies (for which corrections are made) and the sampling rate; (3) the long-period limit will be 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); and (4) pre-event memory capability will ensure that earthquake acceleration, calculated velocity, and calculated displacement can all commence with zero amplitude.

DAMAGE INDICATORS EVIDENT IN STRONG-MOTION STRUCTURAL RECORDS

If any of the following characteristics are evident in strong-motion records at specific locations, they may be indicative of damage. The damage, at the same time, may be readily seen during a visual inspection. The appearance of these characteristics in the record is a warning that the structure needs to be evaluated for the existence of damage. There may be no damage apparent on visual inspection, and an evaluation by a structural engineer with experience in seismic evaluation may be necessary.

<u>Ground Acceleration Exceeding Code Values or Design Values</u>. Design code values of acceleration are considered in the design process, and in the design engineer's mind, as constant acceleration values that the foundation experiences. On the application of this acceleration 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. This

constant acceleration and these forces can be more readily visualized and handled in design than short-lived peak accelerations of the same value measured in the free-field or basement level or ground level in the building. A high-frequency peak horizontal acceleration at a free-field location need not be transmitted into the foundation, whose inertia resists such motion and does not follow it. On the other hand, if both the free-field and the foundation are based on hard rock, then the recorded peak acceleration is transmitted to the foundation, and the stiffness, mass and strength of the structure's seismic-resisting elements must resist it. At high frequencies, the velocities and displacements have low amplitudes, and the structure resists with ease (e.g., a sinusoidal acceleration amplitude of 0.5 *g* at 10 Hz produces a displacement amplitude of 0.05 inches). Depending on the stiffness of the soil, and on the amplitude and frequency of the peak recorded acceleration, there may be damage.

Based on the above we conclude the following: If a free-field record has a sufficiently high peak acceleration (above the design-specified value), and has a sufficiently low frequency and is on hard rock, there may be damage. If a foundation record has a sufficiently high peak acceleration (above the design-specified value), and has sufficiently low frequency, there may be damage.

<u>Lengthening of the Modal Periods</u>. As described above, the first-mode period of a building lengthens during the response to earthquake excitation as the individual components making up the seismic elements of the building become nonlinear.

Naeim (1996) summarizes his work on 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 (1998) 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 is associated with damage at some level. 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. 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 we conclude that period lengthening indicates a decrease in stiffness. Separation of partitions from structural framing and structural walls, separation of structural infill from structural framing, and structural damage to seismic-resisting elements may contribute to this decrease in stiffness. Whether or not this is visible, an evaluation by a structural engineer is warranted.

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.

The conclusion here is that damage is 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. It is necessary to distinguish this damage indicator from the record of heavy elevated contents falling to the floor in the vicinity of a transducer. This high-frequency burst will not be seen on distant recordings, and will not be accompanied by lengthening periods.

PROCEDURES FOR USING STRONG-MOTION DATA TO EVALUATE STRUCTURAL RESPONSE

Chapter 3 of the ATC-54 *Guidelines* provides 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 Appendix D of the *Guidelines*.

One of the procedures for rapid evaluation of strong-motion data from instrumented buildings is described below. The reader is referred to the ATC-54 *Guidelines* for information on additional procedures, including:

- rapid estimation of changes in building period during strong ground shaking, using visual inspection and Fourier analysis techniques;
- rapid estimation of inter-story drifts, including estimates based on response spectra calculated from ground-motion records and estimates based on displacement time-history analysis involving differencing of displacement time histories calculated from acceleration time-histories recorded at different story levels; and
- procedures to define and verify mathematical computer models of building behavior.

Hand Modal Analysis of Data from Instrumented Buildings. The hand modal analysis technique was developed by the Structural Engineers Association of Southern California Seismology Subcommittee on Seismic Instrumentation and Testing (SEAOSC, 1971), as documented there by R. B. Matthiesen. It was used on instrumented buildings in which strong-motion data were recorded during the 1971 San Fernando, California, earthquake, and case studies of eight buildings analyzed using this method are documented in Gates (1973). The procedure is described in detail in the ATC-54 *Guidelines* and is summarized here, along with an example application. The procedure consists of the five following steps:

1. Estimate the maximum recorded building acceleration and compare it to the acceleration seismic loading criteria used in design. If the peak acceleration on all horizontal recorded accelerograms is less than the design value, no further action is necessary.
2. Estimate the building periods and modal acceleration components. This is carried out by visual inspection of the records from different levels in the building (often near mid-height and at the roof level) in comparison with mode shapes for the first three or four modes of response (see Figure 1).
3. Estimate the maximum acceleration response at each floor level by sketching the corresponding mode shapes of response as overlays on an elevation view of the building.
4. Evaluate the building forces, shears, and overturning moments, using the story accelerations determined in Step 3 and estimated story weights. "If the peak acceleration response is produced by the combination of several modes, each contributing a significant component to the total response, then the final force, shear, and overturning moment response should be based on the superposition of the modal components" (Gates, 1973).
5. If the modal response components cannot be recognized easily, a more rigorous dynamic analysis is required.

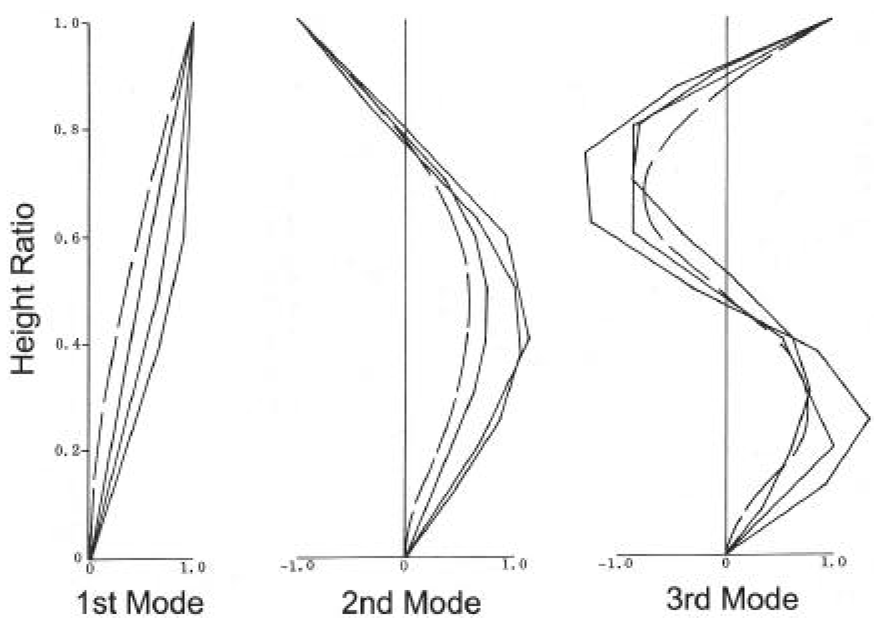

Figure 1. Experimental and analytical mode shapes for buildings (from Gates, 1973).

We use the example provided in Gates (1973) that analyzes 1971 San Fernando earthquake strong-motion recorded in the K-B Valley Center, a 16-story moment-resisting steel-frame office tower. The recording instruments were located at the basement level, 9th floor, and roof level. Strong-motion accelerograms recorded at the basement level, 9th floor and roof level for the reference east-west direction are provided in Figure 2, which also shows superimposed drawings of estimated contributions of the first and second modes (see records for 9th floor and roof). Based on visual observation and hand calculations, the fundamental periods for the first and second modes are estimated as 3.0 and 1.1 seconds, respectively.

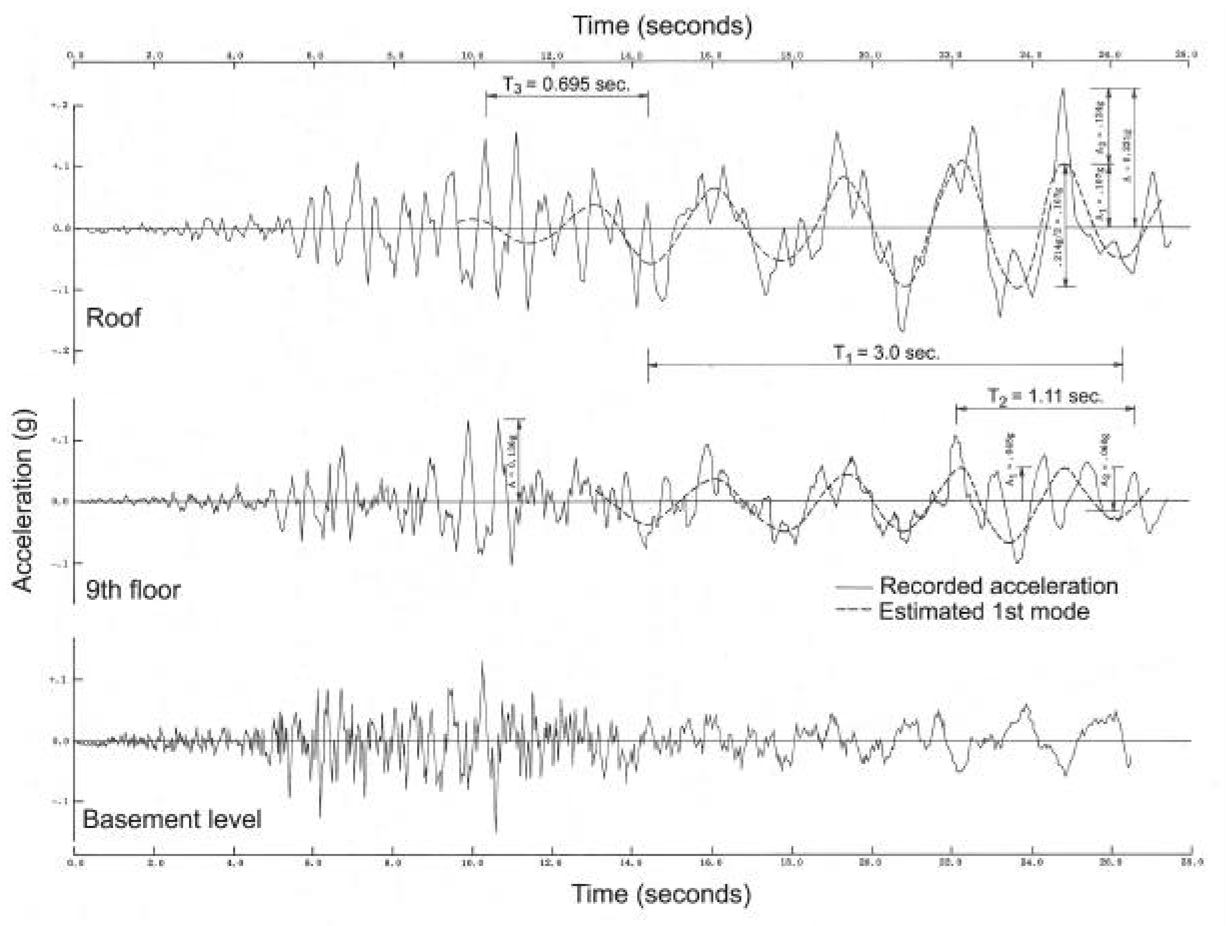

Figure 2. KB Valley Center, east-west acceleration response (from Gates, 1973).

By superimposing estimated mode shapes for the first and second modes of response (see Figure 1) on an elevation view of the building (a partial scale drawing), it is possible to estimate modal accelerations at each floor level. From this information and estimated story weights, both story shears and overturning moments are estimated. Plots showing story shears and overturning moments, in comparison to 1970 *Uniform Building Code* (ICBO, 1970) specified values and values calculated using time-history analysis, are shown in Figures 3 and 4. While the force levels during earthquake motion were roughly 2 to 2.5 times the seismic code levels, the building "performed in a very satisfactory manner … and there were no signs of structural distress in any of the [structural] members" (Gates, 1973).

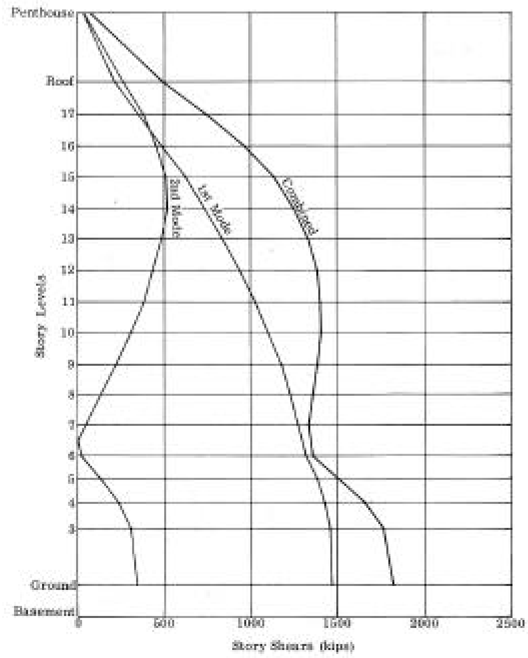

Figure 3a - MAXIMUM MODAL SHEARS

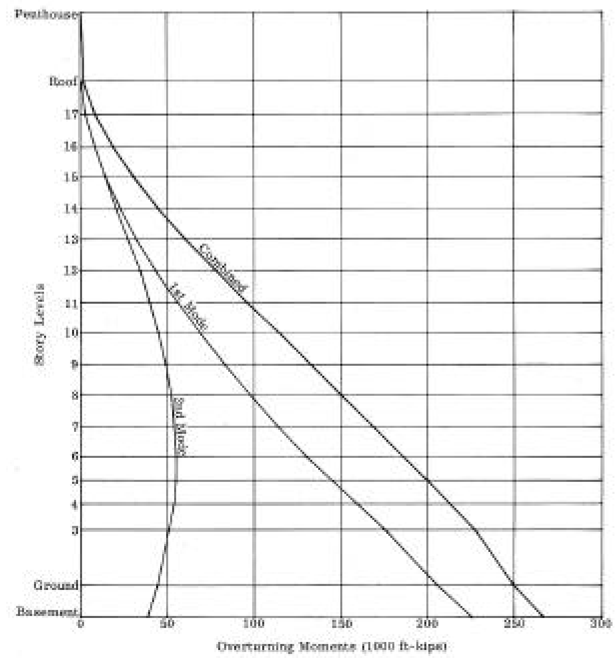

Figure 3b - MAXIMUM MODAL OVERTURNING MOMENTS

Figure 3. KB Valley Center, approximate modal responses—east-west direction (from Gates, 1973).

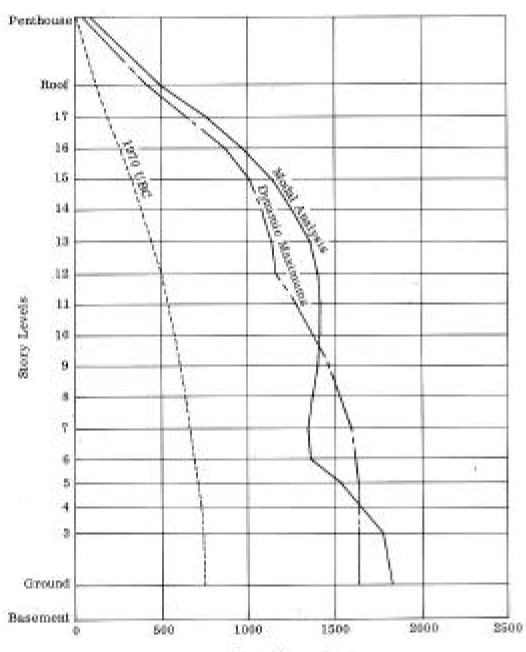

Figure 4a - MAXIMUM SHEARS

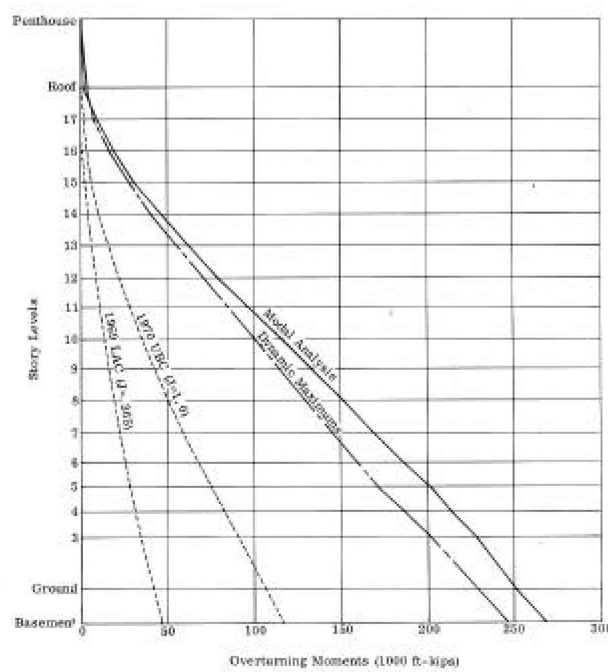

Figure 4b - MAXIMUM OVERTURNING MOMENTS

Figure 4. KB Valley Center, comparison of approximate modal response with code seismic values and dynamic time-history response—east-west direction (from Gates, 1973).

CONCLUDING REMARKS

The number of strong-motion records from instrumented structures obtained over the last several decades is impressive. From the 1994 Northridge earthquake alone, records were obtained from 400 buildings and 50 other structures. Although some recordings from the last 70 years do not have amplitudes much greater than the triggering amplitude, many records are significant for the purposes of this paper, namely, the indication of damage and the evaluation of the instrumented structures, using techniques ranging from a visual inspection of the record to a full nonlinear dynamic analysis of the building response. The number of instrumented buildings actually analyzed is surprisingly low, and although the techniques used at the time of analysis (in some cases, thirty or more years ago) were at the top technical level, it is surprising how few advances have been made in rapid evaluation techniques over the last several decades. The reasons for this are probably related to a lack of research funds, building owners' complacency, engineers' lack of available time for developmental work, and the wait for a bigger earthquake.

REFERENCES

ATC (in preparation), *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, Applied Technology Council, Redwood City, California.

Archuleta, R., et al., 1999, "A virtual strong-motion data center for data dissemination through the Internet", *SMIP99 Seminar on Utilization of Strong-Motion Data: San Francisco, California, September 15, 1999: Proceedings*, California Division of Mines and Geology, Sacramento, pages 145-154.

Darragh, R.B., Shakal, A.F. and Huang, M.J., 1995, "Strong ground motion data from the 1994 Northridge, California, earthquake", *Special Publication 116, The Northridge, California, Earthquake of 17 January 1994*, California Div. of Mines and Geology, Sacramento, pages 55-63.

Gates, W. E., 1973, "Modal Analyses of Instrumented Buildings," in L. M. Murphy (Scientific Coordinator), *San Fernando, California, Earthquake of February 9, 1971*, Vol. 1, Part B, NOAA, Department of Commerce, Washington, DC, pages 609-624.

Graizer, V. M., et al., 1998, "Strong motion data from ground-response sites and structures recorded during the 1994 Northridge earthquake", *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, California Universities for Research in Earthquake Engineering, Richmond, California, Vol. II, pages II-331 to II-338.

Huang, M. et al., 1991, *CSMIP strong-motion records from the Sierra Madre, California earthquake of 28 June 1991*, Report OSMS 91-03, California Office of Strong Motion Studies, Sacramento, 108 pages.

Huang, M. J., ed.., 1992, *SMIP92 Seminar on seismological and engineering implications of recent strong-motion data, Proceedings*, California Division of Mines and Geology, Sacramento, 1992, 1 vol.

Huang, M. J. ed., 1993, *SMIP93 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, California Division of Mines and Geology, Sacramento, 114 pages.

Huang, M. J. ed., 1994, *SMIP94 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, California Division of Mines and Geology, Sacramento, 120 pages.

Huang, M. J. ed., 1995, *SMIP95 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, California Division of Mines and Geology, Sacramento, 105 pages.

Huang, M.J. and Shakal, A.F., 1995, CSMIP strong-motion instrumentation and records from the I10/215 interchange bridge near San Bernardino, *Earthquake Spectra*, 11, 2, pages 193-215.

ICBO, 1970, *Uniform Building Code*, 1970 edition, International Conference of Building Officials, Whittier, California.

King, S.A., Comartin, C.D., Reis, Evan, Nathe, S.K., and Power, M.S., 2001, Guidelines for utilizing ShakeMaps for emergency response, *Proceedings, SMIP01 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Los Angeles, California, September 12, 2001, California Division of Mines and Geology, Sacramento.

Naeim, Farzad, 1996, "Performance of 20 extensively-instrumented buildings during the 1994 Northridge earthquake", *Proceedings, SMIP96 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Sacramento, California, May 14, 1996, California Division of Mines and Geology, Sacramento, pages 19-36.

Naeim, Farzad, 1998, "Seismic performance of extensively-instrumented buildings during the January 17, 1994 Northridge earthquake: an interactive information system", *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, California Universities for Research in Earthquake Engineering (CUREe), Richmond, California, Vol. III-A, pages III-405 -- III-412.

Porcella, R.L. and Switzer, J.C., 1989, *Catalogue of U.S. Geological Survey strong-motion records, 1987*, Circular 1044, U.S. Geological Survey, 44 pages.

Reichle, M.S. et al., 1990, "Overview of SMIP strong motion records from the Loma Prieta earthquake of 17 October 1989", abstract, *EOS Transactions*, American Geophysical Union, 71, 8, pages 291-294.

Rezai, Mahmoud; Rahmatian, Peyman; and Ventura, C.E., 1998, "Seismic data analysis of a seven-storey building using frequency response function and wavelet transform", *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, California Universities for Research in Earthquake Engineering (CUREe), Richmond, California, Vol. III-B, pages III-421 -- III-428.

Rojahn, Christopher, Comartin, C.D., and King, S.A., 2001, "Guidelines for utilizing strong-motion and ShakeMap data in postearthquake response: an overview", *SMIP01 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Los Angeles, Sep 12, 2001, California Division of Mines and Geology, Sacramento.

SEAOSC, 1971, *Basic Interpretation of Strong-Motion Accelerograms in Buildings*, Structural Engineers Association of Southern California Seismology Subcommittee on Seismic Instrumentation and Testing Preliminary Report, Los Angeles, California.

Shakal, A.F. et al., 1989, *CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California, earthquake of 17 October 1989*, Report OSMS 89-06, California Office of Strong Motion Studies, 196 pages.

Shakal, A.F. and Huang, M.J., 1995, Northridge earthquake of January 17, 1994: reconnaissance report, Volume 1 -- recorded ground and structure motions, *Earthquake Spectra*, 11, Suppl. C, pages 13-96, EERI Publication 95-03.

Shakal, A.F. and Huang, M.J., 1996, Strong motion instrumentation and recent data recorded at dams, *Earthquake Engineering for Dams: 1996 Western Regional Technical Seminar, Proceedings*, Assn. of State Dam Safety Officials, Sacramento, California, pages 111-126.

Shakal, A.F., Huang, M.-J. and Ventura, C.E., 1989, "State-of-the-art report: the California strong motion instrumentation program – objectives, status and recent data", *Proceedings, Ninth World Conference on Earthquake Engineering*, Japan Assn. for Earthquake Disaster Prevention, Tokyo, Vol. VIII, Paper SB-R2, pages 105-116.

Viksne, A., Wood, C. and Copeland, D., 1993, Technical note: Bureau of Reclamation Strong Motion Instrumentation Program, *Earthquake Spectra*, 9, 4, pages 885-887.